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PhD Thesis
May 2019

DTU Environment
Department of Environmental Engineering

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This PhD project followed the Industrial PhD Programme offered by Innovation Fund Denmark (Innovationsfonden, File No. 0603-00523B) and was conducted as a collaboration between The Technical University of Denmark (DTU) and Ulandshjælp fra Folk til Folk – Humana People to People.

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Preface

The research for this PhD thesis was carried out at the Department of Environmental Engineering of the Technical University of Denmark (DTU) under the supervision of Professor Charlotte Scheutz and Senior Researcher Anders Damgaard and at the charity organisation Ulandshjælp fra Folk til Folk – Humana People to People under the supervision of Collection Manager Kaj Pihl. The project followed the Industrial PhD programme offered by Innovation Fund Denmark (www.innovationsfonden.dk).

The thesis is organized in two parts: the first part puts into context the findings of the PhD in an introductive review; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-V**.

I **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2018. Development and testing of a sorting and quality assessment method for textile waste. *Waste Management*, 79, 8-21. https://doi.org/10.1016/j.wasman.2018.07.008

II **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2019. Quantity and quality of clothing and household textiles in the Danish household waste. *Waste Management*, 87, 454-463. https://doi.org/10.1016/j.wasman.2019.02.020

III **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2019. Evaluation of a European textile sorting centre: material flow analysis and life cycle inventory. *Resource, Conversation and Recycling*, 143, 310-319. https://doi.org/10.1016/j.resconrec.2019.01.010

IV **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2019. Replacement rates for second-hand clothing and household textiles – a survey study from Malawi, Mozambique and Angola. Journal of Cleaner Production. Manuscript accepted with revision in March 2019.

V **Nørup, N.,** Scheutz, C., Pihl, K., Damgaard, A., 2019. Life cycle assessment of increased collection and reuse of textiles currently discarded with residual waste. Draft manuscript in preparation for *Industrial Ecology*.

In this online version of the PhD thesis, paper **I-VI** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

In addition, the following publications, not included in this thesis, were also concluded during this PhD study:

Nørup, N., Pihl, K., Damgaard, A., Scheutz, C., 2016. Quality of textile waste: a case study of residual household waste from Odense Municipality, Denmark, ISWA World Congress, 19-21 September, Novi Sad, Serbian, Conference paper.

Nørup, N., 2018. Stil nu krav til tekstilindsamlingen (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/stil-nu-krav-til-tekstilindsamlingen

Nørup, N., 2018. Kan man upcycle? (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/kan-man-upcycle

Nørup, N., 2018. Regulering, tak (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/regulering-tak

Nørup, N., 2018. Bliver det den sidste sorte mode uge? (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/bliver-det-den-sidste-sorte-modeuge

Nørup, N., 2017. Genbrug er ikke mode! (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/genbrug-er-ikke-mode

Nørup, N., 2017. Skal vi løse problemerne eller fjerne symptomerne? (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/skal-vi-l%C3%B8se-problemet-eller-fjerne-symptomerne

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Nørup, N., 2017. Bæredygtig mode - andet end visioner? (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/b%C3%A6redygtig-mode-andet-end-visioner

Nørup, N., 2016. Er der værdi i dine underbukser? (in Danish) Forskerzonen, Videnskab.dk, Carl Jacobsens Vej 16, opg. 16, 2. sal, 2500 Valby. In Danish. https://videnskab.dk/miljo-naturvidenskab/er-der-vaerdi-i-dine-underbukser

Nørup, N., 2015. Status på verdens vigtigste år (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/status-p%C3%A5-verdens-vigtigste-%C3%A5r

Nørup, N., 2015. Er grønt forbrug muligt? (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/er-gr%C3%B8nt-forbrug-muligt?page=9

Nørup, N., 2015. Der skal råbes højt (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/der-skal-r%C3%A5bes-h%C3%B8jt?page=57

Nørup, N., 2015. Gør det nemt at smide tøjet (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/g%C3%B8r-det-nemt-smide-t%C3%B8jet

Nørup, N., 2015. Vi kan forebygge tøjaffald (in Danish) Klimakommentar, Arbejderen, Hillerødgade 30A, 220 København N, https://arbejderen.dk/blog-indl%C3%A6g/nynne-n%C3%B8rup/vi-kan-forebygge-t%C3%B8jaffald

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To my colleagues at UFF-Humana in Denmark and in Humana, especially in Lithuania, Norway, Germany, Malawi, Angola and Mozambique, thank you for supporting the project and providing the data and insights into the second-hand textiles industry.

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Summary

The textile sector is a highly polluting industry, in terms of the high emission of greenhouse gases, and has many resources tied up in the production of each piece. The consumption of textiles is high, and rising, especially for clothing, the worldwide figures for which are projected to grow to 160 million tonnes annually in 2050. Nevertheless, it is only in recent years that textiles have been integrated into the waste area as an independent waste fraction that requires separate handling. In spite of this increased focus, there is a real lack of data and knowledge on the topic, especially on assessing the potential for improving collection, studies into what used textiles actually replace through further sales for reuse and recycling and assessments of the environmental effects of improved management.

Previous environmental assessments (such as life cycle assessments (LCAs)) indicate that the best waste treatment of textiles follows the waste hierarchy. However, these environmental assessment studies, particularly in relation to the waste management of disposed textiles, have been limited by a lack of data. Furthermore, despite the fact that international textile sorting centres are essential for ensuring the highest possible use of textiles, the database for these is severely inadequate, and the replacement rate for sorted textiles is a crucial factor in environmental assessment studies where the database is almost non-existent. The replacement rate is used to determine how much reused clothing replaces the purchase of new clothes. In general, textiles are complex to model in an example LCA, and this complexity increases when looking at the textile waste fraction. The proper handling of textile waste requires determining each product according to whether it can be reused or recycled, depending on the type of product, its state, method of manufacture and fibre composition.

As a result of an EU requirement to ensure the mandatory separate collection of textiles, an increase in this practice is expected, and so it is important to clarify how large quantities can potentially be collected and what the quality of these are. Most textiles currently collected are exported from Western countries, mainly due to the very high consumption of new clothing, so with any collection, it will be even more relevant and urgent to include concrete collection, sorting and handling details in environmental assessments such as LCAs.

The purpose of this PhD study is therefore to assess the environmental potential of an increase in the collection of textiles from Danish households. The environmental assessment is based on determining the potential for collecting more textiles from the Danish household waste, thereby improving data on the collection, handling and sorting of discarded textiles, and determining the replacement rates for second-hand textiles in three African countries.

The focus on the potential of household waste was chosen because material flow analysis (MFA) studies have indicated that the potential is highest from households, and because the potential in the waste represents a quantity of textiles citizens have decided to discard. In order to determine this potential, it was necessary to develop a definition of textiles and a method for assessing their quantity and quality in waste. A review of the literature showed that this lack of a clear definition and method means that the amounts of textiles found in waste vary greatly at between 1% and up to 22% of the total amount of waste. Developing the definition and method was an iterative process based on a literature study, field study and waste sorting, as well as an evaluation of the method in relation to previous methods. The definition and method were applied to collected waste samples of residual waste and small combustibles from recycling stations, and this formed the basis for determining the Danish potential to increase the collection of textiles from household waste.

An MFA, a life cycle inventory (LCI) and an economic analysis were used to analyse an international textile sorting centre's mass flows and sorting rates, with the purpose of generating data for use, for example, in an environmental assessment.

The replacement rates of used textiles exported and sold in Angola, Malawi and Mozambique were established based on a total of 3,485 face-to-face interviews and 14,100 products, and the statistics program JMP was used for data management and replacement rate calculation. The calculation model itself was the same as found in a previous study of the replacement rate, which is why the results are comparable, albeit the study was also used to evaluate the method especially in relation to its use in an African context.

Based on the identified potential for increasing the collection of textiles from Danish households, and improved data for the textile management system, an LCA model was set up in EASETECH to assess the environmental benefits of realising this potential. This was done by setting up four scenarios: 1) Scenario

0, a baseline scenario with no sorting; 2) scenario 0a, which only included sorting out the potential found in rags; 3) scenario 1 where the full potential was sorted out followed by sorting at an international textile sorting centre; and 3) scenario 2 where the full potential was sorted out followed by sorting at a Danish textile sorting centre.

The results of the studies carried out showed that with a clear and functional definition and method for sorting textiles. The amount of textiles in household waste was small, but compared to the yearly consumption of new textiles per Dane it was high. In residual waste, an average of 1.4 ± 0.5% was Clothing, and an average of 0.6 ± 0.3% was Household textiles (based on weight). On an annual basis, this corresponds to 2.4 ± 1.9 kg Clothing and 1.1 ± 0.5kg Household textiles per citizen in Denmark. In small combustibles discarded at Danish recycling stations, an average of 4.5 ± 2.1% was Clothing and an average of 2.6 ± 1.2% was Household textiles. However, in terms of the quality of the fraction, the potential for improvement was high. In the residual waste, an average of 65 ± 8% and 65 ± 19% of Clothing and Household textiles, respectively, could be reused, while an additional average of 12 ± 5% and 15 ± 11%, respectively, could have been recycled. For small combustibles, an average 69 ± 6% of Clothing and 66 ± 10% of Household textiles could be reused, while an average 14 ± 4% of Clothing and an average 16 ± 9% of Household textiles could be recycled. In the residual waste, a large share of the reusable Household textile potential consisted of rags that were discarded in a condition similar to new (21± 15%). Both the definition and the method are essential to ensuring that the generated data are usable across different types of analyses and that there is transparency in relation to, for example, the validity of the results. In relation to understanding how a given potential can be realised, a clear method for determining quality is important, as there are differences in the possibilities of reusing, for instance, a rag compared to a blouse.

The study of the international textile sorting centre showed that although the import of textiles into the facility increased in the period 2015-2017 (total imports were 35,739 tonnes in 2015, 35,668 tonnes in 2016 and 36,292 tonnes in 2017), the share of sorted textiles for reuse decreased from 80% to 75%. Furthermore, it was not just the quantity that fell, but also the quality of the reusable textiles, which was reflected in the fact that sorting levels from the centre’s fine sorting unit fell from 33% to 29%, and this happened at the same time as an increase in imports of pre-sorted textiles only fine-sorted. This in turn led to the consumption of more resources to sort out a tonne of reusable textiles. In addition, the costs of sorting amplified, especially for those categories demanding the most sorting, including the categories from fine sorting. Exports to countries outside Europe also increased during the period. At the same time, the amount of textiles exported for recycling increased from 13% to 17% and waste from 5% to 6%.

The replacement rates for African countries were found to be lower than expected (63 ± 6% Angola, 35 ± 1% Malawi and 37 ± 5% Mozambique, average 45 ± 4%), demonstrating not only the need for the replacement rate to be based on actual investigations, but also the need for more knowledge and further development of the method for determining replacement rates in general. In this study, there was a strong indication that the respondents' economic purchasing power affected the outcome of the replacement rates, seen in relation to both a national and a cultural context. Thus, the respondents did not have the opportunity to buy new textiles, which meant that the replacement rates were higher in the African countries, the richer the respondents were, while this seemed to be the opposite in the few previous studies conducted in European countries.

The environmental assessment showed that even by only ensuring that rags are (re)used in households, there is a considerable environmental benefit in terms of avoided CO_2-eq emissions (-1.4 kg per person or equal to -7,899 tonnes for the total Danish population). By modelling the full potential for increasing collection, the best handling method would save 30.2 kg of CO_2-eq per person (172,104 tonnes for the total Danish population). Having the total potential sorted in Denmark only gives a saving of 12.4 kg CO_2-eq per person, as less textiles would be sorted out for reuse or recycling, and because a larger share of the textiles are sorted out as waste. However, it should be considered that these savings are uncertain estimates, as the modelling of textiles in LCAs is extremely complex and highly limited by sparse data. Even with the large data collection in this PhD thesis there is still a need for improvements, especially with regards to the impact from production of textiles and the replacement rates.

This PhD study has been part of the Innovation Foundation's industrial PhD programme and has been a collaboration between the Department of Environmental Engineering at the Technical University of Denmark (DTU Environment) and the charity organisation Ulandshjælp from Folk til Folk - Humana People to People (UFF-Humana).

Dansk sammenfatning

Tekstilsektoren er en stærkt forurenende industri med en høj udledning af drivhusgasser og mange ressourcer bundet i produktionen af hvert enkelt stykke tekstil. Forbruget af tekstiler er højt og stigende, særligt for beklædning. På verdensplan fremskrives forbruget af beklædning at vokse til 160 millioner tons årligt i 2050. Alligevel er det først inden for de senere år, at tekstiler er ved at blive integreret i affaldsområdet som en selvstændig affaldsfraktion, der kræver særskilt håndtering. Til trods for den øgede opmærksomhed er der en reel mangel på data og viden inden for området. Der mangler især viden om, hvad potentialet er for at forbedre indsamling af tekstiler; undersøgelser af hvad de brugte tekstiler reelt erstatter på grund af videresalg til genbrug og genanvendelse, samt hvad effekten er af denne forbedrede håndtering på baggrund af miljøvurderingerne.

Tidligere miljøvurderinger (herunder livscyklusvurderinger (LCA'er)) af tekstiler indikerer, at den bedste håndtering af tekstiler følger affaldshierarkiet. De hidtil udførte miljøvurderinger af affaldshåndtering af bortskaffede tekstiler har dog været særligt begrænsede af manglende data på området. Til trods for at de internationale tekstilsorteringsanlæg er afgørende for at sikre højst mulig anvendelse af tekstilerne, er datagrundelaget for disse også stærkt begrænset. Desuden er erstatningsgraden for de sorterede tekstiler en afgørende faktor i miljøvurderinger, hvor datagrundlaget er næsten ikkeeksisterende. Erstatningsgraden bruges til at bestemme, hvor meget for eksempel genbrugstøj erstatter køb af nyt tøj. Generelt er tekstiler komplekse at modellere i for eksempel LCA. Kompleksiteten øges yderligere, når man ser nærmere på tekstilerne i affaldsfraktionen. Korrekt håndtering kræver, at der tages stilling til hvert enkelt produkt i forhold til, om det kan genbrugs eller genanvendes, hvilket afhænger af produkttype, produktets tilstand, fremstillingsmetode og fibersammensætning.

Med EU's krav om obligatorisk separat indsamling af tekstiler forventes en stigning i indsamlingen af tekstiler. Det er derfor væsentligt at få klarlagt, hvor store mængder der potentielt kan samles ind, og hvad kvaliteten er af disse. Allerede ved den nuværende indsamling eksporteres størstedelen af de indsamlede tekstiler, hvilket blandt andet skyldes det meget høje forbrug af ny beklædning i de vestlige lande samt et relativt lille marked for brugt tøj. Med en øget indsamling bliver det yderligere relevant og presserende at inkludere den konkrete indsamling, sortering og håndtering af tekstilerne i miljøvurderingerne.

Formålet med denne afhandling er derfor at vurdere, hvad det miljømæssige potentiale er ved at øge indsamling af tekstiler fra de danske husholdninger. Miljøvurderingen er baseret på en kortlægning af potentialet ved at indsamle mere tekstil fra det danske husholdningsaffald; forbedring af data fra indsamling, håndtering og sortering af kasserede tekstiler samt bestemmelse af erstatningsgraden for brugte tekstiler solgt i tre afrikanske lande.

Fokus på potentialet i husholdningsaffald er valgt, fordi massestrømsanalyser (MFA) har indikeret, at de største muligheder for forbedring er fra husholdningerne, og fordi potentialet i affaldet repræsenterer en tekstilmængde, borgerne i forvejen har besluttet at skille sig af med. For at kunne fastlægge dette potentiale, har det været nødvendigt at udvikle en klar definition af tekstiler samt en metode til kvantitativt og kvalitativt at vurdere tekstiler i affald. Gennemgang af litteraturen viste, at den manglende definition og metode gør, at mængden af tekstiler fundet i affald opgøres med stor variation på mellem 1% og op til 22% af den samlede affaldsmængde. Udvikling af definition og metode har været en iterativ proces, og er baseret på litteraturstudie, feltstudie og affaldssortering, samt evaluering af metoden i forhold tidligere metoder. Definitionen og metoden blev anvendt på indsamlede affaldsprøver af husholdningsaffald og småt brændbart indsamlet på genbrugspladser, og danner grundlag for fastsættelsen af det danske potentiale for at øge indsamling af tekstil fra husholdninger, som i dag bortskaffes via affaldet.

En MFA, livscyklusopgørelse (LCI) og økonomisk analyse har været brugt til at analysere et internationalt sorteringsanlægs massestrømme og sorteringsrater med formålet om at genere data til brug i eksempelvis miljøvurderinger.

Erstatningsgraden af brugte tekstiler sorteret på sorteringsanlæg, eksporteret og solgt i Angola, Malawi og Mozambique er bestemt ud fra i alt 3.485 face-to-face interviews vedrørende 14.100 produkter, og statistikprogrammet JMP har været brugt til datamanagement og beregning af erstatningsgrader. Selve beregningsmodellen har været den samme som fundet i et tidligere studie af erstatningsgraden, hvorfor resultaterne har kunnet sammenlignes, men undersøgelsen har også kunnet bruges til at evaluere metoden, især i forhold til brug i en afrikansk kontekst.

Med udgangspunkt i de forbedrede data om affaldshåndtering af tekstiler er der udført en miljøvurdering i EASETECH til at evaluere klimaeffekten af realisering af hele eller dele af mængden af de tekstiler, der i dag bortskaffes via affaldet fra husholdninger. Modellen blev sat op med fire scenarier: a) et basisscenarie (scenarie 0) som repræsenter status quo, dvs. ingen udsortering; b) scenarie 0a, hvor der sker en udsortering af karklude; 3) scenarie 1, hvor der sker en udsortering af det fulde potentiale med efterfølgende sortering på et internationalt tekstilsorteringsanlæg; og 4) scenarie 2, hvor der sker en udsortering af det fulde potentiale med efterfølgende sortering på et dansk tekstilsorteringsanlæg.

Resultaterne af de udførte affaldssorteringsundersøgelser viser, at en klar og funktionel definition og metode er afgørende ved sortering af tekstiler. Mængden af tekstiler i husholdningsaffaldet var dog lille, men i forhold til det årlige forbrug af nyt tekstil pr danske var det højt. I dagrenovation var mængderne 1,4 ± 0,5% beklædning og 0,6 ± 0,3% husholdningstekstiler, hvilket svarer til at hver dansker årlig smider 2,4 ± 1,9 kg beklædning og 1,1 ± 0.5kg husholdningstekstiler ud. I småt brændbart fra genbrugspladser var 4,5 ± 2,1% beklædning og 2,6 ± 1,2% husholdningstekstiler. I forhold til kvaliteten af fraktionen, var potentialet for forbedringer højt. I alt ville gennemsnitligt 65 ± 8% og 65 ± 19% af henholdsvis beklædning og husholdningstekstilerne i dagrenovation kunne genbruges, mens yderligere gennemsnitligt 12 ± 5% og 15 ± 11% kunne genanvendes. For småt brændbart var tallene gennemsnitligt 69 ± 6% beklædning og 66 ± 10% husholdningstekstiler, der kunne genbruges, mens gennemsnitligt 14 ± 4% beklædning og 16 ± 9% husholdningstekstiler kunne genanvendes. I husholdningstekstiler i dagrenovation bestod en stor del af det genbrugelige potentiale af karklude (21 ± 15%), der var kasseret i tilsyneladende næsten ny stand. Definition og metode er desuden afgørende for at kunne sikre, at de genererede data er anvendelige på tværs af analysetyper og sikrer gennemsigtighed i forhold til eksempelvis validiteten af resultaterne. Men også i forhold til at forstå, hvordan et givent potentiale kan realiseres, er en klar definition og metode afgørende. Eksempelvis er der forskel på mulighederne for at genbruge klude frem for bluser.

Undersøgelsen af det internationale sorteringsanlæg viste, at selvom importen af tekstiler til anlægget steg i perioden 2015-2017 (total import var henholdsvis 35.739 tons i 2015, 35.668 tons i 2016 og 36.292 tons i 2017) faldt andelen af udsorterede tekstiler til genbrug fra 80% til 75%. Det var ikke kun mængden der faldt, kvaliteten af de genbrugelige tekstiler faldt også. Dette gav sig til udtryk i, at udsortering fra anlæggets finsorteringsenhed faldt fra 33% til 29%, hvilket skete samtidig med en øget import af præ-sorterede tekstiler, der sendes direkte til finsortering. Dette medførte et øget forbrug af ressourcer til udsortering af et ton genbrugelige tekstiler. Ligeledes steg omkostningerne til udsortering, især for de mest sorteringskrævende kvaliteter, herunder kvaliteterne fra finsorteringen. Eksporten til lande uden for Europa steg også i perioden.

Samtidig steg mængden til genanvendelse fra 13% til 17% og affald fra 5% til 6%.

Erstatningsgraden for de afrikanske lande viste sig at være lavere end forventet (63 ± 6% Angola, 35 ± 1% Malawi og 37 ± 5% Mozambique, gennemsnitlig 45 ± 4%), hvilket påviser behovet for, at erstatningsgraden skal være baseret på faktiske undersøgelser, men også viser, at der er behov for mere viden og yderligere udvikling af metoden til at fastsætte erstatningsgraden. Ved undersøgelsen sås en stærk indikation af, at respondenternes økonomiske råderum påvirkede udfaldet af erstatningsgraden set i forhold til en kulturel kontekst. Respondenterne havde dermed ikke mulighed for at købe nyt tøj. Dette betød, at erstatningsgraden blev højere i de afrikanske lande, jo rigere respondenterne synes at være, mens det virkede til at være modsat i de få tidligere undersøgelser udført i europæiske lande.

Miljøvurderingen viste, at selv ved kun at sikre, at karklude bliver (gen)brugt i hjemmet, er der en reel miljøgevinst klimamæssigt (1,4 kg CO_2-eq per person eller hvad der svarer til 7899 tons CO_2-eq for hele den danske befolkning). Ved modellering af det fulde potentiale for at øge indsamlingen var der ved den bedste håndtering mulighed for at spare 30,2 kg CO_2-eq per person (172.104 tons for hele befolkningen). Udsortering af det fulde potentiale med sortering i Danmark gav kun en besparelse på 12,4 kg CO_2-eq per person, fordi der udsorteres mindre til genbrug og genanvendelse, og en større mængde udsorteres som affald. Det er dog vigtigt at erkende, at resultaterne af vurderingen skal ses om usikre estimater, da modelleringen af tekstiler i LCA'er er yderst kompleks og stærkt begrænset af tilgængelige data. Selv ved den store dataindsamling udført i dette PhD studie er der stadig behov for forbedringer, især i forhold til data for påvirkningen fra produktion af tekstiler og erstatningsgraden.

Ph.d.-studiet har været en del af Innovationsfondens ErhvervsPhD program, og et samarbejde mellem Institut for Vand og Miljøteknologi på Danmarks Tekniske Universitet (DTU Miljø) og indsamlingsorganisation Ulandshjælp fra Folk til Folk – Humana People to People (UFF-Humana).

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1 Introduction and research objectives

1.1 Background and motivations

The textile industry is one of the most polluting industries in the world (Laitala et al 2012, Rock 1996) and the fourth most polluting sector in the EU (Beton et al., 2014). Production is characterised by high resource consumption, pollution and poor working conditions, and textile use requires water and electricity on a daily basis (Mair et al., 2016; Resta and Dotti, 2015). The production and use phases alone make up 3% of global greenhouse gas emissions (Carbon Trust, 2011), while the production phase (including cotton farming) uses around 93 billion cubic metres of water annually, which accounts for 4% of the global consumption of fresh water (Ellen MacArthur Foundation, 2017).

At the same time, the consumption of textiles is increasing (WRAP, 2017a). Mckinsey (2017) states that 2019 will be the first year in which the consumption of textiles will be distributed evenly between the Western world and the rest of the world, primarily because utilisation in the rest of the world is increasing. Greater prosperity has meant that countries such as China are beginning to approach European and American levels of textile use (Bartle, 2010), and at current levels, the fashion industry predicts consumption in 2050 will be 160 million tonnes (Ellen MacArthur Foundation, 2017). This is an alarming figure, as the environmental impact per product is high compared to other products (Chapman, 2010), and it stresses the importance of improving the entire life cycle of textiles, especially due to reuse, and that the resources in textiles are recycled and thus not lost when disposed of. Although textiles make up a smaller percentage of total waste in comparison to other waste fractions such as food waste, the environmental impact of improvements in textile waste processing is higher per weight unit (Palm, 2011).

Nevertheless, textiles have only recently become part of the discussion on waste, presumably because they were assumed to make up a relatively small percentage of the total amount generated. In many countries, the handling of waste textiles is managed primarily by charity organisations (Payne, 2015). An increased focus on the impact of textiles in recent years has revealed a general lack of knowledge of how textile waste is managed. Consequently, the Nordic Council of Ministers recommended in 2014 that certification be introduced to address this lack of knowledge (Palm et al., 2014).

Previous life cycle assessments (LCAs) of the life cycle of textile products or the handling of textile waste all point to the notion that the most environmentally friendly handling of textiles follows the waste hierarchy – reuse, recycle, incineration and landfill (e.g. Dahlbo et al., 2017; Glew et al., 2012; Lanoë et al., 2013; Sandin and Peters, 2018; Woolridge et al., 2005). Previous LCAs have been characterised by sparsely available data on the subject, and they have often been based on the consumption of textiles rather than on their actual content in waste (e.g. Beton et al., 2014; Dahlbo et al., 2017). In a recent review by Sandin and Peters (2018) of LCAs on textile product, it was found that in the majority of the studies, the sorting and handling of textiles in the waste management phase were omitted or sparsely modelled, due to a lack of data and knowledge. Similarly, resources and emissions associated with treatment prior to reuse and the actual recycling process were often not included. LCAs have no, or only sparse, data for the replacement rates for second-hand textiles (which determine the degree that an item replaces a new textile item), even though this is an essential factor when making an LCA analysis (Sandin and Peters, 2018; Schmidt et al., 2016; Vadenbo et al., 2017). There is therefore a need to provide data for textile waste management and to determine replacement rates, as the majority of LCAs carried out on handling textiles in terms of reusing and recycling either leave these out or use estimates, as data are very limited.

Chapman (2010) found that in general it is a complex undertaking to acquire data for LCAs on textiles, a point that is generally recognised (e.g. Beton et al., 2014; Koszewska 2015; Muthu, 2015). Chapman (2010) also concludes that the production of textiles is the phase with the most and best available data, but it is still characterised by data being sparse and old. The complexity of modelling textiles does not diminish by modelling this as a waste fraction but increases, because the waste consists of many different textile products and proper handling depends on a range of factors, such as the condition of the individual product, product type, manufacturing method and fibre composition.

With the EU requirements for the mandatory separate collection of textile waste, it is expected that the amount of collected textiles will increase (EC, 2018). Previous studies have indicated that the greatest potential is from households (Beton et al., 2014; The Danish EPA, 2018; Tojo et al., 2012); however, there is currently limited knowledge on this potential, as only very few studies have examined how households dispose of textiles, what is in household waste and (WRAP, 2017a), not least, the level of quality. Thus, it is uncertain what the effect of an increased textile collection regime would have overall. Furthermore, there is no uniform definition of what defines textiles, and previous studies often do not state clearly what textile products and types were included, or if other products were also considered (e.g. Ayeleru et al., 2004; Kadir et al., 2017; Saidan et al., 2016), which is why studies are difficult to compare. It is even unclear what charity organisations include in their understanding of textiles, and so without a clear definition, it is difficult to determine any potential, both quantitatively and qualitatively, in improving collection procedures.

At the same time, increased textile collection will increase further the need for more knowledge and data about collection, sorting and the final fate of recovered textiles. In relation to the existing collection of textiles in many Western countries, there is no domestic market for all reusable or recyclable textiles (Palm et. al. 2014; Watson et al., 2016, Wrap, 2017b). The majority of the textiles are sold on the international market primarily to textile sorting centres, which are essential to ensuring that as large a fraction of the collected textiles is used through either reuse or recycling. As such, they serve as an important link between collection and the second-hand textiles market.

In addition, it should be pointed out that only a very limited portion of the collected textiles are reused domestically, and most of these are of higher quality than those eventually sold to the Middle East or Africa (Watson et al., 2016). However, the few studies that have investigated the replacement rate were all conducted in European countries (Castellani et al., 2015; Farrant et al., 2010; Stevenson and Gmitrowicz, 2013). It is therefore essential to establish replacement rates for non-European countries, as the majority of textiles end up in these regions. Imports of second-hand textiles into African countries represent a large percentage of imports by value (Watson et al., 2016); as an example in Malawi, approximately 60% of the total textile imports in 2003 were second-hand (Baden and Barber 2005). However, the replacement rate is a complex unit to determine, as it relates to the individual citizen's economic purchasing power, and therefore it is difficult to measure accurately and to do so in a way so that uncertainties are reduced when scaling up to the national level.

Therefore, there is a great need for improving knowledge regarding the potential for better textile waste management regarding estimating both the quantities and qualities of textiles that could be collected, and improving the data for assessing the best environmental handling and treatment options.

1.2 Research objectives

The overall objective of this PhD thesis is to improve the basis for and to determine and assess the environmental impact of the increased collection, sorting, reuse and recycling of clothing and household textiles in Denmark. As a basis for this environmental assessment, the following sub-objectives were identified:

• To establish a clear definition of textiles and develop a method to quantify and qualify textiles discarded in household waste.

• To determine the potential for reusing and recycling clothing and household textiles that are currently discarded in Danish residual waste and small combustibles (household waste).

• To determine sorting rates for reuse, recycling and waste, respectively, at international, full-scale textile sorting centres.

• To determine the replacement rate for second-hand textiles in an African context and evaluate the applied method.

• To carry out an environmental assessment of the environmental impact of increasing the collection of clothing and household textiles that currently are thrown away with household waste.

1.3 PhD thesis structure

This PhD thesis is structured into five research subjects that can be grouped into three main areas: a determination of textile collection potential, data improvements regarding sorting and replacement rates and an environmental assessment of increased textile collection, reuse and recycling. The structures and correlations between the sub-objectives and areas are shown in Figure 1.

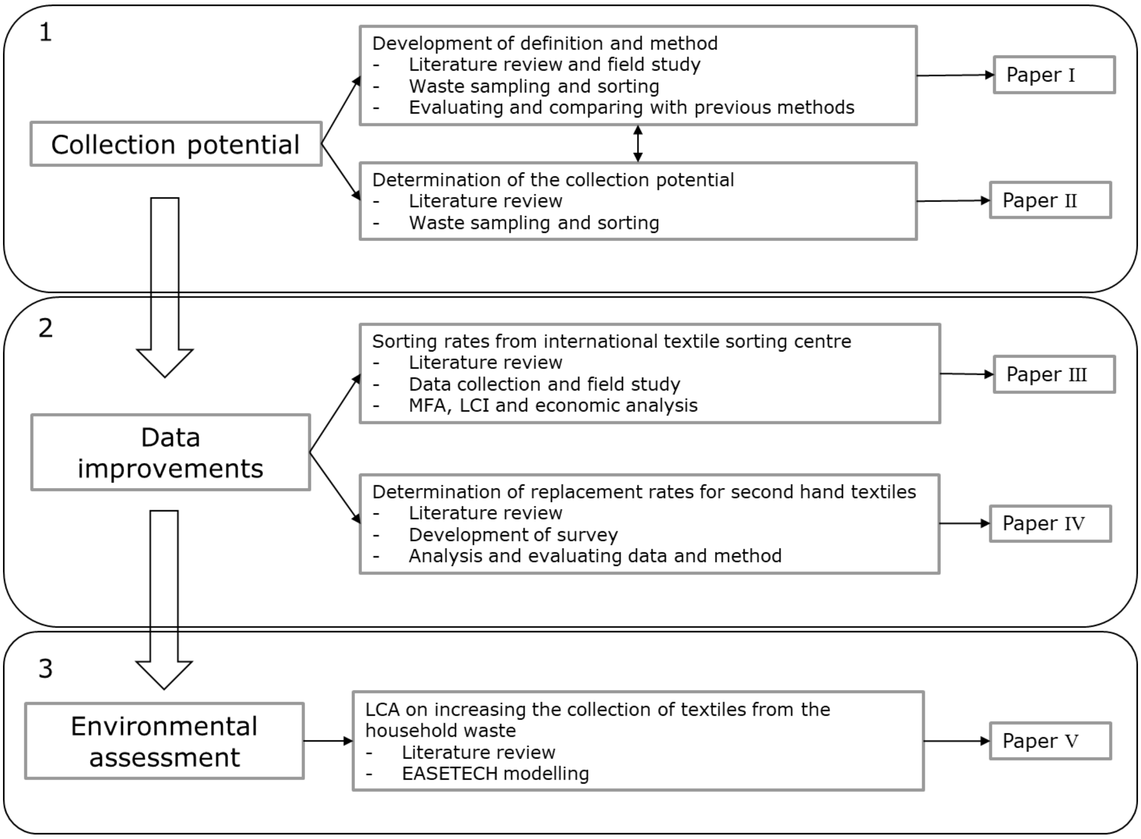

Figure 1. Overview of the structures and correlations between research sub-objectives and areas. Within each area are shown the sub-objectives and the main methods applied to obtain the sub-objectives. Finally, the outcome in terms of scientific papers is shown.

Textile collection potential: In order to assess the potential for improving the collection and the current handling of textiles discarded in household waste, it is necessary to investigate the amount and quality of the textiles currently discarded.

Data improvements: In order to analyse and assess how textiles are best handled, insights and knowledge about existing handling (collection, sorting, reuse and replacement) need to be gathered and the quality improved.

Environmental assessment: By analysing the environmental impacts of the current handling of textiles, it is possible to propose improvements in future handling. This will be done by incorporating knowledge and data from the two previous areas. Likewise, an LCA will allow for an analysis of the parameters of greatest importance with regards to uncertainty and data needs, thus clarifying further where future research should be targeted.

2 Danish textile flow and the international market for reuse and recycling

2.1 Textile flow in Danish households

The private consumption of clothing and household textiles is high (WRAP, 2017a; Beton et al. 2014), and mass flow analyses (MFAs) indicate that the potential for improving textile collection in overall quantities is greater from households than from other consumers (e.g. private industries or the public sector) (Koligkioni et al., 2018; The Danish EPA, 2018; Tojo et. al, 2012). Current annual textiles consumption in Denmark, Sweden, Norway and Finland stands at between 13 and 16 kg per person (Tojo et al., 2012; Palm et al., 2014).

The collection potential for textiles from households can be divided into three categories: 1) the volume that is already separately collected/sold, 2) accumulated volume in private households and 3) the volume in household waste (Figure 2). The volume of textiles collected separately today is the best known of the three, as this has been investigated in studies by, for example, the Nordic Minister Council, and there are already several suggestions on how to improve and increase this process (e.g. Palm et al., 2015). The amounts of textiles accumulated in private households are unknown, though, as there are limited studies regarding this topic, and no Danish studies have been found (Klepp and Laitala, 2015; Maldini et al., 2017). This part of the potential could be regarded as passive, and can be considered a stockpile in the household regardless of whether household members use them or not. Moreover, when a person wants to dispose of these items, the possibilities on offer are either separate collection (1) which includes donations to charity, private sale, trading, etc.) or via household waste (3). The textiles in household waste can potentially be realised and recovered for reuse or recycling, as citizens have already decided that they do not want to keep them any longer.

In 2012, the Nordic Minister Council recommended that the quantities and qualities of textiles in household waste should be determined (Tojo et al., 2012), although five years later, WRAP (2017a) found that in a European context, the quantities in waste still could not be established based on the available literature at the time of the study.

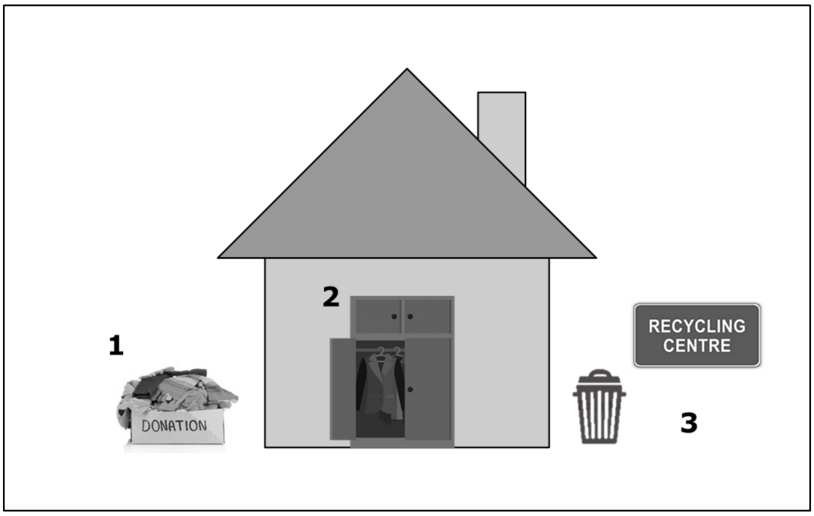

Figure 2. Potential textile sources in the household. 1) Separately collected textiles including textiles already given away or sold e.g. to charity, family or friends through formal and informal channels. 2) Textiles accumulated in the household including active and passive stock ± Δ stock (in use, not-in use and non-used textiles). 3) Textiles thrown out in the waste, including reusable, recyclable and waste disposed of in household waste (residual waste and small combustibles).

By reviewing scientific articles, technical reports and sorting manuals in English and Scandinavian, it was established that generally there is no consensus on a definition of what textiles include; furthermore, only a few articles and guides included an actual assessment of quality in this regard. The review found that the content of textiles in waste ranged from 0.5% to 22% (Paper I), and when considering the Danish waste stream only, it was found that the amount was between 1.8 kg to 14.8 kg per person per year (The Danish EPA, 2018). However, most of the studies did not have a clear definition of textiles, and in many of them textiles were not actually considered a separate waste fraction but were rather included in a bulk fraction referred to as 'combustibles'. Without a clear textile definition and a quality assessment, it is highly unlikely that any generated data can be used either quantitatively or particularly qualitatively. An example of the broad understanding of the term 'textile' is evident in the EU's nomenclature Chapters 50-63, which consider anything from yarn and fibre residues to diapers, tents and shirts (Statistic Denmark, 2018).

A recently made MFA on the Danish textile flow from summer 2018 included an examination of both the quantities and the qualities of the nation's residual waste (The Danish EPA, 2018). The study found that the average household throws out 7.5 kg of clothing and household textiles annually, which is equal to 3.6 kg per resident. The quality was assessed separately for multi-family houses and single-family houses, and it was found that 33% and 21% of the textile waste from multi-family housing could be reused or recycled, respectively. For single-family housing, the numbers were 16% and 28%, respectively. However, it is not clear if the full definition of textiles used in this study was the same as the one used for waste sorting. The sorting method used for assessing quality was the same as for assessing separately collected textiles, but without any adaptation to cover textiles thrown out in the waste. In the study, all textiles sorted out from the waste were washed before quality assessment, which could have affected their quality. The study also focused on the economic value of the textiles and thereby what textiles could be sold for reuse – a move that could have underestimated the true amount, as it could have left out functionally working textiles. Profits on the international market for second-hand textiles are marginal (Hawley, 2006), and as sorting is mainly manual work, the wage level has a high influence on the quality of textile products. If sorting is done in a high-wage country like Denmark, it means less time will be invested in sorting the textiles, which why only high-quality items are considered. Even though the majority of the collections in Denmark are done mainly by charity organisations with primarily volunteer workers, the sorting costs mean that most textiles are sold unsorted into the international second-hand market.

2.2 The international reuse and recycling market

In order to understand the international textile market, it is necessary to appreciate how the market has evolved and what has caused this development.

The international textile market has existed for a long time, but it has changed somewhat over the years (Lemire, 2012). It is only in recent times that the overuse of textiles has become a problem, mainly in the Western world, due to the development of new fibre types and production methods, as well as a rise in prosperity of a large part of the global population. Until the late eighteenth century, reuse was common practice for the majority of the population, except for the wealthiest (Hansen, 2000). However, even among the nobility, there was a tradition of repairing and giving away clothes for reuse (Sanderson, 1997).

When textiles could no longer be reused, they were often recycled. Cotton formed the largest parts of the textiles, and these were recycled into cloths/rags with different uses and sold to the paper industry (Hansen, 2000). In 1813, machinery for recycling mainly wool, but also cotton and linen, into shoddy yarn was invented (Malin, 1979), and this is in principle the same technology that is still used for recycling into the yarn and part of the non-woven process today.

From mainly being reused, repaired and recycled in the household, or sold or swapped to generally one-man companies, the international second-hand market today consists mainly of charity organisations which collect and re-sell to large international textile sorting centres (Hansen, 2000). The largest share of the reusable textile categories is sorted out for reuse in Eastern Europe, Africa and the Middle East (Watson et al., 2016), and the largest share of the recycling of post-consumer textiles is still cotton-based products that are cut into rags (Morley et al., 2006).

The market for textiles for reuse is influenced predominantly by economic and legal conditions, e.g. country-specific requirements or the prohibition of specific products, whereas technological development and commodity prices have a greater influence on recycling options. In 2006, the competitiveness (e.g. lower sales prices, changes in import legislation) of the second-hand textiles market had increased to a degree that threatened the profit margins of the textile-sorting centres, making it a less attractive business to enter and causing businesses to close down (Hawley, 2006).

3 Materials and methods

This chapter contains the materials and methods used in the PhD study. The first section outlines the development of the textile definitions used throughout this research, and the second section concerns the method developed for textile sorting and assessment, which was also applied for determining the quantity and quality of the textiles in household waste. The third section deals with the main elements of the method used for the MFA, LCI and economic data, to determine the sorting rates at a textile sorting centre located in Vilnius. The fourth section concerns the survey method and the calculation model used to determine the textile replacement rate in Angola, Malawi and Mozambique. The fifth and last section concerns the method applied for screening for the environmental benefits for realising the potential for increasing collection of textiles from the household waste.

3.1 Definitions

Table 1 presents the definition of the overall textile fraction, which consists of three sub-fractions: Clothing, Household textiles and Other textiles. This definition enables the use of the generated data in analyses and assessments, such as MFAs, where data on waste are normally used. At the same time, the definitions were constructed so that they could be used in connection with the quality assessment that relies on each specific product. Finally, this definition is also usable when describing sorting systems, such as the second-hand market that operates with a broader understanding of textiles than Clothing and Household textiles, but which also includes part of Other textiles, e.g. shoes, bags or duvets.

Table 1. Overview of the definition of textile fractions in residual waste, divided into three sub-fractions: Clothing, Household textiles and Other textiles. The 'Other textiles' fraction contains all textile products that are not included in the other two fractions (Paper I).

Clothing	Household textiles	Other textiles
25 product types: 1. T-shirts 2. Tops 3. Blouses 4. Shirts 5. Trousers 6. Shorts 7. Winter clothing (with and without insulation) 8. Dresses 9. Skirts 10. Vests 11. Jackets 12. Infants' clothes, incl. socks & gloves 13. Work wear 14. Apron 15. Swimwear 16. Underwear 17. Nightwear 18. Bathrobes 19. Socks 20. Gloves 21. Scarfs & ties 22. Handkerchiefs 23. Costumes 24. Parts of clothing 25. Pieces of clothing Clothing matching the listed products made in leather is also included. Homemade products are included as well.	13 product types: 1. Linens 2. Decoration pillow-cases 3. Bedcovers 4. Curtains 5. Towels 6. Dishtowels 7. Facecloths 8. Potholders 9. Rags 10. Tablecloths 11. Place mats 12. Plaids 13. Pieces of household textiles. Household textiles matching the listed products made in leather are also included. Homemade products are included as well.	Types of products included: duvets, shoes, belts, toys, yarn hats, caps, flags, beanbags, cushions, textile pieces and parts of soft furniture (couch cushions or couch cover). Belts, shoes and bags made of leather are also included. Product types not included: • Carpets with backside coated • Upholstery, if not for the entire couch, box mattresses or armchairs. • Any kind of obvious production waste, e.g. fibres, balls of cotton. • Any kind of disposable personal hygiene products, disposable diapers as well as disposable napkins, tablecloths and gloves.

Table 2 shows the definitions for reuse, recycle and waste that are used throughout the PhD thesis and are a central part of the quality assessment. The quality assessment was developed based on knowledge from sorting centres and through sorting campaigns. In the waste sorting process (Papers I and II), material for reuse is divided into three quality categories, namely A, B and C, to indicate if products were directly reusable or if there were other conditions that should be considered.

The textile sorting centre's quality categorisation is thus not comparable to the quality categories A, B and C used in waste sorting (seen in Table 2). The categories at the sorting centre refer to the economic value of each category. As the sorting at the centre is largely also fashion- and/or trend-based, a reusable product can move between the categories, depending on the market, to ensure the best earnings. The divisions in A, B and C in waste sorting are there exclusively to ensure an objective assessment of an item’s reuse potential, including an understanding of the international market and avoiding an assessment in relation to individual preferences. The A potential consists of products that could have been used if they had not been disposed of in the waste. The B potential consists of products with minor defects, and so the product thus requires a minor repair to be fully functional or more appealing. The C potential consists solely of rags that can be reused, which means that there is a very limited reuse market both nationally and internationally, so reusable rags are kept separate to show that here is some potential, but it requires another handling to be realised (like an information campaign to make users that discard them reuse them instead). In waste sorting, avoidable conditions are registered, such as if the textiles are wet/moist or have become contaminated by other waste when thrown out in household waste (Table 4). These conditions do not affect the quality assessment, whereas products with avoidable conditions for economic reasons are only treated at sorting centres as reusable if the product also has an economic value that makes it profitable to process it accordingly.

Table 2. Definitions of reuse, recycling and waste. The specific division of the three quality categories (A, B and C) in reuse was used in the waste sorting method development and its application (Papers I and II).

Def.	Description
Reuse	Products that can be used again as they are or with minor defects or reparations. **A)** Product types that can definitely be reused. **B)** Product types that still are functional but have minor defects. These products are kept by their owner, mended or sent to a professional sorting centre. The definitions of textiles with minor defects that are still reusable are based on the international market for low-quality clothing and household textiles and consist of products with small stains, minor holes and broken zippers. **C)** Rags (wipers), as these do not fit in the normal reuse system. They can still serve a purpose, even with stains.
Recycle	Product types that are not reusable but can be recycled. The recyclability of a textile product is determined by its fibre composition, how it is produced and its size.
Waste	Product types that cannot fulfil the requirements for being reused or recycled.

3.2 Method for sorting and quality assessing Clothing and Household textiles

A review of the literature showed a need for a method to determine the amount and quality of textiles in waste. The development of this method was an iterative process of dialogue with textile sorting centres, waste sorting plants and testing on waste samples. In addition, an evaluation of previous sorting methods was tested and compared to the new method developed in this study.

The method consists of two parts, namely sorting and a quality assessment, each consisting of two levels (Figure 3). In Section (3.2.1), sorting (Levels 1 and 2) is described, while the quality assessment (Levels 3 and 4) is described in Section (3.2.2).

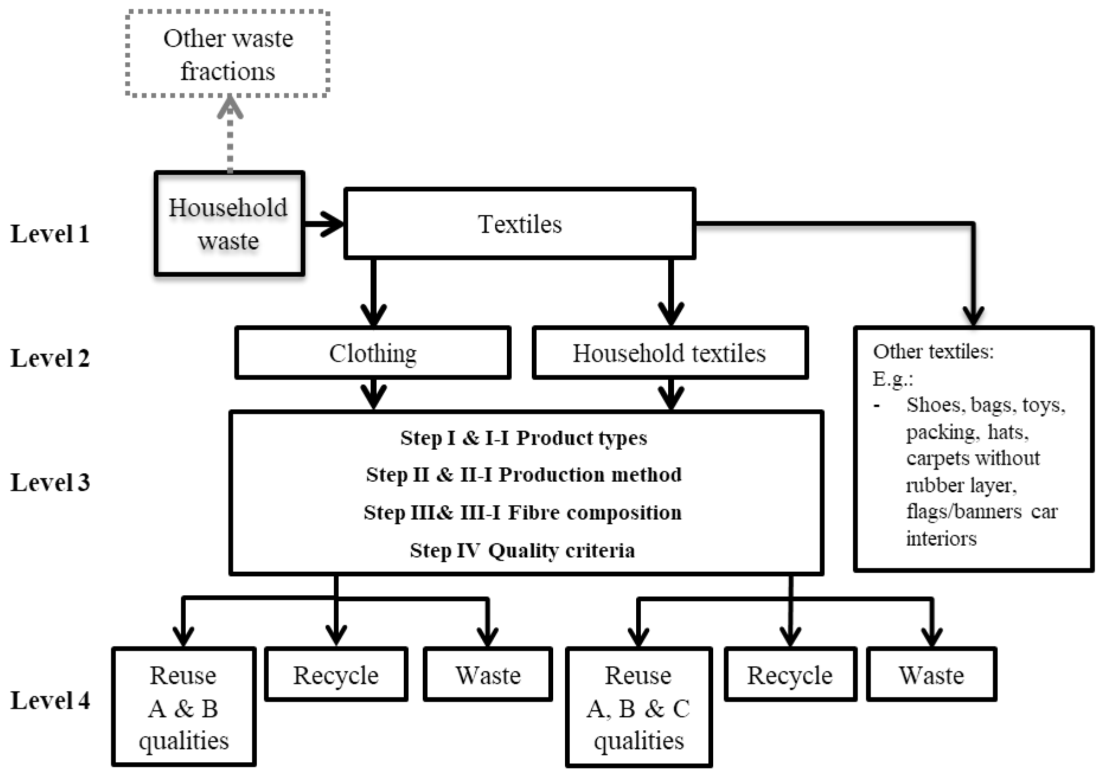

Figure 3. Model for sorting and quality assessing clothing and household textiles (Paper I).

3.2.1 Sorting

The basic sorting principles and initial sorting follow the general guidelines for the waste sorting of household waste as described by Edjabou et al. (2015) and Nordtest (1995). The method is based on NRF (2005) recommendations for the sample size of textiles from household waste collection analyses, to ensure a 90% confidence level. This also ensures that the sample size takes into account that textiles in general are not discarded on a daily basis. At Level 1, textiles are manually separated from the waste, and at Level 2, the separated textiles are divided into the three sub-fractions “Clothing”, “Household Textiles” and “Other Textiles”. In order to avoid any overlap between the fraction “Other Textiles” and other waste fractions, a list of products categorised as “Other Textiles” should be prepared for sorting at Level 1. The method can be applied for sorting out textiles from all types of waste.

3.2.2 Quality assessment of clothing and household textiles

The quality assessment (Level 3) of Clothing and Household textiles is very complex and depends fundamentally on four factors (Steps I to IV): product type, manufacturing method, fibre composition and condition of the product, as shown in Table 3.

In Step I, the product type is determined, for example T-shirts, socks and curtains. The rest of the steps in the quality assessment depend on the product type. For example, the product type tells something about the size of the item, which in turn affects the application possibilities and whether there should be a pair in order for the product to be functional. There are 25 product types for clothing and 13 for household textiles. Step I-I describes additional specifications for all products. An example: underwear is divided into types of bras, underpants, etc., for information on the size of the textile material in the product.

In Step II, product types are sorted according to the manufacturing methods: knitted or woven. Additional information about the manufacturing methods, such as lining or velour, is noted in Step II-I. This information is used primarily to evaluate recyclability potential. The manufacturing method is important for how well the surface absorbs water and/or how easily the textile can be shredded (Elander and Ljungkvist, 2016; The Danish EPA, 1997; Wulfhorst et al., 2006). The denser a product is woven, the harder it is to shred, which is also why knitted products are easier to recycle.

In Step III, the fibre composition of the product types is examined, primarily to determine the recyclability of clothing and household textiles. The specific fibre composition is found by reading the statutory label attached to the products. Where this is not possible, a physical assessment is made of whether the clothing or household textile is made of natural or synthetic fibres, or a mixture thereof. Knowledge of typical fibre types or fibre compositions for a variety of products must support this assessment. If it is not possible to determine the fibre type, the composition must be noted as “unknown.” Although some fibre combinations are more prevalent than others, the variation is high, and therefore fibre composition is divided into seven groups to provide an overview of fibre-level composition (Table 3). “Natural fibres” are naturally occurring fibres, i.e. cotton, wool, silk, etc. or are based on natural products such as viscose. “Oil-based fibres” are based on (the refining of) oil, such as polyester and elastane. “Mixed fibres” are mixed natural and oil based fibres. “Natural fibres” and “Oil-based fibres” are divided into 13 subgroups and “Mixed fibres” into 12, all of which are shown in Step III-I in Table 3. The number of subgroups in “Estimated Fibre Composition” depends on the knowledge level of the products, as well as the assessor’s experience in determining fibre types. “Leather” consists of products consisting primarily of leather. “Incorrect label” is where the label was not sufficient, and “Unknown” consists of products where it was not possible to determine the fibre composition.

Table 3. Overview of Level 3: the different steps for sorting clothing and household textiles after quality (Paper I).

Level 3		**Quality assessment**	
Step		**Sorting criteria**	
I	Sorting into products:	Clothing (25 products): T-shirts, tops, blouses, shirts, trousers, shorts, winter clothing (with and without insulation), dresses, skirts, jackets, vests, work wear, infants' clothes incl. socks + gloves, underwear, nightwear, bathrobes, socks, gloves, scarfs, ties, handkerchiefs, costumes, parts of clothing and pieces of clothing.	Household textiles (13 products): linens, decorative pillowcases, bedcovers, curtains, towels, dishtowels, facecloths, potholders, rags, tablecloths, place mats, plaids, pieces of household textiles.
I-I	Products requiring further specifications:	Clothing: The same as above, e.g. underwear sorted further into kinds of underwear, such as types of bra etc.	Household textiles: The same as above, e.g. linen sorted further into kinds of linen, such as pillowcases, bed sheets, etc.
II	Manufacturing method:	Knitted/tricot fabric Woven	
II-I	Further specifications:	Tricot fabric: jersey, double-face, fleece, etc. Woven: corduroy, velour, flannel, etc.	
III	Fibre composition	Fibre composition (six compositions): natural fibres, man-made fibres (including viscose), mixed fibres, estimated fibres composition, leather and unknown.	
III-I	Further specifications:	Natural-based fibres and oil-based fibres divided into 13 sub-groups*: 100%; 50x50%; mix of three all less than 50%; mix of two, one ≥50-59,9%; mix of three, one ≥50-59,9%; mix of two, one ≥60-69,9%; mix of three, one ≥60-69,9%; mix of two, one ≥70-79,9%; mix of three, one ≥70-79,9%; mix of two, one ≥80-89,9%; mix of tree, one ≥80-89,9%; mix of two, one ≥90-99,9%; mix of three, one ≥90-99,9%; Mixed fibres divided into 12 groups: the same as for natural- and oil-based fibres except from 100% Estimated: Natural fibres; cotton, wool, etc. Man-made fibres: synthetic, polyester, etc. Mixed fibres: cotton-mix, cotton/cotton-mix, wool mix, etc. Unknown Leather Imprecise label	
IV	Assessment of the state of the product type	Assessing clothing and household textiles for defects, avoidable conditions and informal use.	

*All ranges, except 100%, must be understood as such that the product consists of several fibres, of which one fibre type is a value within the range mentioned.

In Step IV, the condition of the products is assessed on the basis of the criteria shown in Table 4. When a defect is found, the defect's nature, extent and location should be noted. In Step IV, the product type, determined in Step I, is used to assess if a minor defect, such as a hole, makes the product unsuitable for reuse. For example, a dress can be used as a dress if there are holes in the lining, but not if there are big holes on the front. There is no international reuse market for underpants with smaller holes, so the initial owner, unlike the example of the dress, can only reuse them. However, it is a very complex task, and in order to reduce subjectivity, the assessment should be based on the international reuse market. Larger products, knitted products and cotton/natural fibre products are more frequently recycled. A regular recycling method is the production of rags, requiring that squares of at least 30×30 cm can be cut out of the product, it has an absorbent surface and is made of a minimum 70% cotton (Elander and Ljungkvist, 2016). When in doubt about categorising the product, the lowest quality should be chosen. "Avoidable conditions" (as seen in Table 4) must be registered, as they may affect the weight of the product type and can make it difficult to spot defects, but they do not affect the functionality of the product. The composition of the waste source may cause contamination of all clothing and household textiles. If it is uncertain whether the product became dirty from the waste (avoidable condition) or was already dirty when discarded, it should be noted as belonging to both conditions.

Table 4. Overview of the criteria used to assess the state of Clothing and Household waste in Step IV (see Table 3) (Paper I).

Criteria	Description	Assessment
Defects	Stitching Wear and tear Holes Stains Faded/discoloured Paint Over-washed Zipper Single glove/sock (solo) Other things	Conditions where it is essential: which product type it is, where the defect is and how extensive it is, and whether the product has more than one defect. This is crucial: • Product type • Defect location • Defect size • Is there more than one defect?
Avoidable condition	Thrown out dirty Becomes dirty in residual waste Wet Moist	Conditions that can be avoided. It can be difficult to determine when the defects have occurred, and which may affect the assessment of whether the product has defects. They can also affect the weight of the product type.
Informal recycling	Used as cloth Cut into pieces Other	The product is used for purposes other than the original; this may be both with and without processing of the product. Cutting up of products is considered informal recycling.

At Level 4, the overall assessment of the product is made based on the information provided at Levels 1-3. All conditions must be noted for each individual product. The weight is noted, and it is important to make clear whether it is wet or dry. Products of a similar type with the same quality assessment can be grouped and weighed together.

3.2.3 Evaluation of the method

The method was tested and compared to five previous waste methods: EU Swa-Tool (Method 1); NRF (2005) Sorting Guide (Method 2); ASTM (2003/2008) Sorting Guide (Method 3); Sorting Guide Waste Norway (2015) (Method 4) and Liikanen 2016 (Method 5). The methods were selected based on a review of 26 scientific articles, three reports and five sorting guidelines. The five methods were applied to the waste samples collected in this study, and the results compared the application of the developed method. For each method, the definitions and instructions were followed, and in a case of doubt about where to place a product, it was omitted. In case of doubt about the quality of a product, the lowest quality was chosen, which is comparable with this study's method, thus achieving uniformity in the use of methods. For a further description of the comparison, see Paper I.

3.3 Estimation of the amount and quality of textiles in Danish household waste

To determine the potential for collecting more textiles from Danish household waste, the developed method was applied in order to determine the quantities and quality of the textiles in residual waste and waste from recycling station containers with "small combustibles". The study areas are described briefly in section 3.3.1, but for further details see Paper II.

3.3.1 Study area and waste collection

In general, none of the sample areas had separate collection of textiles, and so they could therefore be disposed of in residual waste, bulky waste collection or in small combustible containers at recycling sites. Alternatively, textiles could be delivered to collection organisations, via either second-hand shops or clothing containers located in different places in the municipality and at recycling stations.

All samples were collected in 2015 and with a geographic spread covering all five regions in Denmark. It was not possible in this study to take account of seasonal variations or socioeconomic conditions that may affect the disposal of textiles. All values are given as wet weight, to take into consideration when textiles were found with avoidable conditions.

Table 5 provides an overview of the collected and sorted residual waste samples, showing the types and numbers of households, numbers of citizens per household, amounts of collected residual waste and amounts of manually sorted waste. The residual waste was collected from 15 areas, encompassed 2,808 households (Table 5) and provides a representative image of the residual waste collection system in large parts of Denmark. In total, 30 tonnes of residual waste was collected, of which approximately 27 tonnes was sorted. Areas MF1 and MF2 consisted of multi-family houses with a shared waste disposal solution, while areas SF1 to SF15 consisted of single-family houses with individual waste containers.

Quality assessments of clothing and household textiles were only performed in the MF1-MF2 and SF1-SF10 areas. All sorted clothing and household textiles were classified as “had become dirty from the waste”. For the SF11-SF15 areas, sorting was only performed on the total amounts of the three sub-fractions, as the development of the quality framework was not final and therefore did not allow for a consistent quality score.

Table 5. Overview of residual waste showing the type and number of households, numbers of citizens per household, amount of collected residual waste and amount of manually sorted waste. MF is multi-family housing, SF is single-family housing. In total, 29,722 tonnes of waste was collected from 2808 households, whereof 27,322 kg waste was manually sorted (Paper II).

Area	**Korsø, MF1**	**Vord-ingborg MF2**	**Morsø, SF1**	**Sejs, SF2**	**Kjellerup, SF3**	**Hinnerup, SF4**	**Voldum, SF5**	**Mørke, SF6**	**Lemming, SF7**
Housing[1] type	Multi family	MF	Single family	SF	SF	SF	SF	SF	SF
Citizens per household[2]	1.6[3]	1.4[3]	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Number of households per sampling unit	198	122	229	100	100	221	214	372	117
Sampling period (week)	1	1	2	2	2	1	1	1	2
Sampling month	Sep.	Sep.	May	Oct.	Oct.	Nov.	Nov.	Oct.	Oct.
Total amount of collected waste (kg)	1,328	722	1,441	1,790	1,670	1,896	2,077	2,845	2,373
Amount of sorted waste (kg)	1,328	772	1,441	1,482	1,487	1,896	1,442	2110	1,757

Area	**Esbjerg, SF8**	**Brøndby, SF9**	**Serup1, SF10**	**Serup2, SF11**	**Lemvig, SF12**	**Struer, SF13**	**Skive, SF14**	**Holstebro, SF15**
Housing[1] type	SF	SF	SF	SF	SF	SF	SF	SF
Citizens per household[2]	2.6	3.85[4]	2.6	2.6	2.6	2.6	2.6	2.6
Number of households per sampling unit	418	161	100	100	106	76	76	76
Sampling period (week)	1	1	2	2	2	2	2	2
Sampling month	Nov.	Oct.	Oct.	May	May	May	May	May
Total amount of collected waste (kg)	4,543	981	1,563	1,689	1,104	1,089	1,190	1,491
Amount of sorted waste (kg)	2,307	861	1,563	1,310	1,104	1,089	1,190	1,421

[1] Dominant housing type
[2] Weighted average calculated based on Statistics Denmark 2017
[3] AffaldPlus, 2016
[4] Petersen and Hansen, 2015

Table 6 provides an overview of the recycling stations where small combustibles were collected, as well as the total number of users and small combustibles at the recycling stations. The waste from small combustibles came from six different recycling stations located in six different municipalities. The recycling stations SB1, SB4, SB5 and SB6 are inter-municipal stations with a significantly larger upland than the other stations. From each recycling station, one to three containers of small combustibles were collected, corresponding to 2,080-6,432 kg of waste (Table 6).

Table 6. Overview of the recycling stations where small combustibles (SC) were collected, and the total number of users and small combustibles at these recycling stations (Paper II).

Area	Gentofte (SC1)	Randers (SC2)	Ryomgård (SC3)	Holstebro (SC4)	Kaastrup (SC5)	Lemvig (SC6)	Total	Average
Residents in the surrounding area	890,000[1]	98,000[1]	80,000[1]	146,188[1]	146,188[1]	146,188[1]	-	-
Visitors in 2015	211,466[1]	459,507[1]	42,120[1]	206,747[1]	97,900[1]	97,241[1]	-	-
Total amount of small combustibles 2015 (tonnes)	2,930	3,028[2]	222/2,610[1]	ND	ND	ND	-	-
Total amount of textiles collected separately at the recycling station (tonnes)	ND	1.6	1.44 [3]	ND	ND	ND	-	-
Number of waste fractions submitted at the recycling station	27	35	32	26	27	29	-	29
Sampling months	July	Sep.	Sep.	June	June	June	-	-
Amount of collected small combustibles waste (kg)	6,432	2,460	4,587	3,054	3,085	2,080	21,699	3,616
Number of container loads	3	2	2	2	2	1	12	2
Total amount of sorted combustibles waste (kg)	5,593	1,624	3,411	2,706	2,949	1,751	18,034	3,006

ND= No data
[1] Data are based on municipality statistics for the area
[2] Total from the municipality's four recycling stations
[3] The value is based on data from DanChurchAid, which collected this amount in 2016

3.4 Evaluation of a European textile sorting centre: material flow analysis and life cycle inventory

The textile sorting centre (TSC) operated by Humana People to People (HPP) in Vilnius, Lithuania, was chosen as a case study. For the period 2015-2017, a material flow analysis (MFA) of the textile flows in the TSC, and a life cycle inventory (LCI) along with an assessment of the main economic factors, was carried out (Paper III).

3.4.1 Field site and material flow analysis

In 1998, the TSC was established, and in 2013, it moved to new facilities. The TSC has a sorting capacity of approximately 200 tonnes per day. In the reference period covering 2015 to 2017, total annual imports were between 36,600 and 37,100 tonnes with an average daily sorting flow of 130 tonnes. The TSC handles all kind of textiles belonging to the main textile fractions Clothing and Household textiles, as defined in section 2.1, as well as part of the product types belonging to the fraction Other textiles, such as shoes, bags and soft toys (see Paper III).

To ensure a complete mass balance, the flows of sorted reusable non-textiles and recyclable non-textiles were included. The software STAN (version 2.6.801) (Cencic and Rechberger, 2008) was used for data reconciliation and visualisation, as illustrated in Figure 4.

The first step in the TSC is the warehouse, which is modelled as two processes with two separate inputs: imports from original collection (unsorted textiles directly from collection) (process 1) and imports from pre-sorted (textiles that have undergoing sorting after collection) (process 2), with both including stock and delta stock. All received textiles are weighed and registered. The stocks and delta stocks in terms of imports are based on data from the TSC, while STAN calculated the stock occurring between production and sale as the one stock placed into fine sorting. All textiles originating from collection have to undergo full sorting at the sorting centre, whereas part of the pre-sorted textiles and returned textiles are sold directly without any sorting, with the remaining parts only undergoing fine sorting or special sorting.

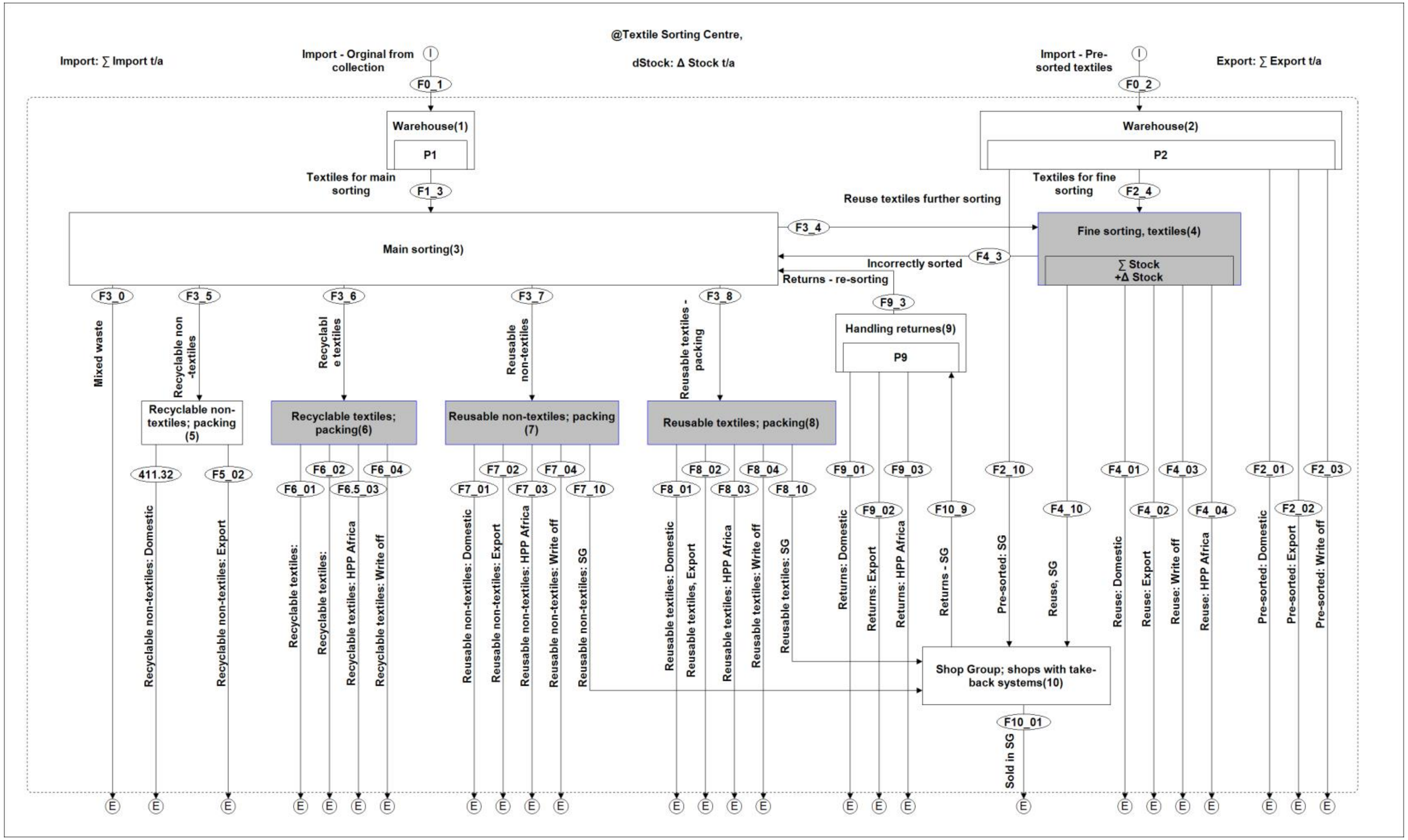

Figure 4. Overview of the TSC. Grey-coloured processes indicate that the process has a subsystem. Processes are numbered from the top down, starting from left to right. Flows are numbered after the process from which they come and the process to which they are going. Flows numbered with a zero as a first value represent flows entering the system, and with a zero in the last number a flow leaving the system, a zero followed by a number is used when there is more than one flow from the same process. Sub-processes are found in Appendix B, Paper III.

The second step includes the sorting processes main sorting (process 3) and fine sorting (process 4), where fine sorting is modelled with a sub-system. All textiles received and originating from collection are unpacked and loaded onto a conveyor belt, from where a robot unloads on demand a batch of textiles to each of the sorters at the main sorting station (process 3). Each sorter manually sorts the textiles into 37-39 categories, which are explained further in Appendix A, Paper III. In this modelling, the sorted textiles in the 37-39 categories were grouped into six main categories based on whether or not they were reusable or recyclable, textile or non-textile, and if they were further sorted: “Reuse for further sorting”, “Reuse directly for packing”, “Recyclable textiles”, “Reusable non-textiles”, “Recyclable non-textiles” and “Mixed waste” (Table 7).

The most valuable category, “Reuse for further sorting,” is transferred into polypropylene (PP) bags via forklifts or a hand truck to the fine sorting station (process 4). Fine sorters manually segregate the textiles into approximately 200 categories according to the quality of each product, season and special request from purchasers. Each category is directly packed into PP bags in the sorting process and afterward transferred by trolleys or forklifts to a scale and registered before storing prior to transfer. Products not belonging to categories in fine sorting (wrongly sorted), but which by mistake have been sorted out for fine sorting or been part of the received pre-sorted textiles, are taken out and placed into the correct main sorting category. The flow of textiles from main sorting to fine sorting was modelled using transfer coefficients, based on the fact that returned textiles as well as incorrectly sorted textiles are never returned to fine sorting. The flow of incorrectly sorted textiles from fine sorting (flow 4_3) is based on transfer coefficients calculated based on an estimation of the total amount of incorrectly sorted textiles. For calculations, see Appendix C, Paper III.

Table 7. Overview of the different main and sub-categories, and what they consist of overall. More details and specifications on the different categories are available in Appendix A, Paper III. The numbers refer to the flows illustrated in Figure 4. A to E refer to the quality of the textiles, where A is the highest, B is the second highest and so on (Paper III).

Main category	Sorting sub-category from main sorting	Flows included in the MFA
Reuse for further sorting	Seven sub-categories: Shop clothes, Shop clothes Ukraine, Shop household textiles, C mix, Trend/vintage mix, Shoes mix, Bag mix	Main system: • Reuse textile further sorting (3_4) Sub-system (4): • Shop A (4.1_4.2) • Other A(4.1_4.3) • Shop B (4.1_4.4) • Shoes B (4.1_4.5) • Winter C (4.1_4.6) • Summer C (4.1_4.7) • Trend (4.1_4.8) • Shoes C (4.1_4.9) • Bags C (4.1_4.10) • Bags b (4.1_4.11a) • Other B (4.1_4.11b) • Shoes A (4.1_4.11c) • C mix (4.1_15a) • Trend mix (4.1_4.15c)
Reuse directly for packing	14 sub-categories: Tropical mix, D mix, Winter mix, Children winter clothes, Trouser E, Women jackets E, Men jackets E, Home textiles E, Velour E, Fleece E, Winter clothing E, E mix, Single shoes, Leather E	Main system: • Reusable textiles packing (3_8) Sub-system (8): • B mix (8.1_8.2) • Tropical mix (8.1_8.3) • Children winter clothing D (8.1_8.4) • Winter clothing D. 3(8.1_8.5) • Clothing and home textiles E(8.1_8.6) • Shoes E(8.1_8.7) • Shop A+B without further sorting(8.1_8.12)
Recyclable textiles	Four sub-categories: White and coloured cotton, knitted and other recyclable textiles*.	Main system: • Recyclable textiles (3_6) Sub-system (6): • White Cotton (6.1_6.2) • Coloured Cotton (6.1_6.3) • Knitted (6.1_6.4) • Other recyclable(6.1_6.5)
Reusable non-textiles	Three sub-categories: Soft and hard toys and Bric-à-brac	Main system: • Reusable non-textiles (flow 3_7) Sub-system (7): • Toys (7.1_7.2) • Bric-a-Brac(7.1_7.3)
Recyclable non-textiles **Mixed waste**	Three sub-categories: Paper, mixed plastic and polypropylene. Mainly consists of waste from the sorting but also includes waste generated at the TCS	Main system: • Recyclable non-textiles (3_5) Main system: • Mixed waste (3_0)

*Other recyclable textiles contain more categories. The number of categories and their share vary over the years, but it is kept as one overall category in the MFA

To allow for modelling for end destination in the form of purchaser groups, the system is set up with the sub-systems recyclable textiles (process 6), reusable non-textiles (process 7) and reusable textiles from main sorting (process 8), all of which contain sub-systems (all sub-systems can be found in Appendix B, Paper III). This means that all outgoing flows can be divided into main categories and purchaser groups, as presented in section 3.4.1. It should be kept in mind that the only textile categories and soft toys sent to fine sorting are sent through more than one sorting step at the TSC in Vilnius, and so all other categories are sorted out directly from main sorting. Textiles returned (un-sold) from second-hand shops (flow 9_3) are mixed with the output from main sorting at the TSC, which is why it was not possible to model these as separate process. “Reuse directly for packaging” consists of categories where the price for further sorting is not regained in sales prices. Via a conveyor belt, most categories are transferred to the packaging and transfer area, where the majority are wrapped, baled, weighed and registered before being stored prior to transfer. “Recyclable textiles” consists of various categories over the referenced years. In this analysis, four categories were included (Table 7) that after sorting are sent for baling via a conveyor belt. Only the cotton recycling categories are wrapped in used cotton sheeting before baling, with the rest baled with wire only. “Reusable non-textiles” contains one category that undergoes a special sorting process, but all subcategories are packed into PP bags before being weighed and registered prior to transfer. “Recyclable non-textiles” are packed in PP bags directly when sorted out, weighed and registered before transfer. “Mixed waste” is thrown out in the trash bags and picked up by a local waste company. The total number of categories sorted out vary over the years in relation to demand and sale, i.e. according to market interest. A quality control system controls and monitors all of the different sorting steps each week, and it takes at least a year to train a sorter for the main sorting facility.

3.4.2 Purchaser groups and take-back system

Knowledge of where the textiles are sold is important for understanding the different mechanisms in the international textile market and when modelling the environmental benefits of reusing and recycling textiles. The TSC has organised all sales into five purchaser groups:

- Domestic sales (Domestic): all national sales in Lithuania to non-HPP purchasers.
- HPP in Africa (HPP Africa): sale to HPP organisations in African countries.
- Export: sale to all countries, including a minor part of European HPP organisations.
- Write-off: donations and emergency aid, mainly national.

- Shop Group (SG): Sale to HPP second-hand shops, which are part of the take-back system with the TSC.

The TSC is part of the HPP organisation, which employs a unique take-back system between the sorting centres and second-hand shops run by members of the organisation. The system functions to ensure as high a reuse rate as possible, by returning all unsold textiles from the second-hand shops to the TSC from where they originally received the items. The TSC in Vilnius has a take-back system with a shop group (SG) that consists of HPP second-hand shops in six countries: Lithuania, Ukraine, Hungary, Latvia, Belgium and Estonia.

3.4.3 System boundaries, resources and materials

Figure 4 shows the system boundaries for both the MFA and LCI and includes only the internal use of resources and materials at the TSC. The receipt of imported textiles is the first process at the TSC, whereas the last process involves loading sold textiles for transfer.

The model does not include the following pre-processes or subsequent downstream processes:

- The collection and transport of textiles
- Treatment and handling of textiles as well as non-textile products after sale
- Transport to and from second-hand shops with returns systems
- Running of second-hand shops
- Transport and treatment of waste
- Reuse and recycling of textiles
- Avoided virgin material production, due to reuse and recycling

The system boundaries for the economic analysis also include certain modes of transport, as the TSC pays for the transport of imported textiles. In addition, it covers the costs for textiles returned from the Lithuanian SG.

Data included for resources and materials are electricity, heating (gas), gas (used in trucks), water and packing materials. The economic costs of these elements are also included. Specifications regarding equipment affecting the consumption of electricity and gas in the TSC can be found in Paper III.

Labour requirements are included in the total number of full-time employees (FTEs), and a cost for this is included in the 2016 data. Import costs are included for all three years, and the data for 2016 include other fixed costs. To avoid doublecounting, the normalised values for imported textiles include returned textiles, whilst delta sales stock are not included.

All data were collected through correspondence with the TSC manager (Starkauskienė 2018), site visits to the TSC and from a transparency report created for the TSC by the consulting company Mepex (Mepex, 2016) (further information is found in Paper III).

3.5 Survey questionnaire to determine the replacement rates

The determination of replacement rates for second-hand textiles was based on a face-to-face survey conducted in three districts in each of the countries: Angola, Malawi and Mozambique. Data were collected during the spring of 2016. In this section, the method is briefly explained, but more details are available in Paper IV.

The questionnaire consisted of 40 questions with 11 sub-questions divided into five sections: demographics, clothing budget, shopping habits – new textiles, shopping habits – second-hand textiles and reuse behaviours. Furthermore, it included a section for the interviewer regarding interview ID, district, weekday, etc. and two control questions to exclude non-relevant respondents. The full questionnaire can be found in Appendix B, Paper IV.

The questionnaire was inspired by two studies that previously examined replacement rates through survey studies, namely Farrant et al. (2010) and Stevenson and Gmitrowicz (2013).

Angola, Malawi and Mozambique were chosen, as they all legally import second-hand textiles and because the charity organisation Humana had a local branch in each of the countries. Interviews were carried out in three different districts, i.e. Angola (1. Luanda, 2. Benguela, 3. Huambo), Malawi (1. Limbe, 2. Thyolo, 3. Lilongwe) and Mozambique (1. Manica, 2. Sofala, 3. Nampula) and at three different locations, namely in second-hand shops, markets or on the street. The numbers of interviews conducted were spread relatively equally over the districts.

3.5.1 Data management and analyses

The data were managed and processed using the software programme JMP (software for statistical analysis) and underwent data quality control to ensure the datasets were complete and robust. The criteria for quality control were based on how the respondents answered the question regarding whether or not they had been interviewed before, had said yes to a least one of the control questions, had not responded that all purchased items were for purchase for re-sale and had given a minimum of one response each regarding questions 24 (items purchased) and 27 (question for calculating replacement rate). Respondents were filtered out if one or more of these criteria were not met. Non-textile items and items not possible to translate were also filtered out.

Based on the quality criteria, a total of 3,485 respondents and 14,910 second-hand textile items were included in the calculation of the replacement rates (see Table 8).

Table 8. Total numbers of respondents and textile items in both the original dataset and the filtered dataset that were included in the calculation of the replacement rates (the filtered dataset). The distribution is given per district in each country, along with the percentage of the original dataset after removing respondents due to the quality criteria. Missing responses for items are not included in numbers for items in the original dataset (Paper IV).

		Respondents				Textile items			
	District	**Angola**	**Malawi**	**Mozambique**	**Total**	**Angola**	**Malawi**	**Mozambique**	**Total**
1	Original dataset	568	521	532	-	2486	1232	2207	-
	Filtered dataset	532	308	435	-	2287	1153	2066	-
	% of original dataset included	93	59	82	-	92	94	94	-
2	Original dataset	615	526	521	-	2810	1257	2091	-
	Filtered dataset	534	313	393	-	2038	1067	1801	-
	% of original dataset included	87	59	75	-	74	85	86	-
3	Original dataset	623	523	532	-	3025	1502	1785	-
	Filtered dataset	264	368	340	-	799	1368	1611	-
	% of original dataset included	42	70	64	-	26	91	90	-
Total	**Original dataset**	**1806**	**1570**	**1585**	**4961**	**8321**	**3991**	**6093**	**18,501**
	Filtered dataset	**1329**	**988**	**1168**	**3485**	**5124**	**3578**	**5478**	**14,190**
	% of original dataset included	**74**	**63**	**74**	**70**	**70**	**62**	**90**	**77**

3.5.2 Replacement rate calculation

The replacement rates were calculated based on the following question:

- Q 27: For each textile item purchased, would you have bought a similar item new, if you had not found it in a second-hand shop or market?

Each respondent could respond no, yes or maybe for a maximum five purchased textile items, which is in line with the method used by Stevenson and Gmitrowicz (2013) and partly in Farrant et al. (2010).

Calculation for replacement rates; R:

$$= \frac{\text{Q27 (Total number of items with Yes responses + ½ of the number of items with Maybe responses)}}{\text{Q27 Total number of items purchased}}$$

Replacement rates were calculated for each country, on all second-hand textiles, the main categories (Clothing, Household textiles and Other textile products) and product types, as well as average and weighted averages for all three countries. As part of analysing the results, the replacement rates were also grouped and plotted in relation to questions Q5 household income, Q8a monthly clothes budget, Q8b monthly clothes budget for the household and Q35a share of wardrobe consisting of second-hand clothes.

By comparing replacement rates calculated without including "maybe" responses with rates calculated as shown in the formula above, the influence of the "maybe" responses effect on the replacement rates was analysed. These values were used to assess uncertainty and are given as error bars.

3.6 The environmental assessment

The environmental assessment considered the modelling of the improved management of the textile waste currently discarded with household waste (residual waste and small combustibles).

3.6.1 Environmental assessment

The environmental assessment of the potential for collecting more of the textiles currently discarded with household waste followed the iterative phases of a consequential LCA (ISO, 2006a; 2006b), namely goal and scope definition, life cycle inventory, life cycle impact assessment and results interpretation.

The goal of the study was to evaluate the environmental impact in terms of climate change from four different scenarios, in order to realise the potential for increasing the collection of textiles found in household waste or only some of the items found. The functional unit was set as the amount of textile waste currently generated per person in Denmark, ending in residual waste and small combustibles (Table 9), and is based on the results presented in Paper II. The boundaries of the assessment included all stages, from collecting the textile waste, transport and sorting, to the "new product" (reuse and recycling), as well as the replacement effect of the new product (Table 10). The use phase and disposal of the second-hand and recycled products were not included, as these are considered similar to the use phase and disposal of new products. The main focus of the assessment was on the collection of inventory data and setting up correct systems for how textile waste is handled.

The modelling was carried out in EASETECH (Clavreul et al. 2014). Primary data came from Papers I, II, III and IV and two survey studies for supplementing the data regarding replacement rates for reuse clothing in Europe and for use of rags made of recycled textiles (Appendix, Paper V). Secondary data, which included the production of energy and heating, as well as primary production of textiles and products, were chosen according to their technological, geographical and temporal relevance and were based mainly on Ecoinvent v3.5 or other internationally recognised databases. Background data for the production of the replaced products were based on Roos et al. (2015) and were linked to background data as available in Ecoinvent v3.5 or emissions data that were directly in Roos et al. (2015).

Table 9. The composition of the share of the Functional Unit (FU) and specification of product types and the fibre compositions. The total reference flow of 6.2 kg per citizen were split over residual waste (RW) and small combustibles (SC) as shown. For details see Appendix, Paper V.

Fraction	kg per citizen	Product	Manufacturing	Composition in: RW (%)	Composition in: SC (%)	Sub-product specifications of fibre[1]
Clothing	RW: 2.4 ± 0.9 SC: 1.7 ± 0.8	Trouser	Jeans, woven	26.1	33.5	100c
		Blouse	HK[2] style	15.9	33.3	100w
		T-shirt	Knitted	1.0	12.9	100c
			Knitted	10.8	0.6	95c,5e
			Knitted	4.8	5.5	100p
		Socks	Knitted	23.9	7.6	76c,22n,2e
		Underwear	Underpants, knitted	11.4	4.4	100c
			Underpants, knitted	4.0	1.1	85n,15e
			Bras w. wire, knitted	2.1	1.2	90n,10e
Household textiles	RW: 1.1 ± 0.5 SC: 1.0 ± 0.4	Linen	Woven	60.1	57.2	50c, 50p
		Curtains	Knitted	6.1	33.1	60p, 40c
			Lace	0.9	4.9	100n
		Rags/wipers	Non-woven	32.9	4.8	85v, 15pp

[1] c: cotton; w: wool; e: elastane; p: polyester; n: nylon; v: viscose; pp: polypropylene
[2] HK: Home knitted

Table 10. Replacement rate for each continent and the share in percentage of the reusable textiles that are reused in each continent in the two scenarios (Paper I; Paper III; Paper V appendix, The Danish EPA 2018).

Continent	Replacement rate (%)	Share of the reusable textiles that are reused in each continent (%): Scenario 1	Scenario 2
Western Europe	34	1	N/A[2]
Eastern Europe	34	5	79
Asian	45	21	0
Africa	45	34	21
HPP shop group[1]	34	39	-

[1] HPP shop group; Humana People to People shop group. The international sorting centre modelled is part of the umbrella organisation Humana where the sorting centres have take-back systems for unsold goods with shops within the same organisation. These are grouped so each centre is providing the service for a group of shops, which in this case mainly are located in Eastern Europe.
[2] The study by The Danish EPA (2018) did not find any clothing that had a quality for potential reuse in Denmark.

In this PhD thesis, the focus is on climate change impact (IPCC, 2013), whereas the article (Paper V) includes all the ILCD (2010) recommended impact categories except for water and land use, which are considered too uncertain in terms of data availability. Sensitivity analysis and uncertainty propagation were used to investigate the results of the life cycle impact assessment phase (Clavreul et al., 2012). The main contributors to the climate change impact were identified through a contribution analysis.

3.6.2 The Scenarios

The modelled scenarios are illustrated in Figure 5. Scenario 0 represents the current handling of textiles, while scenario 0a represents a situation whereby only the potential in reducing the disposal of useable rags is realised. The difference between scenarios 1 and 2 is that in scenario 1, all textiles were sent to an international textile sorting centre (as described in section 3.4), whereas in scenario 2, all textiles were sorted at a Danish sorting centre. The data and sorting rates for the Danish sorting centre were from the recent Danish EPA report on Danish textile flows (The Danish EPA, 2018). In both scenarios 1 and 2, the potential for reducing the disposal of usable rags was included. The replacement rates used in the different scenarios were the same for the different regions of the world receiving the waste, but the amount of textiles reused in the different regions (e.g. Europe, Africa) differed according to the sorting that the centre performs. In both scenarios 1 and 2, two types of textile recycling were considered: textiles recycled as rags, and textiles shredded and spun for shoddy yarn for the production of blankets.

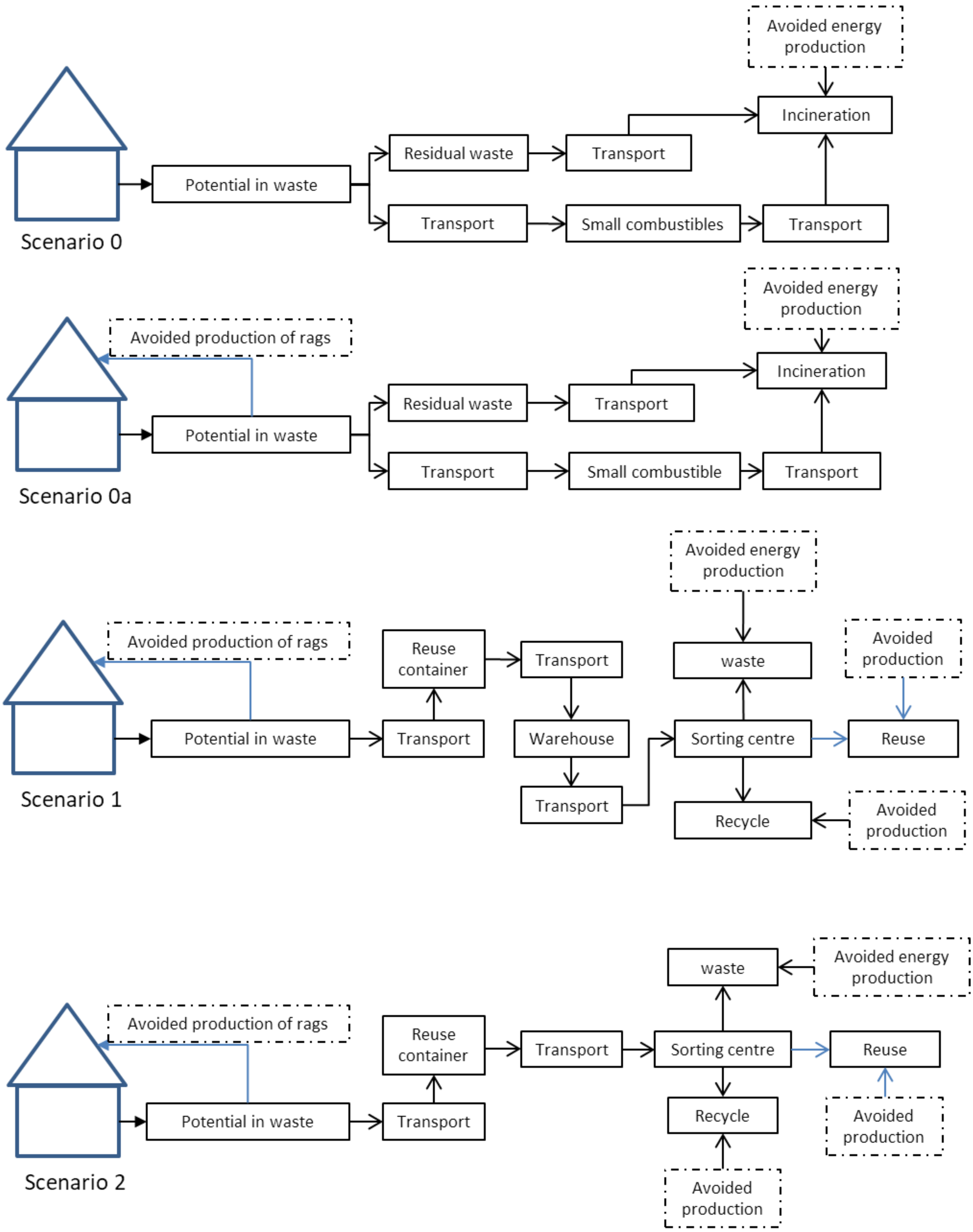

Figure 5. The four different scenarios modelled in EASETECH.

4 Results and discussion

In the first part of this chapter, the main results of the data generation activities related to the potential and data improvements are presented and discussed, and the second part presents and discusses the results of the LCA.

4.1.1 The textile collection potential in Danish household waste

The definition and method developed to examine and determine the potential for improving the collection of textiles, by reducing the amount of textiles discarded in household waste, were presented herein in the method section 2.2 and can be found in detail in Paper I.

The average content of textiles found in residual waste from Danish households was 2.9 ± 0.9%, with Clothing the largest fraction (average 1.4 ± 0.5%) and Household textiles the smallest (average 0.6 ± 0.3%), as illustrated in Figure 6. The fraction Other textiles made up an average of 0.6 ± 0.3%. On an annual basis, each citizen discards kg 2.4 ± 0.9kg of Clothing and 1.1 ± 0.5kg of Household textiles with their residual household waste.

In small combustibles, the average content of textiles was 11.9 ± 4.2%, with an average of Clothing at 4.5 ± 2.1% and 2.6 ± 1.2% for Household textiles. Other textiles made up an average of 4.9 ± 2.3%.

This shows clearly the need for a clear understanding of what is sorted out as textiles. If “Other textiles” is included, the volume is significantly higher than when only considering the fractions Clothing and Household textiles. This was also found when comparing this study’s method with previous methods for sorting waste, in that the amount of textile differed between 2.3 and up to 4.3% in residual waste and 6.3% and up to 37.8% in small combustibles, when five of the methods were applied to the same waste samples (Paper I). This sets great demands on waste companies/municipalities and textile collectors to be precise in which textile products they receive, because although a product can be made of textiles, the possibility of reusing or recycling it may vary significantly between products, depending on the type and quality of the each single item.

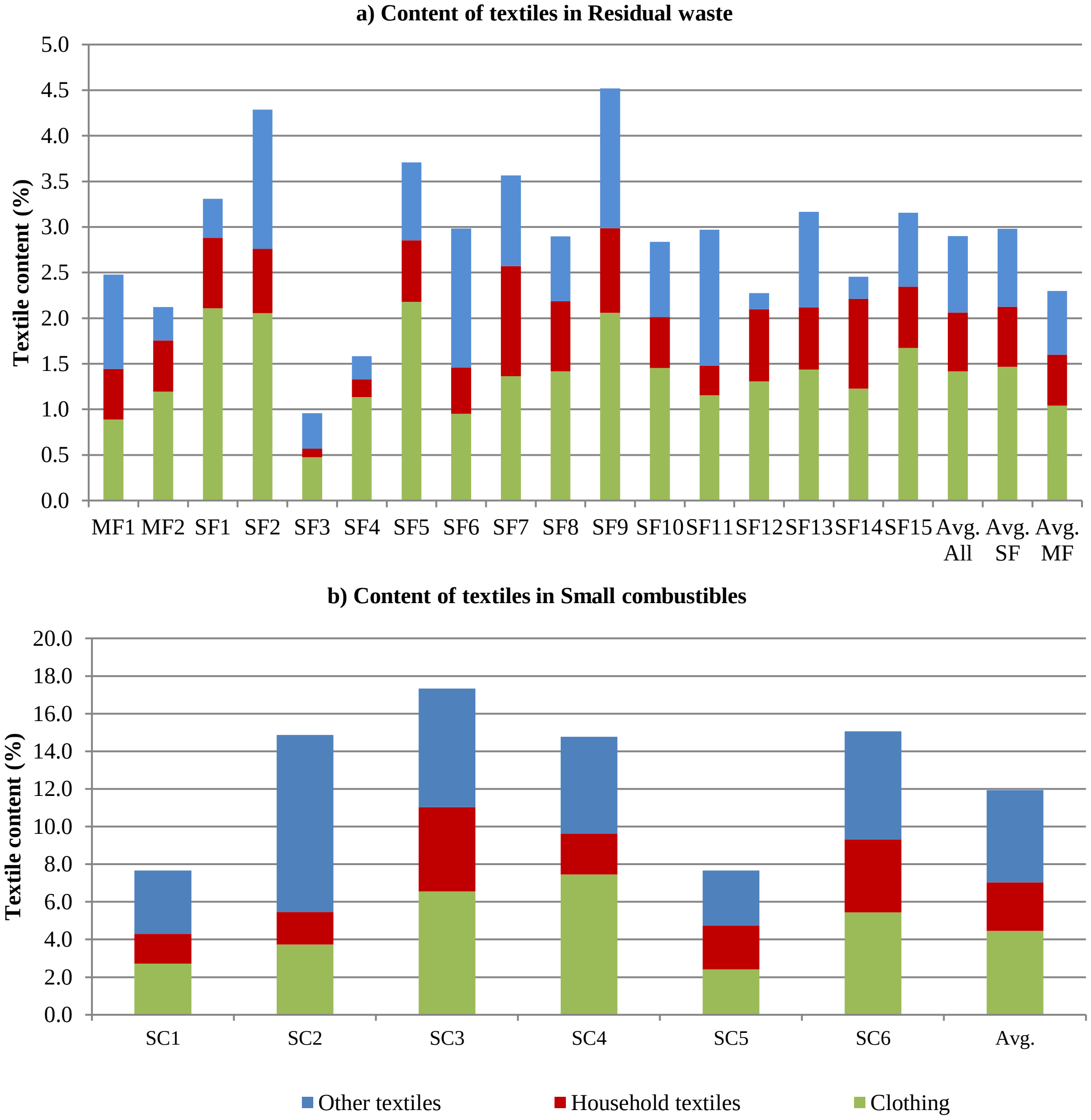

Figure 6. Textile contents divided into three sub-fractions: Clothing, Household textiles and Other textiles. a) Residual waste; the standard deviation of the total amount is 0.66%. b) Small combustibles; the standard deviation of the total amount is 4.16%. Content is based on wet weight (Paper II).

Considering the quality of the textiles found in the waste, an average of 65 ± 8.0% of Clothing and 65 ± 19% Household textiles could be reused from the residual waste, while this figure was 69 ± 5.8% and 66 ± 9.6% for small combustibles (Figure 7). In addition, an average of 12 ± 5.3% and 15 ± 11% and 14 ± 3.9% and 16 ± 8.7% of the Clothing and Household textiles could be recycled from residual waste and small combustibles, respectively (Figure 7). Although the share of the textiles that can be reused in percentage terms is relatively similar between residual waste and small combustibles, the mix of product types that the potential is based on differs. In residual waste, 21 ± 15% of the reusable Household textiles consists of C quality (reusable rags), while this was only 3.1 ± 2.3% in small combustibles. For rags, the only option for reuse is (re)use in the household, as there are no or very limited options for recycling these items. Likewise, an average 11 ± 5.9% of the textiles in the residual waste were classed as underwear, while this was only 3.9 ± 2.9% in small combustibles (Paper II). This is an example of a type of product that is currently primarily possible for reuse, as it can rarely be recycled. This underlines the importance of understanding the basis for how the quality assessment was conducted, as this is influenced by the international market for reuse and recycling. In particular, currently applied recycling technologies are limited to just a few fibre types, and furthermore they are dependent on the type of product and production method. Therefore, it is essential that a product is reusable, because the recycling possibilities currently are very limited and the amount of textiles in household waste can thus mainly be reduced by increasing reuse.

The assessment was based on weight and carried out on the waste as found in the bin. This could have some influence on textile content, as some of the sorted items were found to be moist/wet, due to contamination from other wet waste fractions. Contamination could be reduced if the waste samples were sorted immediately after collection, which was the case with most of those considered in this study. Washing and/or drying the textiles could influence the quality assessment, as the washing/drying processes affect appearance, but they can also make it more difficult to assess whether a stain originated from other waste fractions or was on the item before it was thrown out. In residual waste, the share of moist or wet textiles was between 19 and 27% of the Clothing and 19 and 42% of the Household textiles, while in small combustibles it was, respectively, between 6 and 9% and 0.2 and 4% (Appendix B, Paper II). The higher share of wet/moist textiles in Household textiles in residual waste was explained by the high content of rags, which were more often moist or wetter than other products. However, in both residual waste and small combustibles, the share of the moist or wet textiles was spread quite equally between reuse, recycle and waste.

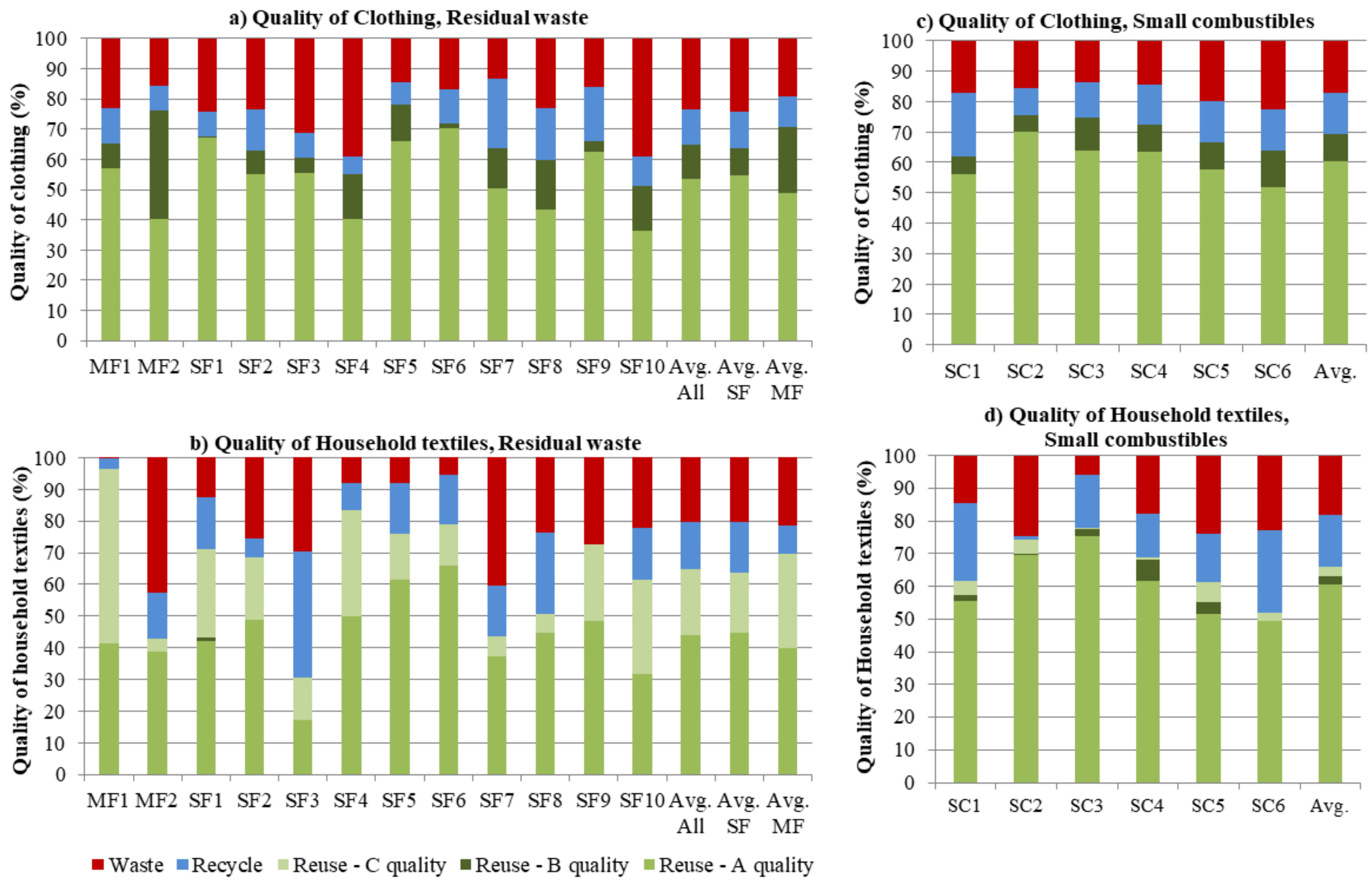

Figure 7. The overall distribution between the qualities of Clothing and Household Textiles. a) Quality of clothing in the residual waste. b) Quality of Household textiles in the residual waste. c) Quality of Clothing in small combustibles. d) Quality of Household textiles in small combustibles (See Appendix B, Paper II for further specifications).

4.2 Data improvements

The data improvements section consists of two parts. First, the results from the sorting centre are presented (Paper III), and second, the results regarding the replacement are presented (Paper IV).

4.2.1 Sorting rates at a full-scale textile sorting facility

Table 11 shows the overall composition of output from the textile sorting centre in percentages of total imports. The overall results from 2015 to 2017 showed that in spite of an increasing import as well as an increasing output from main sorting, the reuse rate for sorted input textiles decreased from 80% to 75% (Table 11). Textile categories from fine sorting were most affected, and both the overall share (drop from 33 to 29%) and amounts in tonnes (drop from 12,270 to 10,834 tonnes) decreased. Consequently, the shares of both recycling and waste increased, respectively, from 13 to 17% and from 5.4 to 6.0% (Table 11).

Table 11. The overall composition of output from the sorting centre in percentages of total imports ± Δ stock (Paper III).

	2015		2016		2017		Average		Standard deviation of average		Change from 2015 to 2017
	[tonnes]	**[%]**	**[tonnes]**	**[%]**	**[tonnes]**	**[%]**	**[tonnes]**	**[%]**	**[tonnes]**	**[%]**	**[tonnes]**
Reuse	**29,751**	**79.8**	**27,993**	**77.0**	**28,411**	**74.9**	**28,721**	**77.2**	**917**	**1.3**	**-1,340**
Reuse, fine sorting	12,270	32.9	10,618	29.2	10,834	28.6	11,240	30.2	898	0.8	-1,436
Reuse, main sorting	15,817	42.4	15,549	42.8	16,063	42.3	15,810	42.5	257	0.2	+246
Reuse, pre-sorted + returns sold directly	1,665	4.5	2,328	5.0	1,522	4.0	1,671	4.5	430	0.5	+6
Recycle	**4,827**	**12.9**	**5,413**	**14.9**	**6,550**	**17.3**	**5,596**	**15.0**	**610**	**1.3**	**+1,723**
Non-textiles Reuse	**291**	**0.8**	**263**	**0.7**	**270**	**0.7**	**275**	**0.7**	14	**0.01**	**-21**
Non-textiles Recycle	**398**	**1.1**	**363**	**1.0**	**429**	**1.1**	**397**	**1.1**	**33**	**0.1**	**+31**
Waste	**2,031**	**5.4**	**2,317**	**6.4**	**2263**	**6.0**	**2,204**	**5.9**	**151**	**0.3**	**+232**

The results of the MFA for 2017 are illustrated in Figure 8 (results from 2015 and 2016 are found in Appendix D, Paper III). In all three years, the largest share of the total output was sold to the purchase groups Export (42-50%) and the Shop Group (SG) (32-37%). However, the share of reusable textiles sent to Export and SG decreased, and the share of recyclable textile for Export increased with 5.1% from 2015 to 2017 (Paper IV). SG purchased the largest share of pre-sorted textiles and those from fine sorting, while the largest share of textiles from main sorting was sold to HPP Africa. The share of reusable textiles sold to HPP Africa increased, thus indicating a drop in the quality of the sorted textiles and a shift in exports to more distant markets. The total amounts of reusable and recyclable textiles purchased by each purchaser group are shown in Table 12, which also illustrates the end destinations for each purchase group in 2016. It is important to keep in mind that the share of each end destination only states the amount purchased and not the type of category that was purchased. The international market for second-hand textiles is governed by trade legislations. As an example, India has a ban on importing any kind of reusable textile, which is why anything exported to India only contains recyclable items.

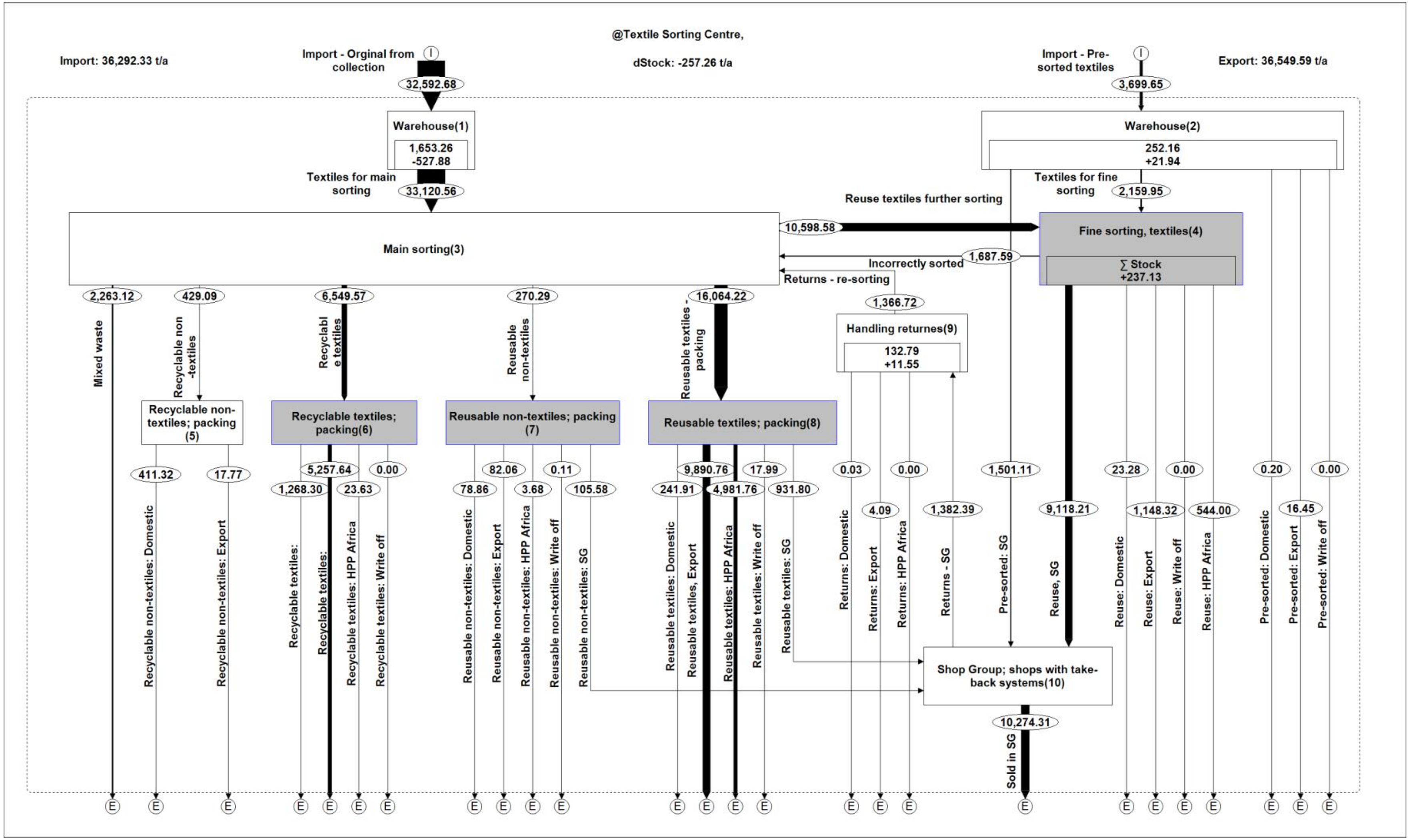

Figure 8. MFA results for TSC 2017, main system; sub systems and results from 2015 and 2016 are found in Appendix D, Paper III

Table 12. Total amount of reusable and recyclable textiles bought by each purchaser group and the distribution and share for of countries that the purchaser groups consisted of in 2016 based on Mepex Consult, 2016 (Paper III including the Appendix D).

Purchaser group	**Shop Group (SG)**			**Domestic**			**Export**			**HHP in Africa**			**Write Off**		
Year	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
Total Reuse (kg)[1]	12,953	11,345	11,551	340	275	265	14,714	10,637	11,060	1723	5709	5526	22	29	18
Total Recycle (kg)[1]	0	0	0	14	24	23	3308	3878	5258	0	0	24	0	0	0
Share of specific countries in purchaser group, 2016	Ukraine 42.8% Lithuania 41.4% Hungary 9.8% Latvia 2.1% Belgium 1.9% Estonia 0.3%			-			Pakistan 37.8% Benin 11.3% Russia 10.0% Togo 9.0% India 6.3% Burkina Faso 4.5% Ukraine 4.4% Cameroon 4.2% Turkey 3.6% Slovakia[2] 3.2% Africa[3] 2.7% Netherlands 1.4% Romania 0.4% USA 0.3% Poland 0.2% Taiwan 0.2% Latvia 0.2% Germany, HPP 0.2% Sweden, HPP 0.1%			Africa[3] 93.0% Kenya 6.2% Togo 0.8%			N.D.[4]		

[1] Including pre-sorted and returned textiles sold directly. [2] 2.8% is to HPP. [3] Not specified further [4] No data.

Table 13 shows the textile sorting centre's total consumption of resources and materials as well as staff employed. Over the three years, the consumption of various resources increased per tonne of sorted textiles. The increase for lower-quality and recyclable textiles resulted in higher costs in terms of electricity, packing materials (only for reusable materials) and baling wire. The main water consumption was for staff sanitary and hygiene requirements, since only a small number of textiles from sorting were washed, which is why water consumption is relatively stable over the years. The need for heating differed over the years, depending on weather conditions. In general, the expenses for running the sorting centre follow in line with resource consumption, but increases in electricity prices from 2015-2016 particularly raise costs (Table 13).

Though it was not possible to relate the consumption of resources to sorting different textile categories, for example those sorted at the main sorting area required more electricity than the fine sorting textile area due to the baling process, the normalised values provide a good indication of the resource consumption required for sorting different qualities.

Table 13. Total annual use of resources, materials and labour and associated monetary costs, as well as the normalised use and cost per tonne of total imports, total sold and sold for reuse (Paper III).

	Year	Electricity		Heat (gas)		Trucks (gas)		Water		Baling packing		Baling wire		Employs		Fixed costs	Total cost
		[kWh]	[€]	[m³]	[€]	[kg]	[€]	[l]	[€]	[kg]	[€]	[kg]	[€]	[FTE][3]	[€]	[€]	[€]
Total	2015	529,868	93273	23,000	7362	-	15,487	3871	3868	89,860	372,652[2]	24,042	372,652[2]	-	-	-	-
	2016	532,653	20,933	28,400	8735	31,500	21,195	3735	4006	109,057	349,052[2]	24,875	349,052[2]	392.5	4,851,053	51,615	5,306,589
	2017	579,355	21,436	27,260	8797	34,111	26,398	3759	3890	99,088	381,427[2]	24,823	381,427[2]	-	-	-	-
Per tonne total import[1]	2015	14.28	0.25	0.62	0.20	-	-	0.10	0.10	2.42	0.10[2]	0.65	0.10[2]	-	-	-	-
	2016	14.61	0.56	0.78	0.24	0.86	0.58	0.10	0.11	2.99	0.10[2]	0.68	0.10[2]	0.01	133.1	1.42	145.6
	2017	15.18	0.56	0.71	0.23	0.89	0.69	0.10	0.10	2.60	0.10[2]	0.65	0.10[2]	-	-	-	-
Per tonne sold textile[1]	2015	15.49	0.27	0.67	0.22	-	0.45	0.11	0.11	2.63	0.09[2]	0.70	0.09[2]	-	-	-	-
	2016	16.17	0.64	0.86	0.27	0.96	0.64	0.11	0.12	3.31	0.09[2]	0.76	0.09[2]	0.01	147.2	1.57	161.1
	2017	16.57	0.61	0.78	0.25	0.98	0.75	0.11	0.11	2.83	0.09[2]	0.71	0.09[2]	-	-	-	-
Per tonne sold reused textile[1]	2015	18.87	0.33	0.82	0.26	-	-	0.14	0.14	3.20*	0.08[2]*	-*	-*	-	-	-	-
	2016	20.37	0.80	1.09	0.33	1.20	0.81	0.14	0.15	4.17*	0.07[2]*	-*	-*	0.01	185.4	1.97	202.8
	2017	21.54	0.80	1.01	0.33	1.27	0.98	0.14	0.14	3.68*	0.07[2]*	-*	-*	-	-	-	-

[1]Includling import stock, not sale stock. [2]These values are costs for both baling packing and wire. [3] Calculated as full-time employment (FTE). *Baling packing is only used for reuse export categories; wire is only used for recycling categories.

Table 14 shows annual expenses connected to the import (purchasing of textiles at the sorting centre) of textiles. This includes the costs of transporting textiles from the source of purchase to the TSC, and the value of stock carried over from one year to the next. The larger share of pre-sorted textiles was the main reason for the increase in total costs, as the average price for 1 kg of pre-sorted textiles increased over time. On the other hand, the average prices of 1 kg of textile original from collection lowered, due to the fact that the prices of textiles received from collection are based on sorting scores that grade the quality of the unsorted items received at the facility and are specific for each customer. The lowered price is therefore also an indication of lower quality in the general composition of the received textiles as well as a more competitive market (e.g. more collected textiles without the same increase in demand), thus placing pressure on the collection of used textiles, as also noted in Ljungkvist et al. (2018).

Table 14. Total costs of purchasing textiles, including costs for the transport and transfer of stock (€) and average prices in euro per kg per year (Paper III).

	Import cost			Avg. prices		
	2015 €	**2016 €**	**2017 €**	**2015 €/kg**	**2016 €/kg**	**2017 €/kg**
Textiles originating from collection	21,588,963	20,741,242	20,589,394	0.66	0.63	0.63
Δ Change in textile stock originating from collection	-653,030	486,258	-311,033	-	-	-
Transport of textiles originating from collection	3,128,152	2,576,006	2,314,528	0.10	0.08	0.07
Pre-sorted textiles	3,917,869	4,065,871	4,989,728	1.30	1.51	1.35
Transport of pre-sorted textiles	275,953	202,527	276,338	0.09	0.08	0.07
Total import cost €	**25,098,324**	**25,214,643**	**25,502,817**	**-**	**-**	**-**

*Includes return Δ stock.

Even though the collection potential in household waste was shown to be high in terms of the quality of the textile products found, considering that the products were discarded as waste, an increased collection regime would affect the sorting centres. The fact alone that the number of small textile items would increase (e.g. larger share of underwear and socks), in line with the increased collection rate, will consequently affect sorting, as small products need the same attention from the sorter as larger and heavier items. The lower the quality of the small products, the less economic value they contribute, which leads to either more expensive sorting or less sorting, as sales prices are based mainly on weight. In general, payroll is the highest cost at the sorting centres, and as the prices of the sorted textiles sold on the market are marginal, this sorting cost affects sorting rates. As an example, sorting in Denmark is so expensive that the only fully commercial sorting centre only sorts approximately 10% of all collected items, and thus the waste rate is much higher (The Danish EPA, 2018; Trasborg Denmark, 2018).

4.2.2 Replacement rates for textiles reused in Africa

The replacement rates for second-hand textiles sold in the three countries surveyed were Angola 63 ± 6%, Malawi 35 ± 2% and Mozambique 37 ± 5% (Figure 9). In general, the replacement rates were higher in Angola than in the two other countries at 59 ± 6% Clothing, 67 ± 6% Household textiles and 77 ± 5% Other textile products.

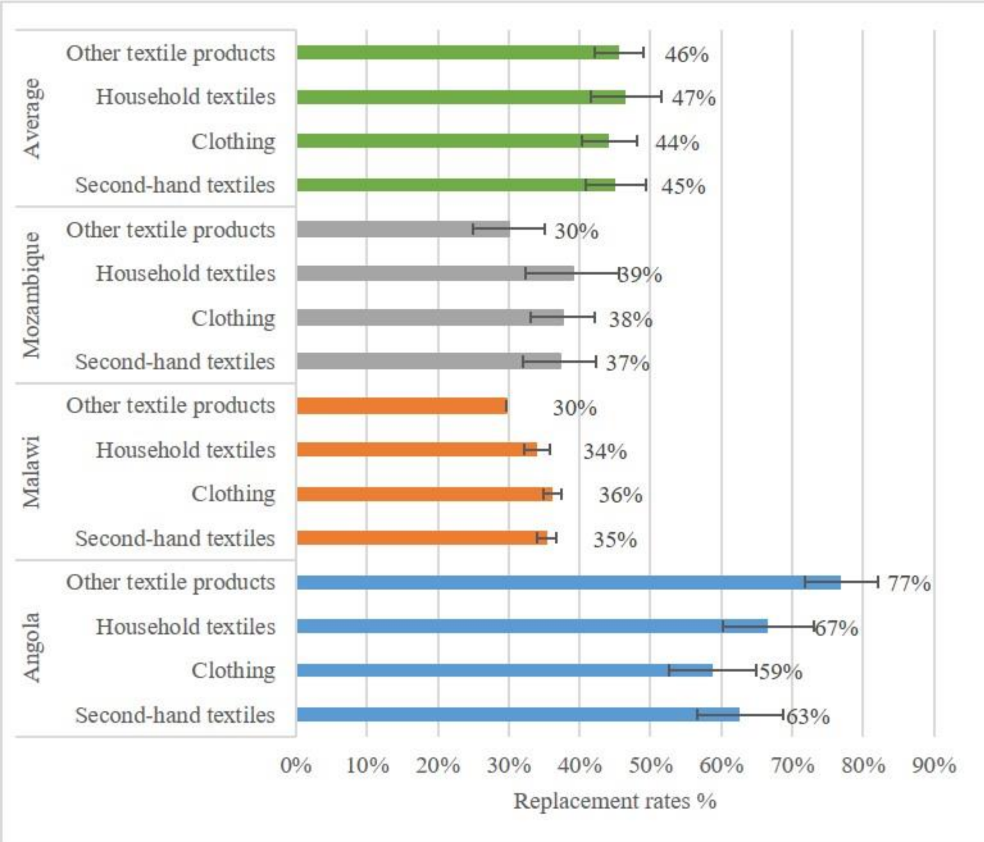

Figure 9. Replacement rates for second-hand textiles shown as averages of all textile products (Second-hand textiles) and as averages of the main categories Clothing, Household textiles and Others. Replacement rates are calculated for each country, as well as the average for the three countries combined (n = Angola: 5124, Malawi: 3588, Mozambique: 5478 and total n = 14,190 items). Specific data for the replacement rates are found in Tables 1F and 2F in Paper IV, Appendix F.

The spread of respondents in relation to the specific country demographic regarding, age, occupation, income and household composition is fairly representative (CIA, 2018a-c). In Angola, the larger share of the participants were women, while in Mozambique there were more men. Despite the gender difference in respondents in these two countries, it is fair to consider the results as representative of the three countries. The replacement rates were significantly lower than 85%, which was the replacement rate used for sub-Sahara in a previous study (Farrant et al., 2010). However, the replacement rate of 85%

suggested by Farrant et al. (2010) is a best guess based on general knowledge of the population regarding their consumption of second-hand textiles.

The few previous studies of replacement rates were all conducted in Europe and found replacement rates between 28% and 75% (Castellani et al., 2015; Farrant et al., 2010; Stevenson and Gmitrowicz, 2013), all of which are comparable or even higher than the results found in this study. This was surprising, as higher replacement rates were expected for the African countries. However, when compared with the findings from this study, there was a good indication that the respondents' economic purchasing power certainly influenced the replacement rate. This study found that the majority of the respondents had a wardrobe that contained a large share of second-hand textiles, and in general they purchased more of these items than new. The main reasons for buying second-hand textiles in Great Britain were related to getting a good bargain and spur of the moment purchases (Stevenson and Gmitrowicz, 2013). On the contrary, the main reasons for purchasing specific second-hand textile items in the African countries were the need to upgrade an item or replace a broken item, and the main reason for purchasing it second-hand was that it was cheaper. It was also found that those respondents with a large share of the wardrobe consisting of second-hand had the lowest replacement rates as well the lowest clothing budget (Appendix F, Paper IV). This could be due to this group not being able to buy as new, and thus not actually leading to a replacement per se, albeit it was not possible to verify this notion based on the survey questions.

The fact that the replacement rates only were remarkably higher in Angola than in the European countries contradicts the assumption that the replacement rate should be lower in wealthy countries (as assumed, for example, in Beton et al., 2014; Schmidt et al., 2016). This indicates the need for more studies of replacement rates and a special focus on understanding the reasons behind the respondents' answers to the key question (if the respondents would have purchased the item as new, if not found second-hand).

Second-hand textiles sold in African countries are of lower quality than those sold in Europe, and the sorting centre increased its sales to HPP Africa from 2015 to 2017 (as shown in section 4.2.1 and Paper III). It is interesting how this would affect the replacement rates in these countries or any other country that generally imports lower-quality textiles. Although the primary reason given in the survey study for purchasing second-hand was that it was the cheapest option, better quality or a brand more well-known than available new products were also main reasons (Appendix D, Paper IV). This, combined with the idea that it is plausible that an increase in welfare in a country will lower the general use of second-hand clothes seen in the Western world (see section 2.1), makes it very relevant to keep studying the replacement rate and understanding the factors influencing it. This is also of relevance for understanding how to increase the use of second-hand textiles.

4.3 Environmental assessment

4.3.1 Climate change effects of realising the potential for increasing textile collections from the households

Figure 10 illustrates the climate change impact potential for realising the potential for increasing textile collections from Danish households by reducing the amount of textiles thrown into residual waste and small combustibles (household waste). As evidenced, scenario 1 gives the highest savings of 30.2 kg CO_2-eq per person, which corresponds to 172,140 tonnes for the total Danish population. Savings are though already seen by encouraging consumers to reduce the amount of usable rags discarded in the waste and instead reusing them, with a savings of 1.4 kg CO_2-eq (equal to 7,899 tonnes for the total Danish population). The largest contribution to the savings in all scenarios is the textiles replaced due to reuse, which explain why scenario 1 is better than 2, as the amount of textiles sorted out for reuse is highest in scenario 1. In scenario 1, the largest saving comes from reuse in the rest of the world, which is explained by the larger amount of the textiles sent for reuse in the rest of the world (55%) and the higher replacement rate (45% versus 35% for Europe). Scenario 2 gives a saving of 12.4 kg CO_2-eq per person, which is less than half of the savings found for scenario 1. This is predominantly due to the sorting in Denmark categorizing more of the textiles as waste, leading to overall lower reuse rates. In addition, there are small differences due to the waste management, which in Denmark is incineration with energy replacement, while the largest share of the waste in Lithuania, where the international sorting centre is located, is landfilled. Due to the high amount of synthetic textile material, the incineration of the textile waste leads to a net release to the atmosphere even though energy is substituted. In contrast, landfilling leads to carbon sequestration as the textile fibres (i.e. natural fibres) are only slowly degraded under anaerobic conditions. It should be noted that scenario 2 is based only on the sorting scores of the potential of textiles found in residual waste, and that the scores might have been affected because the waste samples have been washed before quality checking. However, the sorting carried out in Denmark is currently non-profitable when sorting all collected material, even for charity organisations with mainly volunteer workers. The likelihood that lower-quality items will be sorted in Denmark is therefore low. The higher contribution from collection in scenario 1 compared to scenario 2 is due to the transport to the international sorting centre. The differences between the sorting in the two scenarios are due to the electricity- and heating-mix in the two countries. In scenario 1 it has not been possible to model the full potential for recycling found in the waste as mentioned in section 4.1 (Appendix B, Paper I), as some of the products in the reference flow is not recyclable, whereas some of the smaller fractions they represent would be recyclable, and therefore this gives a higher percentage of textiles sorted out as waste in the modelling.

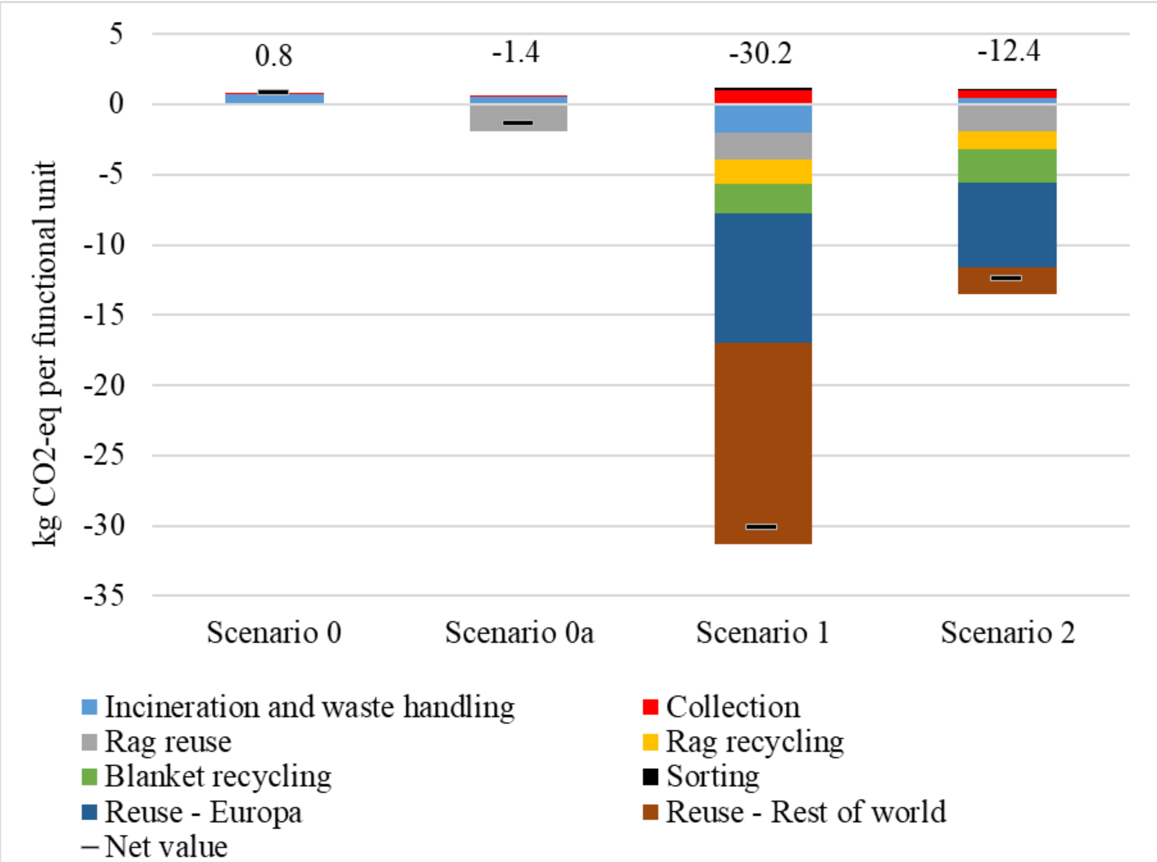

Figure 10. Climate change effects from the four scenarios for management of textiles currently discarded in the waste. Scenario 0 is management with residual waste, Scenario 0a is reuse of rags, Scenario 1 is sorting at international sorting centre for reuse, and Scenario 2 is sorting for reuse at Danish sorting centre. Results given in kg CO2-equivalents per functional unit (6.2 kg of textiles per person).

These results should be considered uncertain, as the data for modelling the production of products replaced by second-hand textiles or made from recycled textiles were limited. Correct modelling of textile waste is complicated as the fraction consists of many types of products. Furthermore, correct textile handling includes both reuse and recycling, which both depends on the condition of the individual textile product, and this not only includes an assessment of whether the material is dirty or wet, but it also depends on a variety of other parameters, as shown in Papers I and II. Moreover, if a product cannot be reused, it cannot necessarily be recycled, and so recycling depends further on how the product is manufactured and its fibre composition. Here the sorting facilities most likely will take a conservative approach, and discard material with mixtures of different fibres, as they can only be recycled when the cotton content is sufficiently high.

As the results show, the replacement rate is a key parameter in determining the size of the saving, therefore more studies should be carried out to examine the replacement rate in more countries. Especially since the increased collection will increase the amount of textiles of lower quality than the current separated collection. It is therefore important to better understand how the replacement rate differs between geographical regions and how countries are impacted by the quality of the reusable textiles.

5 Textile quality as a concept

The context for understanding the foundation for improving textile collection is to understand the importance of quality. From the citizen choose to throw out a textile item, through the textile waste management system and until it is resold, it is the understanding of quality that determines how textiles are treated. Based on the work presented in this PhD thesis, a concept of textile quality has been developed, which is presented in this section.

Quality easily becomes a subjective assessment, and so it is of relevance to functionalise textile quality as a concept. An assessment in this regard is complex and depends on several factors, which can be distinguished through functionality, aesthetic appearance and fashion, seen in relation to each individual person's perceptive frame of understanding (Figure 11). These factors all affect whether a person decides to throw away a textile product and how they dispose of it (e.g. into separate collection or in the waste). However, quality is also crucial in determining whether the textiles can be reused, where they can be reused and, to a lesser extent, whether they can be recycled. In contrast, recycling depends mainly on very specific conditions such as product type, production method, fibre composition and the condition of the product. These factors also have an impact on reusability, but they are key for recycling. As an example, a piece of textile may not be recycled if it is too small to be made into a rag, while it may not be recycled as a rag if it has the wrong fibre composition (as found in Papers I and II).

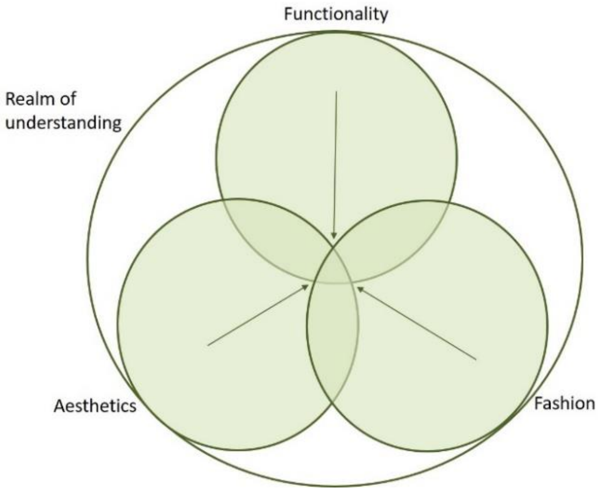

Figure 11. The concept of textile quality distinguished in the three factors functionality, aesthetic appearance and fashion. The closer to the middle a product finds itself, the higher the product fulfils the factors. The realm of understanding is the context in which the factors should be interpreted and is mainly understood as economic purchasing power, albeit for some citizens it is also to some extent their personal relationship with the product (e.g. sentimental value).

Functionality is understood in terms of whether the product is fully functional in its intended use, e.g. a fully functional jacket that can fulfil its purpose without any defects such as a broken zipper. Aesthetic conditions do not make the product unusable but only have an effect in relation to the appearance of the product. It can also be a challenge to distinguish between functionality and aesthetic conditions, because the product type can have a certain influence on this factor, and distinguishing between outer and inner textiles products is needed. As an example if a blouse has a large spot on the front, it is in principle still functional, but the aesthetic appearance will probably mean that it will not be worn if the citizen has the option not to do so. On the contrary, if the spot was on an inner textile such as a pair of underpants, the aesthetic appearance would become less important, and hence the importance now is whether functionality inhibits its use. The third factor is fashion, which also covers personal and social status and the meaning of textiles (as also presented by Klepp and Laitala, 2018). Clothing is highly dependent on these factors, whereas household textiles are less influenced in this regard.

Each individual person subjectively assesses quality from his/her own understanding of functionality, aesthetics and fashion, based on frames consisting of economic purchasing power and to some extent also their personal relationship with the product (such as sentimental value, e.g. a gift from someone special or a baby's first dress). The weaker the economic purchasing power, the less critical the person can be about when to use or dispose of a product, whereas significant economic purchasing power can make it possible to own and store a larger number of products without ever using them. For the buyers of second-hand textiles, what they can afford is an important influence combined with national and cultural contexts, as they influence the ways purchased second-hand textiles are perceived and how they replace a new product (as found in paper IV). Moreover, quality in itself, as defined by the three factors, affects the replacement rate, as a less functional, aesthetic or fashionable product will most likely not fulfil the same needs as a fully functional, aesthetic and fashionable product. For citizens, Clothing is affected more by aesthetic appearance and fashion than Household textiles, although the greater the economic purchasing power, the more these factors are also influenced by the comprehension of Household textiles.

Textile sorting centres and second-hand retailers apply the same concepts when assessing textile quality (distinguishing between the three factors functionality, aesthetics appearance and fashion), in order to operate on a large scale. For them, all three factors are important, and especially the ability to predict the right fashion style has an influence on sales prices, whilst the aesthetic appearance of a product can change its classification from reusable to recyclable, or even waste, depending on the product type, fibre composition and manufacturing method (as found in Paper III).

This concept should be devolved further by looking into more studies, as suggested in section 7, and it would be relevant also to examine the concept in connection with the Sustainability Cards developed by Hasling and Ræbild (2017).

6 Conclusions and recommendations

The potential for collecting more textiles from Danish households by reducing their content household waste is small in terms of volume, at only an average of 2.9 ± 0.9% Clothing and Household textiles thrown into residual waste. However, this corresponds to an average 2.4 ± 1kg Clothing and 1.1 ± 0.5kg Household of textiles per citizen, which is high compared to the consumption of new textiles. The content of textiles in small combustibles from recycling stations was on average 11.9± 4.2%. In comparison, the quality of the textiles found in household waste was high, as 77 to 83% of the Clothing and Household textiles could have been either reused or recycled if they had not been discarded in the waste. Of these items, the largest share could have been directly reused: 65 ± 8% of Clothing and 65 ± 19% Household textiles in residual waste and 69 ± 6% and 66 ± 10% for small combustibles.

This PhD thesis provides a clear definition of textiles, which is necessary for measuring the collection potential and quality thereof. Transparency and information regarding how the textiles are treated and what influences their quality, and thereby how they can be reused or recycled, needs to be provided. Textile collectors especially should communicate this information to citizens and waste companies/municipalities, in order to improve the collection of textiles.

Increased collection will affect textile waste management system, which have seen a rapid upward trend in costs over the last few years. The international textile sorting centre evaluated in this study, despite increased imports of textiles, experienced a decrease in the share of reusable categories (80% to 75%). This occurred mainly from fine sorting process despite that the import of pre-sorted textiles increased from 2015 to 2017. At the same time, the share of textiles for recycling (13% to 17%) and waste (5 to 6%) increased, which caused higher resource consumption per tonne of textile sorted and higher prices for sorting, which in turn affected the average prices paid for imported textiles. The decrease in the average price of imported textiles also indicates that the general quality of the received textiles from collection decreased. This thus lowers the prices for separated textiles collected from households, which will drop even further if more textiles of lower quality are separated for reuse and recycling. When implementing mandatory separated collections, it is also important to have in mind that recycling is still limited to relatively few fibre types found in certain products and items manufactured in certain ways.

This potential change in the quality of textiles sorted for reuse also supports a need for further studies on replacement rates for textile reuse, as the lower quality of second-hand textiles will have an effect on the replacement rates. In this PhD study, the replacement rates for second-hand textiles in Angola 63±6%, Malawi 35±1% and Mozambique 37±5% were determined. The rates were lower than expected, and even if they increased a little when calculating in terms of the main categories Clothing, Household textiles and Other textile products, only the Angolan rates were significantly higher than the replacement rates which previous studies found for European countries. Strong indications were found that economic latitude and purchasing power influence replacement rates, as these were small even when taking into account how large a share of the respondents' wardrobes consisted of second-hand textiles. Those with the largest share had the lowest replacement rates, which indicated a lack of economic latitude. This PhD thesis also provides suggestions for improving the survey method.

The environmental assessment showed a potential for improving the climate impact, from a net impact of 0.8 kg CO_2-eq per person in scenario 0, to a saving of 30.2 kg CO_2-eq per person in scenario 1, which is equal to 172,104 tonnes CO_2-eq for the total Danish population. Furthermore, it was found that only sorting usable rags (scenario 0a) gave a saving of 1.4 kg CO_2-eq. A sorting system in Denmark would only give savings of 12.4 kg CO_2-eq per person, due to the significantly higher proportion of textile sorted out as waste and the composition of the waste. These savings, however, must be seen in relation to the fact that data for textile LCAs are very limited. This means that the savings could be even higher from reuse and recycling, as the data for avoided production most likely still do not consider all the chemicals and energy use needed in textile production.

Based on this PhD thesis, data for setting up and calculating the effect of increasing the collection of textiles from household waste have been provided, and suggestions for further research are provided in the next section.

7 Further research

Based on the results of this PhD thesis, several research projects should be considered in the future. Divided according to the research areas of this thesis, recommendations for future research are as follows:

<u>Textile collection potential:</u>

1. More studies of the textile waste fraction, based on waste sampling, to: a) improve knowledge about textiles in waste, especially for countries other than Denmark, b) improve sampling and sorting methods in relation to the importance of moisture/wet clothing and weight, and influences of factors such as the length of the period between waste collections and sorting, c) ensure better data integration in LCA models and d) ensure also the better presentation of detailed data from the study for use in other studies (e.g. a data collection database).

2. Improved MFAs on textile consumption, with a special focus on quality and material types, to a) breakdown of flows between different textile consumers (e.g. citizens and government) and phases/processes (e.g. the retail business) to determine better where potential for improvement lies, b) determine accumulation both in private households and in overall national wide.

<u>Data improvements:</u>

1. More MFAs and LCIs of TCSs located in other European countries, other parts of the world to investigate the importance of textile compositions received, and national influences on sorting rates.

2. More studies of replacement rates, not only in African countries, but also in Scandinavia, Europe, Asia and the Middle East. With consideration of a need for a large sample size.

3. Investigations of replacement rates for recycled products and generally more knowledge and better data about the existing recycling industry for textiles (a very closed industry).

4. An examination of waste from the TCS, in order to determine both the amount of textile waste resulting from sorting as well as how much of this is currently categorised as waste because it has been passed on incorrectly (e.g. wet or dirty). In addition, it would be necessary to establish the amount of textiles that potentially can be recycled with future recycling solutions.

5. Investigate the current market share for products made from recycled fabrics and thereby clarify the potential for further increases in the amount of recycling.
6. Investigate the stability of the international reuse market for lower grades of textiles. Analyse what factors are crucial for maintaining good reuse habits when economic/purchasing power and the opportunity to purchase new increase, and compare these, among other things, with the influence of second-hand textiles originating primarily from the Western world.

<u>Environmental assessment</u>

1. Include several textile products and fibres in the analysis as overall knowledge and data on the textile chain improve.
2. Set up a more precise LCA for the recycling of textiles.
3. In general, better integrate data from textile waste studies into LCA modelling programs such as EASETECH.

Further devolvement of the concept of textile quality would also ne necessary, to make it measurable and more applicable for improving textile waste management and reducing the amounts being discarded incorrectly.

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9 Papers

I **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2018. Development and testing of a sorting and quality assessment method for textile waste. *Waste Management*, 79, 8-21. https://doi.org/10.1016/j.wasman.2018.07.008

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III **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2019. Evaluation of a European textile sorting centre: material flow analysis and life cycle inventory. *Resource, Conversation and Recycling*, 143, 310-319. https://doi.org/10.1016/j.resconrec.2019.01.010

IV **Nørup, N.,** Pihl, K., Damgaard, A., Scheutz, C., 2019. Replacement rates for second-hand clothing and household textiles – a survey study from Malawi, Mozambique and Angola. Journal of Cleaner Production. Manuscript accepted with revision in March 2019.

V **Nørup, N.,** Scheutz, C., Pihl, K., Damgaard, A., 2019. Life cycle assessment of increased collection and reuse of textiles currently discarded with residual waste. Draft manuscript in preparation for *Industrial Ecology*.

In this online version of the thesis, **papers I-IV** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from:

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The Department of Environmental Engineering (DTU Environment) conducts science based engineering research within five sections: Air, Land & Water Resources, Urban Water Systems, Water Technology, Residual Resource Engineering, Environmental Fate and Effect of Chemicals. The department dates back to 1865, when Ludvig August Colding gave the first lecture on sanitary engineering.

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