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Kirsi Laitala, Ingun Grimstad Klepp and Beverley Henry

Use phase of apparel:
A Literature review for Life Cycle Assessment with focus on wool.

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Sammendrag

Rapporten presenterer resultater fra en litteraturgjennomgang om bruksfasen for klær. Formålet er å undersøke om det er systematiske forskjeller mellom ulike fiber i bruksfasen og om det finnes nok forskningsbasert kunnskap til at dette kan inkluderes i ulike miljøverktøy. Alle tekstilfibrer er inkludert i undersøkelsen, men hovedfokus er på ull. Vi spør om bruk av ull gir annen miljøpåvirkning enn bruk av klær i andre fibre. Rapporten bygger på litteratur fra de siste 20 årene. Den viser at bruksfasen har stor betydning for mange miljøindikatorer, og at klær laget av ulike materialer brukes og gjenbrukes ulikt. Ull vaskes på ca. 10°C lavere temperatur enn gjennomsnittlig klesvask i Europa. Det er mer sannsynlig at klær av ull renses eller vaskes for hånd sammenliknet med klær av andre materialer. Det er også mindre sannsynlig at ull trommeltørkes. Vaskehyppighet for klær er også avhengig av fiber. Vi fant at forbrukere brukte sine ullprodukter dobbelt så lenge som tilsvarende produkter i bomull. Ullprodukter hadde lengre gjennomsnittlig levetid og blir oftere gjenbrukt eller resirkulert enn tilsvarende produkter i andre materialer.

Det er mye forskningsbasert informasjon tilgjengelig om bruk og gjenbruk av klær, men modellering av bruksfasen på mange tidligere livssyklusanalyse (LCA) på klær har ikke vært basert på forskning. Vi mener derfor at bruksfasen i LCA studier bør være basert mest mulig på primær data. Videre mener vi at miljøverktøy som sammenligner ulike fibre men utelukker bruksfase gir misvisende resultater. Derfor er fiberinnholdet en relevant kategori og bør tas hensyn til i modellering av bruksfasen i LCA-studier. Videre peker vi på at det er fortsatt en del metodologiske, konseptuelle og empiriske kunnskapshull som bør fylles.

Summary

This report presents a literature review of clothing use phase. The purpose is to support improved methodological development for accounting for the use phase in Life Cycle Assessment (LCA) of apparel. All relevant textile fibres are included in the review. However, the main focus is on wool. We ask whether the use of wool has different environmental impacts than clothes in other fibres. The report builds on a review of literature from the past 20 years.

The review showed that clothing made from different materials are used, and reused in different ways. Wool is washed differently as it has about ten degrees lower washing temperature than the average laundry in Europe. Wool is also more likely to be either dry-cleaned or washed by hand than other textiles. Moreover, when dried, it is less likely to be tumble-dried. When comparing the number of days between the washes of different types of clothes, we found that respondents were likely to use their woollen products about twice as long between washes compared to their equivalent cotton products. We also found that woollen products had a longer average lifespan and were more likely to be reused or recycled.

There is a lot of research-based information available concerning the use and re-use of clothing, and we believe there are sufficient results available on which to base LCA studies. Furthermore, we believe that environmental tools that compare different fibres but exclude use phase provide misleading results Including the use phase in fibre ranking benchmark tools will improve the rigour and accuracy of these tools for all fibres, compared to reporting results for fibre production only. However, we have also shown that there are several methodological, conceptual and empirical knowledge gaps in existing literature.

Stikkord

Bruksfase, klær, ull, klesvask, tekstiler, gjenbruk, resirkulering, LCA, livssyklusanalyse, bomull, levetid

Keywords

Use phase, clothing, wool, apparel, laundry, textiles, reuse, recycling, LCA, cotton, wearing, lifespans

Use phase of apparel:

A literature review for Life Cycle Assessment with focus on wool

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Preface

Australian Wool Innovation Limited (AWI) has commissioned Kirsi Laitala and Ingun Grimstad Klepp from Consumption Research Norway (SIFO) and Beverley Henry from Queensland University of Technology, Australia to conduct a literature review with the purpose of finding, evaluating and summarising information that can be used to improve the data of the use phase in Life Cycle Assessment (LCA) of apparel. All relevant textile fibre materials are included in the review. However, the main focus is on wool. We also gratefully acknowledge co-funding of the study provided by Cotton Research and Development Corporation.

The use phase is known to be a substantial contributor to environmental impacts from the garment life cycle. Wool is understood to have unique properties that may influence environmental impacts, such as a longer lifetime and higher incidence of re-use and recycling. In addition, washing methods may also be different for wool compared to other fabrics. This review of relevant literature collates the current information on this topic. Impacts of interest include (but are not limited to) climate change (greenhouse gas (GHG) emissions), fresh water consumption, eutrophication, eco-toxicity and fossil energy demand.

Investigation of microfibre pollution from synthetic and natural textiles is relevant to the calculation of environmental impacts but does not readily fall into an existing LCA impact category. A separate, linked report for the topic was written during this project (Henry et al., 2018), and the main results from this work are summarized here. The discussion, therefore, also assesses the methodological options for including microplastic pollution in an LCA study, including the data and life cycle impact assessment that would be required.

The work has been done in close cooperation with Angus Ireland from AWI and Stephen Wiedemann from IntegrityAg Services, and we would like to thank them for good comments and follow-up during the project. We would also like to thank Allan Williams from Cotton Research & Development Corporation, Tone Skårdal Tobiasson from nicefashion.org and Barbara Nebel from Thinkstep for their contributions.

Contents

Summary

This report presents a review of relevant literature with the purpose of supporting improved methodological development for accounting on the use phase in Life Cycle Assessment (LCA) of apparel.

The report identifies, evaluates and summarises information that can be used to improve the scientific basis for LCA research with new data collated from global literature. All relevant textile fibre materials are included in the review. However, the main focus is on wool. We ask whether the use of wool has different environmental impacts than the use of clothes made from other fibres. The report was commissioned by Australian Wool Innovation Limited (AWI), International Wool Textile Organisation (IWTO) and Cotton Research and Development Corporation (CRDC).

Method
The report builds on an extensive literature review including studies over the past 20 years. Studies that discuss clothing use data relevant for modelling the use phase in LCA are included. The review excludes other stages of clothing production, the distribution chain and non-clothing textiles such as furnishing, bed textiles, towels and upholstery.

Results
We found a large number of relevant studies on the use phase of textiles. The amount of information varies geographically and for various aspects related to use. Most available data was for clothing in general and these lack fibre-specific information, thus allowing only limited comparisons between some fibre types.

The review showed that clothing made of different materials are used, and re-used in different ways. Therefore, the fibre type is a relevant parameter and should be included in modelling of use phase in LCA studies. Where information was available, the results have shown that wool is used differently than other textiles, especially those made of cotton. Wool is laundered at about ten degrees Celsius lower temperature than other fibres in average laundry. Wool is also more likely to be either dry-cleaned or washed by hand than other textiles. Moreover, when dried, wool is less likely to be tumble-dried. When surveying the number of days between washing for different types of clothes, we found that respondents were likely to use their woollen products about twice as long between washes as their cotton products. We also found results that showed that woollen products had longer average lifespans and were more likely to be reused or recycled.

The following parameters are addressed in order to be able to properly include the use phase in LCA studies:

- Method of cleaning, e.g. wet process either manually or using an appliance, dry-cleaning, spot cleaning or airing
- Characteristics and efficiency of appliances used for washing, drying and ironing that determine the water and energy consumption.
- Type and quantity of detergents and other chemicals used;

- Consumer behaviour and practice in laundry (decision to launder after use, filling grade of the washing machine, selection of washing cycle, temperature, etc.)
- Period of use of the item (length of effective lifespan)
- Fate at the end of use
- Material properties of textiles, such as ease of cleaning and design aspects that may affect durability and the social lifespans.

There is a lot of research-based information available concerning the use and re-use of clothing, and we believe sufficient results are available on which to base LCA studies. The sensitivity analysis showed that changes that have the largest contribution to energy and water consumption include number of days in use between washes, drying method and cleaning method (dry-cleaning or machine wash).

Several methodological, conceptual and empirical knowledge gaps exist despite the extensive amount of literature on clothing use phase. The ones that cause largest problems for LCA studies are

- The limited amount of empirical data on use frequency, effective lifetimes (service life), and reuse of clothing,
- Data from less studied geographic areas such as Africa, South America and some Asian countries.
- Methodological knowledge gaps related to the lack of suitable methods for studying effective service lifetimes, surveys and practice-based methods.

Use phase has a great importance to the total environmental impact, and should, therefore, be included in analyses that attempt to cover the entire clothing life cycle. The use phase is important to several environmental impact categories such as climate change, ozone depletion, water consumption, eutrophication, human- and eco-toxicity. Use phase also includes environmental impacts that are not covered by the current environmental impact categories used in most LCA studies, such as release of microfibres in laundering. LCA studies should include the use phase based research data, especially when such knowledge is actually available.

The overview and comparison of different fibres and regions globally makes it possible to show where there is greatest potential for improvements. By working towards meaningful use of functional units and recommendations of best practices, it will be possible to align the environmental improvements towards the areas where they make the largest impact. Improvements in textile LCAs will make the various benchmarking tools currently being used better suited to promote sustainable development. We believe that this can be done by incorporating existing knowledge, while at the same time working with filling the key knowledge gaps, and thus contributing to more robust terms, data and parameters in the future.

This study was conducted to analyse whether the use of wool has different environmental impacts than use of other fibres in response to differences in use phase characteristics. We have shown that this is true; wool has a longer life and greater tendency to be reused and has lower cleaning frequency. Including the use phase in fibre ranking benchmark tools will thus improve the rigour and accuracy of these tools for all fibres, compared to reporting results for fibre production only. For wool, this will provide a more accurate and fair ranking result.

However, we have also shown that there are large variations in whether the potential benefit of reduced environmental impact is fully exploited. Thus, implementation of best practice in use will increase the difference between the fibres relative to the current practice.

1 Introduction

Life-cycle assessment (LCA) is a technique that is used to assess environmental impacts of products, processes or services. LCA includes all stages of the lifecycle from raw material extraction, materials processing, manufacture, distribution, use, repair and maintenance, recycling and finally end-of-life (“cradle-to-grave” analysis). Previous literature reviews of LCA studies on clothing have revealed that the consumer use phase often has the largest contribution to many environmental indicators, but also that the studies are often limited to a small number of textiles and are not consistent, which makes comparisons difficult (Chapman, 2010, Dahllöf, 2004). The reviews have also shown that the use phase is often included only using hypothetical assumptions and is seldom based on empirical studies of consumer behaviour, especially related to laundering frequency and temperature.

Only a few complete LCA studies have been made on wool garments, and many analyses exclude the use phase of garments and are only performed as “cradle to gate” studies. These stop at the farm gate or factory gate and thus exclude the consumer stage (Henry, 2012). Therefore, there is a need for more information on the use phase of wool, but also on other fibres if comparisons of the environmental impacts of various materials are to be made. Most fibre ranking tools in use today exclude this phase (Made-By, 2013, Sustainable Apparel Coalition, 2017).

This report includes information on what the analysed literature says about use (laundering, drying), clothing lifespans and the end-of-use phase (disposal, recycling etc.) for wool garments. It identifies knowledge gaps regarding the use phase as well as priorities for future studies. The report also considers the aspect of using ''best practice' scenarios in addition to the current consumer habits, and maximizing the inherent benefits of wool’s properties for lower environmental impact in use.

Investigation of microfibre pollution from synthetic and natural textiles is relevant to the calculation of environmental impacts but does not readily fall into an existing LCA impact category. A separate, linked report for this topic was written during this project, and the main results are summarized here(Henry et al., 2018).

Our main research questions are:

1. Which parameters of the use phase should be addressed in order to be able to properly include this phase in LCA studies?
2. Is there enough information available about the use and re-use phases, to make it possible to base LCA studies on research-based information on use?
3. Does the information indicate that it would be possible and appropriate to use fibre type as one of the parameters for environmental impact in use?
4. Does the information indicate that regional differences are relevant for determining impacts of the use phase in LCA?
5. Where are the largest and most significant knowledge gaps?
6. How can a literature review of the use phase help:
    a) to improve LCA of textiles?
    b) to improve practices related to use in order to reduce environmental impacts?

Our aim is to:

I. Collect and collate use phase data (lifetime, use frequency, wash frequency etc.) for natural fibres (specifically wool and cotton) and other apparel types.
II. Collect and collate life cycle inventory (laundering data – wash temperature, volume, energy) for wool, cotton and other apparel types.
III. Collate and synthesise the data in a format appropriate for use in LCA studies. Include, where possible an indication of the range for variables to enable sensitivity and uncertainty analysis in LCA and model for inclusion in LCA methodology.
IV. Where found, collate data regarding the end-of-use phase (disposal, recycling etc.) for wool and cotton garments.
V. Identify data gaps and opportunities for reducing the environmental impacts of wool and cotton with respect to the use and end-of life phases.

2 Methods

The research for this report was conducted in several stages. First, a list of potentially relevant publications and other sources was prepared. This list included some information on what each publication covered (topic, geographic reach, methods, fibre or textile types). These were scanned through, and data was collected and collated for wool and other apparel types including:

a. use phase data, including lifetime, use frequency, etc.
b. life cycle inventory including laundering data, such as washing frequency, method, temperature, volume, detergents and energy use.
c. Where found, data on end-of-use (e.g. recycling, disposal) was also included.

After the literature review, a qualitative indication of the level of confidence or uncertainty in the data and coverage was prepared where possible. At the final stage, a summarized assumption and data for LCA modelling were prepared in a tabulated format.

The detailed description of these stages is given in sections below.

2.1 Identification of sources

In the first stage of the literature search, the authors listed up publications they already had knowledge of that include relevant information about the use phase of clothing, with the main focus on wool and cotton. In the next stage, in order to find further relevant articles, the electronic databases ISI web of science®, EBSCOhost® Research Databases, and Google Scholar were searched through. Search terms used included clothing, apparel, or fashion combined with use, laundering, drying, ironing, disposition, discard, or recycling in the title, abstract, keywords or the body of the articles. In addition, reference lists of the articles found were scanned through, and this increased the number of sources significantly compared to the original list. After the first search round, additional searches were made to cover areas that were not included in the literature from the first round, such as studies from specific countries, or cleaning methods of clothes that do not involve the use of a washing machine.

In addition to scientific articles, the review includes reports, dissertations (minimum master's degree level), book chapters, and conference papers. However, it is possible that not every existing relevant document was found due to the lack of inclusion in common search databases and lack of referencing by other researchers.

The literature found was organized in an Excel database coded for fields that included the authors of the study, publication name and type, year of publication, research method(s), geographic reach, and variables or themes.

A similar method of identifying literature for the sub-project on microplastics was conducted. In the case of microplastics, however, there was also a strong emphasis on continued identification of the latest sources of information in peer-reviewed publications, reports and popular science during the project period. This was important because research on microplastics is currently an active area and is rapidly evolving. The review on microplastics is presented in a separate report, with only the main findings on microfibres released from textiles into the environment as a result of use and washing synthetic garments summarised in this use phase report.

2.2 Scope

The search was limited to publications for the years between 1997 and 2017, which excludes earlier publications that might be relevant to the topic. However, clothing practices as well as the materials today differ greatly from those older than 20 years, and therefore are not as relevant for the purpose of this study.

Mainly publications in English and Fenno-Scandic languages (Norwegian, Swedish, Danish and Finnish) were included, which means that potentially relevant literature published in other languages has been excluded. However, one French publication with a comprehensive abstract in English, and some studies in German were included. However, English is the main language for scientific publishing on this topic, and the largest number of peer-review journals are in English.

Any studies discussing clothing use that include information relevant for LCA are included in the review. The review excludes other stages of the clothing production and distribution chain. Mainly data relevant to modelling the use phase of clothing in LCA has been included.

The review excludes textiles other than for clothing, such as furnishing, bed textiles, towels and upholstery. Accessories, such as scarves, are included.

3 Results

This chapter includes a review of studies that have measured consumer behaviour during the clothing use phase, including the various aspects of laundering (3.1 and 3.2), length of lifespans and use frequency (3.3), reuse (3.4), end of use (3.5), and recycling (3.6). Laundering related energy and water use figures are reported (3.1.11 and 3.1.12). A number of textiles LCA studies have been conducted, and some of them are presented in section 3.7 with focus on their use phase data.

3.1 Laundering

Laundering practices have been studied in several countries during the past two decades. These studies show that there are huge variations in types of washing machine, and in practices relating to laundering temperatures and frequencies, drying and ironing. In addition, they show how laundering practices are constantly changing due to improvements in technologies, changes in textile materials, consumer habits, and external factors such as government efforts to reduce energy consumption and stricter chemical legislations. Therefore, this report focuses on the more recent studies in the area, and older studies are only included if the data collection method has been solid and covering more than the more recent study on the same topic.

The main sources for laundering life cycle inventory data presented in this chapter are given below, sorted by continent:

Global and cross-continental sources

- The Nielsen Company (2016) conducted a Global Home-Care Survey in 2015 (August to September). The online survey was answered by more than 30,000 respondents in 61 countries throughout Asia-Pacific, Europe, Latin America, the Middle East/Africa and North America. It is weighted to be representative of internet consumers by country. Internet penetration rates vary by country. The Nielsen survey requirement for inclusion was that participating countries have a minimum of 60% internet penetration or an online population of at least 10 million or higher.
- The Nielsen Company (2012a, b, c) conducted a global wardrobe audit for AWI. They studied consumers' wardrobe composition (in particular wool content), occasions where clothes are worn, the age of garments in the wardrobe, recycling methods, laundry habits and behaviour in relation to clothes and particularly wool garments (wash method, frequency, and use of garment care label). The study consisted of an online survey of 467 adult respondents (90 minutes) across seven countries: Australia (n= 56), China (n= 104), Italy (n= 51), Japan (n= 52), South Korea (n= 52), UK (n= 52), and USA (n= 100) (The Nielsen Company, 2012c). Additional qualitative data was collected through face-to-face in-home interviews with 40 participants that were chosen from the consumer segments that could potentially use a lot of wool (4-8 per country). The interviews lasted about 1.5 hours (The Nielsen Company, 2012a, b).

- DuPont (2015) has performed consumer laundry studies in eight countries: USA, Brazil, UK, France, Germany, Turkey, Russia and China. 500 respondents from each country were surveyed. The topics included consumers' sensory needs in relation to laundry behaviour (softness, whitening, odour elimination and maintenance).
- Spencer et al. (2015) presented findings from in-depth qualitative research on laundry behaviours with middle income households in Brazil, India and UK. After an online pilot survey, three qualitative data collection techniques were used; contextual observation, household tour, and contextual interview. These methods explored the everyday behaviours as well as participants' perceptions of the laundry process. The data is less suitable for this review due to the small sample size, but as very little information is available from laundry practices in India and Brazil, some results are included.
- Kim et al. (2015) investigated electricity and water use during washing machine operations in Europe, China, the USA, and South Korea. The data are used to calculate the environmental and economic impacts in terms of CO_2 equivalent emissions and monetary cost. Consumption data were collected for washing machine (first-grade energy efficiency) in each region. Water heating and energy generation type were considered. Laboratory experiments examined optimal washing efficiency and environmental impact in terms of extended mechanical action vs higher water temperature. Number of rinsing cycles was also discussed.
- Pakula and Stamminger (2009, 2010) undertook a survey of published data on energy use and water use for domestic washing across 38 countries representing 1/3 of the global population. They reported on regional differences in washing machine ownership, type, load size and washing cycles per use. The diversity limited the ability to recommend best practice, but point to where savings in water and energy could be made.
- A paper by Yasin et al. (2016) presented a methodology to assess energy consumption, and specifically the energy utilised in the washing and drying processes, of textile products in their use-phase with the help of statistical tools. A pragmatic method consisting of an LCA framework plus principle component analysis (PCA), extended by Procrustes Analysis (PA), was used to determine the energy consumption and to minimise the possible uncertainties in the use-phase of textile product systems. The methodology of LCA plus PCA-PA for energy consumption in textile products was employed to study the gaps in currently available assessments. Using this method, the main factors influencing energy consuming parameters or hotspots in the use-phase of a textile product system could easily be identified and potential sustainable improvements could be proposed.

Europe

- International Association for Soaps, Detergents and Maintenance Products (A.I.S.E., 2014, Vandecasteele et al., 2014) conducts a Pan-European consumer survey on sustainability and washing habits every third year. The last time it was performed in 2014, it included 23 countries in Western, Southern, Eastern Europe and Scandinavia, with approximately 200 respondents taking part per country (exactly 4,741 in total). Their survey data gives an indication of laundering frequency, temperature, filling grade and detergent types used.
- Laitala and Klepp (2016) studied Norwegian and Swedish consumers' laundry habits. Results presented in the article 'Wool wash: technical performance and consumer habits ' are based on surveys, interviews and technical washing tests with information about energy, water and detergent consumption in conjunction with the laundering of wool.

- Laitala and Vereide (2010) studied possible ways to save energy and water in domestic laundry through choosing different washing programs or temperatures. Randomly selected user manuals from 31 different washing machines from 14 producers were studied, and the energy and water use of different programs were registered and compared. This way, information of machines available on the Norwegian market in 2009-2010 was mapped.
- Laitala et al. (2011) discussed options of changing consumer habits in clothing maintenance towards environmentally sustainable direction, and attempted to evaluate which changes would be the most feasible and efficient. Laboratory trial results on washing were compared with earlier research on consumers' washing habits. Laboratory tests on laundering included tests on cleaning effect, energy and water use, and detergent dosing.
- Laitala et al. (2012b) discussed the change in laundering practices during the past 10 years in Norway, and suggested strategies to help consumers change their laundry habits to more sustainable ones. Quantitative information on consumers' experiences, habits and opinions concerning clothing maintenance was collected through three surveys in Norway in 2002 (N=1008), 2010 (N=546) and 2011 (N=1124).
- Braun and Stamminger (2011) have studied laundering practices in Germany based on a consumer survey with 5284 respondents. The topics covered in this article include drying, ironing and use of fabric softeners.
- Kruschwitz et al. (2014) studied consumers' laundry practices in Germany. 236 households participated in a study where they recorded all their laundering during four weeks. Information on 2867 wash cycles was individually recorded, including the dry weight of dirty laundry, amount and type of detergent and other laundry additives, which washing programme and wash temperature were selected. Data were also gathered about the qualitative composition of the load and the soil level of the laundry items. Although the study is not representative of the German population, it gives very detailed data based on actual measurements and diary keeping.
- Stamminger and Schmitz (2016) reported results from a European project where 50 different washing machines were tested for compliance in relation to EU Energy Labelling and Ecodesign legislations. Parameters that were measured and that are relevant for this report are: energy consumption, water use, washing performance, spinning performance, spin speed, load capacity.
- Schmitz and Stamminger (2014) reported from a consumer study in 2011 (online survey) that included 2290 respondents from ten European countries (208-241 respondents per country). The questions concerned washing and drying behaviour, and related energy consumption.
- Presutto et al. (2007) conducted a survey of 2497 households from ten European countries on their laundry and dishwashing behavior (about 250 households per country).
- Participants on the 1st Sustainable Washing Day on May 10th, 2004 were asked to fill in a questionnaire (Stamminger and Goerdeler, 2005). This lead to a rather large sample of 2272 answers, but this cannot be considered representative due to the recruitment methods. No sociodemographic data were collected.
- Two different kinds of consumer data were collected in Germany during 2005 in connection with the event, "Action Day Sustainable Washing" (Stamminger and Goerdeler, 2007). A simple questionnaire was answered by 3750 respondents. Additional data were collected by a supporting homepage, where consumers could calculate online how much water and energy resources were needed to wash clothes, depending on personal washing behavior and the age of the washing machine. Related costs were also estimated. In this way, 1484 records were collected with some background data

on the respondents. Neither of the methods are country representative, due to the recruitment methods.

- Rüdenauer and Grießhammer (2004) presented a product sustainability analysis of washing machines and washing processes. The analysis of the products takes into account the entire product line including global chain and emissions. For consumption and behavioral options, only the German situation is taken into account.
- Rüdenauer et al. (2008) have compared the environmental effects of various forms of laundry drying either in different clothes dryers or drying indoors in heated rooms.
- Berkholz et al. (2007) conducted a metering study in 100 German households. They measured the total electricity consumption for laundry washing in 100 households for 1 month.
- Gooijer and Stamminger (2016) gave an updated review of literature on water and energy consumption for domestic laundering. The literature review is mainly focused on Europe, but also includes data from Asian and North-American countries, as well as Australia.
- Stamminger (2016) Schmitz et al. (2016) and Alborzi et al. (2016) reported from an European consumer survey conducted in 2015 in 11 countries; Czech Republic, Finland, France, Germany, Hungary, Italy, Poland, Romania, Spain, Sweden, and the UK. In total, 4843 valid answers were received, out of which 300 or 600 were from each country, based on the number of inhabitants. The final sample was weighted to represent 82% of EU-28. Only respondents who claimed to contribute substantially to laundering in the given household were allowed to participate.
- Granello et al. (2015) have studied consumers’ laundering behaviour in Sweden through survey (225 respondents) and probes, where 19 households received weighing kit for registering all their laundering cycles during three weeks.
- Bain et al. (2009) have conducted an extensive review of the literature with stakeholder insight and quantitative analysis in the UK in order to study how the environmental impact of cleaning clothes could be reduced, and what kind of effect the various alternatives have.
- Fisher et al. (2008) conducted a study of Public Understanding of Sustainable Clothing in the UK for Defra. They used focus groups; home tasks and deliberative workshops in their consumer studies.
- Arild et al. (2003) conducted consumer surveys and washing trials in Norway, Greece, The Netherlands, and Spain. In each country, a sample of approximately 1000 persons who were in charge of laundry in the household was surveyed in 2002.
- Hulme et al. (2013) conducted Energy Follow-Up Survey (EFUS) in the UK and collected ownership and use patterns for key appliances across England through interviews with 2,616 households. The analysis included washing machines and dryers, and was weighted according to the UK population.
- Paloviita and Järvi (2008) have analysed the use phase of laundry detergents in households. The empirical data consist of interviews in the laundry rooms of 299 Finnish households. Consumers’ use of dosage measuring devices and actual doses of laundry detergents are studied.
- Aalto (2002, 2003) has comprised material on laundering in Finland from several sources. The first one was a time use survey conducted by Statistics Finland between 1999 and 2000. 4677 households were studied, and all household members aged over 10 years (5300 respondents) kept a diary on their time use during two days. The second

source was a survey conducted in 1999 with 443 respondents, and the third was a collection of laundry diaries from 52 households over a period of one month.

- Zimmermann et al. (2012) studied energy consumption in 251 British households through electricity measurements, surveys and laundry diaries in 2010-2011. The number of washing and drying cycles were registered, as well as their electricity consumption.
- Zimmermann (2009) studied electricity consumption in 400 Swedish households during 2005-2008. 40 households were measured for one year and 360 households were monitored for one month. The results were given separately for households living in single-family houses and in apartments.
- The REMODECE project (Almeida et al., 2009) monitored residential Monitoring Energy Use in 12 European countries (Belgium, Bulgaria, Czech Republic, Denmark, France, Germany, Greece, Hungary, Italy, Portugal, Romania and Norway). The measurement campaign was performed in about 1.300 households (about 100 households per country) and 6.000 questionnaires were answered in the survey (500 in each country). About 11.500 single appliances were analyzed.
- Uitdenbogerd et al. (1998) studied domestic energy saving potential for food and textiles in the Netherlands. The material is based on oral survey and interviews of 104 households with children in 1997. The same material has also been used as basis for Uitdenbogerd's PhD (2007).

North America

- Hustvedt et al. (2013) conducted an internet survey of 330 randomly selected US consumers who owned either a front loading washing machine, or top-loading with a vertical agitator. Topics are related to adoption of sustainable laundry technologies, particularly for energy and water savings.
- Hustvedt (2011) reviewed the research conducted by the US Department of Energy concerning clothes laundering over almost 60 years which aimed at tracking growth in energy efficiency. The review gives a summary of findings on laundry habits that affect energy use. However, it draws attention to the shortcomings of the US data as a measure of sustainability as they focus on appliance energy efficiency and do not evaluate water use or practices such as drying on a clothes line which are not dependent on appliances and which may contribute more to sustainability.
- Golden et al. (2010) evaluated energy and carbon impact from residential laundry in the United States based on previous literature.
- Sabaliunas et al. (2006) studied residential energy use and potential conservation through reduced laundering temperatures in the United States and Canada.
- Slocinski and Fisher (2016) conducted an online survey in the US in 2015 to study the use phase of woolen socks and next-to-skin woollen garments.
- Tomlinson & Rizy (1998) reported from a large experiment in Bern, Kansas, which was selected for a clothes washer study. During phase I of the study, 103 clothes washers in the town and surrounding Rural Water District were instrumented so that data on customer profiles, laundry habits, laundry throughput (loads and load weight), and energy and water consumption could be measured. Following a two-month data collection period, all of the washers were replaced by new, horizontal axis (h-axis) clothes washers, and the experiment continued for an additional three-month period. Overall, detailed data were collected and analyzed on more than 20,000 loads and nearly 70 tons of wash done by all of the participants over a wide range of real-world conditions.

- Yun et al. (2017) studied the energy consumption of tumble drying and ironing processes based on laboratory measurements on different types of textiles (regular cotton, cotton-polyester and easy-care treated products).

South America

- DuPont (2013a) performed consumer laundry studies in Brazil in 2013. They talked to 800 consumers (73% female) located in the east of the country. The survey topics included some questions related to laundry methods and sorting.
- Hecht and Plata (2016) studied washing practices in Mexico. They conducted a survey of 600 urban middle class households, and visited 60 of the surveyed households to conduct in-depth interviews.

Australia

- Jack (2013a, 2013b) presented the results of surveying 263 Australians about their jeans laundry habits and resource consumption. They documented how and why people perform laundry and the energy, water and chemicals savings from less frequent washing. The second paper engaged 31 participants from Melbourne to wear the same jeans for 3 months without washing and documented their experience and feelings.

Asia

- The Japan Soap and Detergent Association (JSDA) conducts a laundry survey about every fifth year (JSDA, 2002, 2006, Tsumadori, 2005). The surveys usually include about 200-300 respondents who have purchased a washing machine during the past five years.

- Yamaguchi et al. (2011) looked at the increase in the number of combined washer-dryers and increase in use of concentrated detergents in Japan. They examined the drying performance of sweat-absorbent, quick-drying clothing in domestic washing, and used LCA to compare washing and drying with heat-pump washer-dryers and conventional washer-dryers. The LCA approach used primary data and realistic assumptions of domestic practices e.g. dryer use only for the proportion of rainy days per year in Tokyo. Comparison of heat-pump washer-dryers with conventional washer-dryers, and cotton vs polyester underwear was used to develop possible mitigation strategies. Energy use and CO_2-equivalent emissions were estimated. Water use and detergent use were also calculated.

- Zhang et al. (2015) conducted a LCA of cotton T-shirts in China. For the use phase, they used survey data from 924 Chinese residents. Secondary data from databases, literature, and authoritative statistical data was used when primary data was not available.

- Yuan et al. (2016) used LCA to explore possible improvements in sustainability of washing machines especially for China. Cradle to grave LCA was conducted for a Chinese-produced horizontal-axis washing machine using data from representative household appliance production and recycling firms. Use phase data were collected from 1330 questionnaires for Chinese residents and secondary data were also collected from databases, literature, and technical manuals.

- Wang et al. (2014) visited 993 Chinese households and interviewed the person mainly responsible for laundering.

- DuPont (2013c) reported on consumer laundry studies in India. The data is based on other studies by Euromonitor International: 'Laundry care in India' (September 2012) and DuPont Research: 'Laundry Trends: India' (July 2012). The study was conducted by Iconoculture and commissioned by DuPont. It included information on washing machine ownership and detergent types used,

- DuPont (2013b) performed consumer laundry studies in China in 2013. They surveyed 2150 women from different parts of the country covering large, medium and small cities. This data includes laundering methods, frequency, and use of various laundry products.
- Honold (2000) studied the effect of culture on the use of washing machines, and what happened when European washing machines were introduced to households in India.
- Detergent producing company Kao (Kao, 2010a, b) has conducted consumer research in China in order to study laundering habits and water consumption in laundering, including washing by hand. They studied women living in urban areas through door-to-door surveys of 600 households and home visits with observations and interviews of 52 households.

Africa

- Gordon et al. (2009) investigated pollution resulting from the use of detergents for washing clothes in streams and rivers, the fate of a commonly used anionic surfactant, linear alkylbenzene sulphonate (LAS). The study was conducted at a site regularly used for laundry activities in a reach of the Balfour River (Eastern Cape Province, South Africa). Samples of river water were collected upstream of the main washing site and at a number of locations downstream on several occasions during winter and summer. Sediment samples were also collected and analysed. Interviews were conducted with 40 respondents and combined with discussions at community workshops to ascertain the amount of detergent used and the distribution of washing practices. The results of the survey suggested that the use of riverside locations for laundry activities was seasonal. Most washing tended to be done at home during the winter with riverside sites used more frequently during the summer months.
- Euromonitor International (2011) reported on laundry care in Kenya based on official and trade statistics, as well as trade interviews. Even though the sources were not well specified, this report is included to provide some more information from Africa.

3.1.1 Cleaning methods

The methods for cleaning clothes vary greatly around the world. According to the Nielsen Home Care survey (The Nielsen Company, 2016), use of washing machines dominates, but in some regions, traditional laundry methods are important (Figure 1). Most of the recent studies on laundering habits concentrate on washing laundry in washing machines. Less are concerned with alternative cleaning methods such as washing by hand, airing, steaming, or dry-cleaning, which are often more relevant for products made of wool than of other fibres such as cotton or synthetics. In many western countries, the majority of households own or have access to a washing machine, thus many studies assume that this is the only way people clean their clothes. As a consequence, hand washing and dry-cleaning are often excluded from LCA modelling.

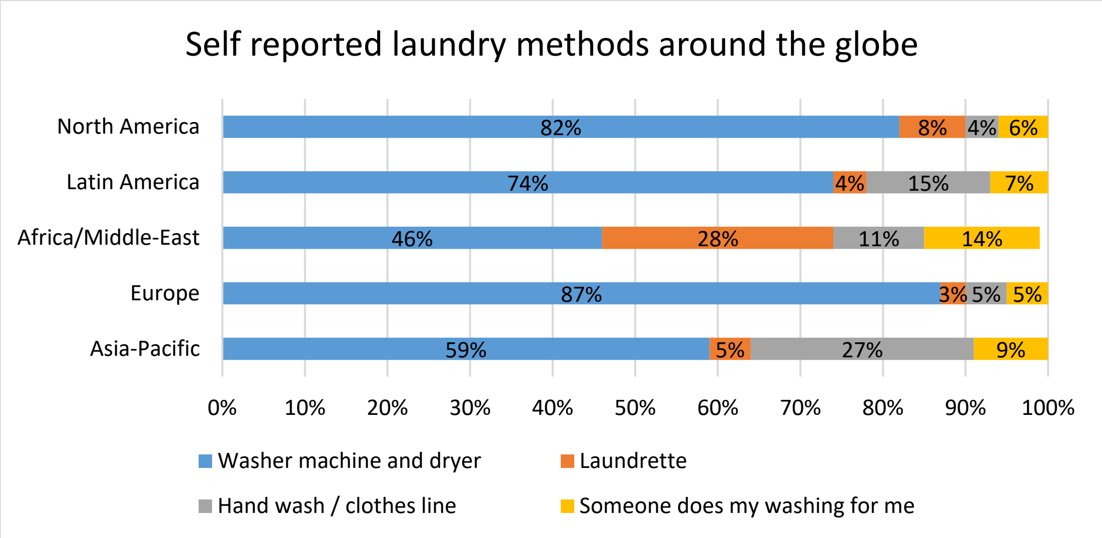

Figure 1 Self-reported laundering methods in different continents based on surveys in 61 countries (The Nielsen Company, 2016) (The only African countries included in this survey are Egypt, Morocco and South Africa)

Even the types of washing machines vary greatly between different regions (Figure 2). Horizontal axis drum machines are common in Europe, and in these machines, only the bottom of the washtub is filled with water and the machine has an internal water heating system. In vertical axis machines, usually the whole tub is filled with water, and if warm water is used, it is usually heated externally. Therefore, there are great differences in water and energy consumption between the different types of machines, in addition to variations in ways of using them. This is discussed further under sections 3.1.11 and 3.1.12. Vertical axis top-loading machines are used mainly in America, Australia, and Asia, although the share of horizontal axis machines is rising in these markets as well (Pakula & Stramminger, 2009; Wang et al., 2014). In the US, about 67% of households own a vertical top loading machine, 20% own a front loading horizontal drum machine, and the remaining 13% either do not own a machine or have one that uses a different technology (Hustvedt et al., 2013). The share of front loading machines is increasing rapidly, as in 2005 they constituted only about 9% (Davis, 2010). Hecht and Plata (2016) reported that in Mexico, 48% of urban households own an automatic washing machine and 39% own semi-automatic machines. Only 4% of washing machines are a front-loading type. In China, of the households that own a washing machine, 58% have an automatic impeller, 12% semi-automatic impeller, and about 30% own a drum washing machine (Wang et al., 2014). In some areas such as India, semi-automatic top loading machine types called “twin tubs” are common (Figure 1e). These machines have two tubs for washing laundry. One of them is for wash, rinse and soak, while the other is for spin-drying the laundry. As the water is filled and drained manually, these types of machines allow reuse of water for several wash loads.

The efficiency of these various types of machines is improving. Traditional vertical top loading washing machines have an agitator in the centre of the tub that rotates back and forth, moving clothes around to clean them. The newer versions do not have the centre agitator anymore, and instead use an impeller or pulsator with rotating tubs and wash plates that toss clothes around in addition to jets and streams of water to rinse the laundry. This also makes more room for larger loads and they use less water and energy than the traditional vertical machines. The machines with an agitator are less suitable for washing delicate clothes, because the aggressive action of the agitator can be hard on textiles. This also increases the shedding of fibres during washing and, hence, the number of synthetic microfibres in effluent (Bruce et al. 2016). In addition to these differences in mechanical cleaning action, the way water is heated also varies.

The European drum machines have an internal heating unit, while in other regions use of either ambient or externally heated water is common (Golden et al., 2010).

Figure 2 Automatic washing machine designs a) Top loading washing machine with agitator and vertical axis drum b) Top loading machine with impeller and vertical axis drum c) Top loading machine with horizontal axis drum d) Front loading machine with horizontal axis drum e) Semi-automatic twin-tub machine [1]

[1] Photos from http://designlike.com/6-major-differences-between-front-loading-and-top-loading-washing-machine/ , https://i.ytimg.com/vi/N6-HP43a_HY/hqdefault.jpg and http://www.italiansoflondon.com/images/bacheca/31997/31997.jpg.

Table 1 summarises studies that report ownership rate of washing machines in different countries. Based on this, it can be seen that western countries have a very high ownership rate, while hand washing is still common in developing countries.

Table 1 Ownership rate of washing machines in different countries and world regions

Country	Ownership rate of washing machines [%]	Year and source
Armenia	39-49	Table 1 (Rao and Ummel, 2017)
Austria	95	Table 2 Pakula & Stamminger (2010)
Australia	97 98	Table 2 Pakula & Stamminger (2010) 2014 (Australian Bureau of Statistics, 2014) Table 7
Belgium	95	Table 2 Pakula & Stamminger (2010)
Brazil	41.5 49.3 (urban)	2009 (Spencer, 2014) Table 1 (Rao and Ummel, 2017)
Bulgaria	44	Table 2 Pakula & Stamminger (2010)
Canada	82	Table 2 Pakula & Stamminger (2010)
China	61 84.3 (98 urban and 67 rural) 81.8 (urban)	Table 2 Pakula & Stamminger (2010) (Yuan et al., 2016) Table 1 (Rao and Ummel, 2017)
Croatia	65	Table 2 Pakula & Stamminger (2010)
Cyprus	95	Table 2 Pakula & Stamminger (2010)
Czech Republic	60	Table 2 Pakula & Stamminger (2010)
Denmark	79	Table 2 Pakula & Stamminger (2010)
East Europe	66	Table 2 Pakula & Stamminger (2010)
Europe	94	Table 4.2 (Almeida et al., 2009)
Estonia	78	Table 2 Pakula & Stamminger (2010)
Finland	89	Table 2 Pakula & Stamminger (2010)
France	97 100	Table 2 Pakula & Stamminger (2010) Table 1 Rao & Ummel (2017)
Germany	95	Table 2 Pakula & Stamminger (2010)
Greece	95 95.2	Table 2 Pakula & Stamminger (2010) 2002 Arild et al. (2003)
Hungary	70 86	Table 2 Pakula & Stamminger (2010) 2007 (Santander Trade, 2017)
Iceland	95	Table 2 Pakula & Stamminger (2010)
Indonesia	30	(The President Post, 2012)
Ireland	95	Table 2 Pakula & Stamminger (2010)
India	8.8 (27.5 urban and 0.6 rural) 17.3 (urban)	(DuPont, 2013c) Table 1 (Rao and Ummel, 2017)
Italy	95	Table 2 Pakula & Stamminger (2010)
Japan	99 100	Table 2 Pakula & Stamminger (2010) Table 1 Rao & Ummel (2017)
Kenya	23 (35 urban and 19 rural)	2010 (Euromonitor International, 2011)
Latvia	65	Table 2 Pakula & Stamminger (2010)
Lithuania	82	Table 2 Pakula & Stamminger (2010)
Luxembourg	95	Table 2 Pakula & Stamminger (2010)
Malaysia	90	EGA 2014
Malta	82	Table 2 Pakula & Stamminger (2010)
Mexico	67	EGA 2014
Myanmar	4	(The Nielsen Company, 2014)
Netherlands	98 98.0	Table 2 Pakula & Stamminger (2010) 2002 Arild et al. (2003)
Nigeria	8 (urban)	(Robertson et al., 2011)
North America	86	Table 2 Pakula & Stamminger (2010)
Norway	89 95.9 91	Table 2 Pakula & Stamminger (2010) 2002 Arild et al. (2003) 2012 (SSB, 2012)
Philippines	32	(EGA, 2014)
Poland	76	Table 2 Pakula & Stamminger (2010)
Portugal	85	Table 2 Pakula & Stamminger (2010)
Romania	51	Table 2 Pakula & Stamminger (2010)
Slovakia	60	Table 2 Pakula & Stamminger (2010)

Country	Ownership rate of washing machines [%]	Year and source
Slovenia	98	Table 2 Pakula & Stamminger (2010)
South Africa	44.1 (urban)	Table 1 Rao & Ummel (2017)
South Korea	100	Table 2 Pakula & Stamminger (2010)
Spain	99.0 95	2002 Arild et al. (2003) Table 2 Pakula & Stamminger (2010)
Sweden	83	Table 2 Pakula & Stamminger (2010)
Switzerland	95	Table 2 Pakula & Stamminger (2010)
Thailand	57	EGA 2014
Turkey	63	Table 2 Pakula & Stamminger (2010)
UK	93 97 97 97	Table 2 Pakula & Stamminger (2010) 2011 (Hulme et al., 2013) 2016 (Statista, 2015c) Table 1 Rao & Ummel (2017)
USA	86 85.2 82	Table 2 Pakula & Stamminger (2010) 2011 (Siebens, 2013) Table 1 Rao & Ummel (2017)
Vietnam	23.6	2013 (Tomiyama, 2015)
West Europe	94	Table 2 Pakula & Stamminger (2010)

In the USA, the ownership rates of washing machines vary between the states. Interviews conducted by the Nielsen company (2012a) showed that it is more common for people living in New York, to use apartment complex washers and dryers, while the respondents from LA commonly own a washing machine.

A survey by A.I.S.E. (2014) included a question "How do you usually take care of the laundry?", and the results show clearly that it is most common to use a washing machine in Europe (Table 2). A combination of washing by hand and using a laundry machine was most common in Eastern and Southern Europe, while Scandinavians and Western Europeans are more likely to use only a washing machine. Overall, women are more likely to wash by hand than men are.

Table 2 A.I.S.E. survey 2014 results on how households usually take care of laundry in Europe (Vandecasteele et al., 2014)

	Usually using laundry machine when doing laundry	Using a combination of both – laundry machine and washing by hand
Europe total	79%	16%
Western Europe	83%	12%
Eastern Europe	75%	20%
Southern Europe	75%	22%
UK /Ireland	81%	15%
Scandinavia	84%	10%

A survey by Arild et al (2003) conducted in four European countries asked how households that do not own washing machine handle their laundry (Table 3). This showed that hand washing was a more common cleaning method in households that do not own a washing machine in Greece, but in the other three countries, use of public laundries was more common.

Table 3 How do households that do not own a washing machine usually handle the laundry (reanalyzed data from Arild et al., 2003)

	Netherlands (N=20, 2.0%)	Greece (N=48, 4.8%)	Norway (N=41, 4.1%)	Spain (N=9, 0.9%)
Washing machine owned by several households	35%	4%	85%	11%
Coin laundry	15%	2%	5%	11%
The cleaners/dry-cleaners	20%	4%	0%	33%
By hand washing	5%	85%	2%	22%
Other ways	25%	4%	7%	22%

The Nielsen Company's global survey in seven countries (2012c) asked respondents how each of the clothing items they own were washed. Men's answers are given in Figure 3 and women's answers in Figure 4. Results show that laundering in a washing machine dominates, but also that various garments are cleaned in different ways. For example, suits and coats are more likely to be dry-cleaned.

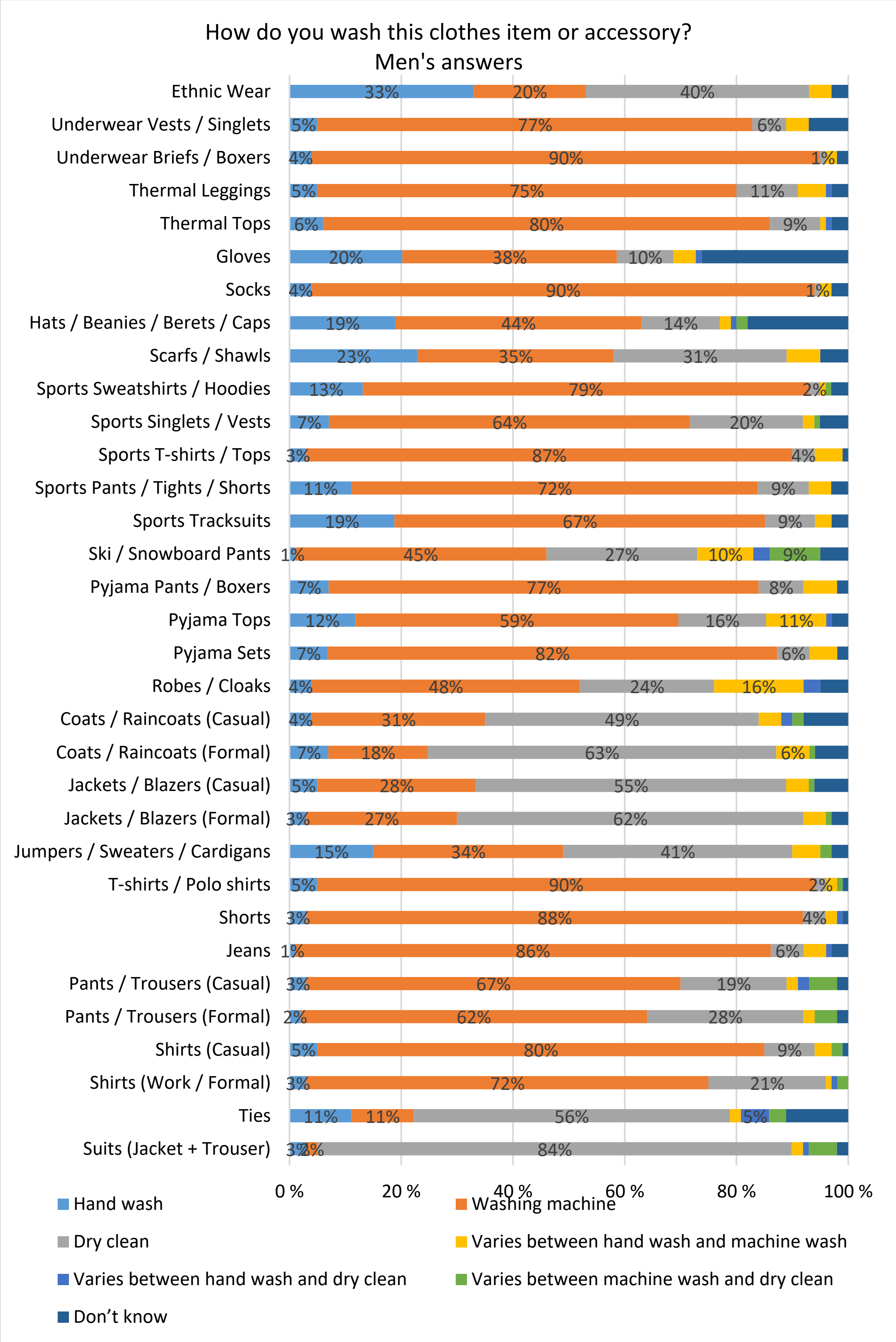

Figure 3 Most common washing methods for various types of clothing items, men's answers (The Nielsen Company, 2012c)

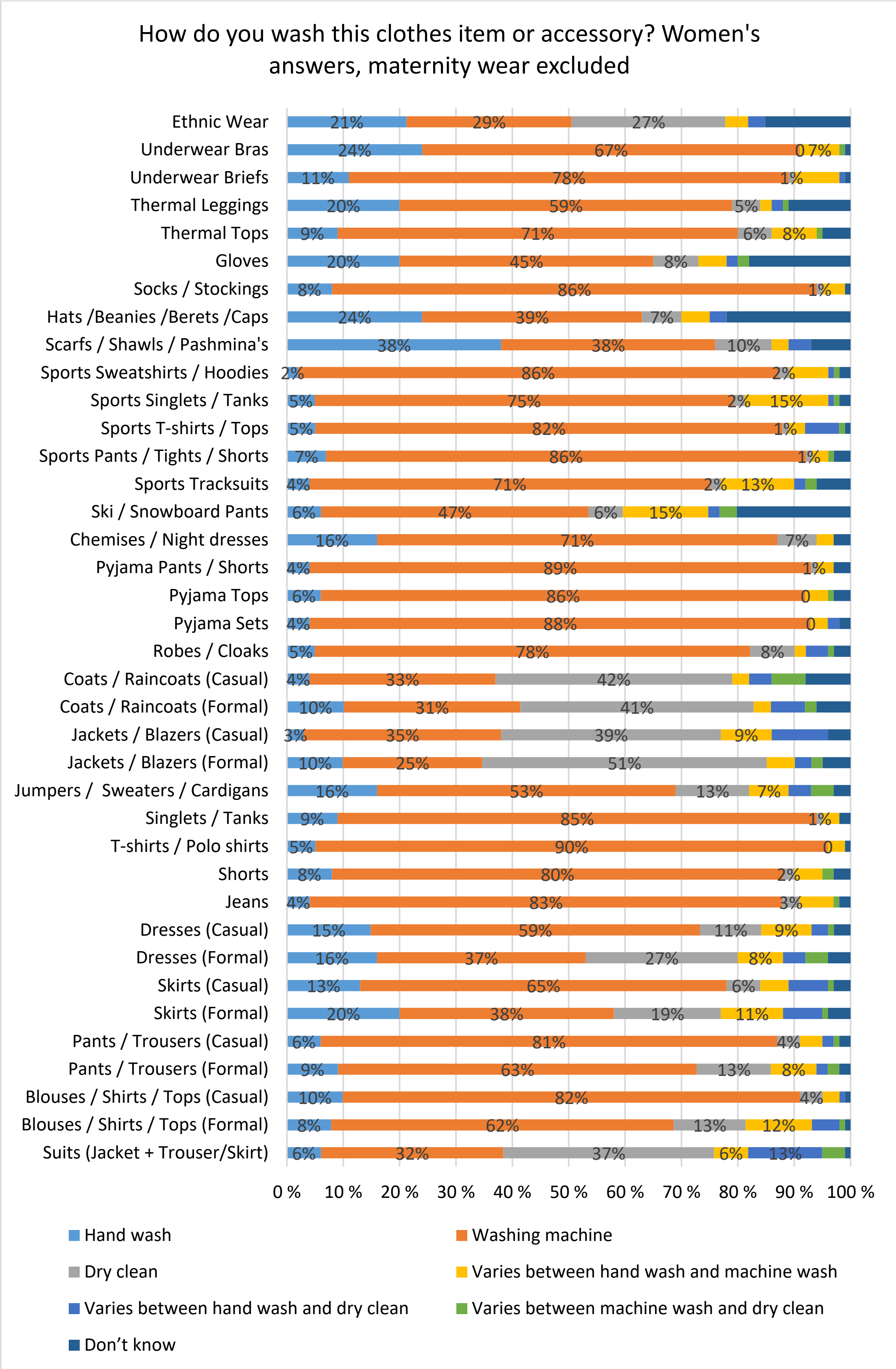

Figure 4 Most common washing methods for various types of clothing items, women’s answers (The Nielsen Company, 2012c)

Hand washing

Hand washing is common in some regions, especially in rural areas of developing countries. For example, in Kenya, washing machine penetration is still low, but is increasing, especially in urban areas (Euromonitor International, 2011). The majority of people handwash clothes. Even in homes which have a washing machine, up to 75% of the clothes are washed by hand. This is mainly due to water scarcity, but also because the consumers believe that washing machines cannot do heavy-duty work such as cleaning the collars and cuffs of shirts. A common trend is to have clothes washed by hired help once or twice a week (Euromonitor International, 2011). A study in South Africa showed that washing at riverbanks was common especially during summer, while hand washing at home was more common during winter (Gordon et al., 2009).

Handwashing is also common in China. Kao (2010a) surveyed urban households, and even though 97% of these respondents owned a washing machine, 90% answered that they also washed laundry by hand. Only 5% used a washing machine exclusively. Another study estimates that 58% of Chinese residents wash cotton t-shirts by hand and dry them outside, without ironing (Zhang et al. 2015 as cited in Yasin et al., 2016). DuPont's (2013b) study shows that 63% of Chinese respondents hand washed predominantly or as often as they used their machine, mainly because they only had a small amount of laundry to be washed at any time, or because they did not think it was hygienic to wash some items such as underwear or socks in the machine (DuPont, 2013b). This result was confirmed by Kao's study (2010), as over 90% of respondents washed socks and underwear by hand. The distribution between machine and hand wash of t-shirts, shirts and skirts was about equal. Bedclothes and outerwear were most commonly washed in a machine, followed by trousers (Kao, 2010). Main reasons for washing in a machine was that heavy/large loads are difficult to wash by hand (90%), and that sometimes they were too busy or tired (50%). Main reason for washing by hand was superior cleaning performance (70%), followed by less water required (about 53%) and less damage to clothes (about 47%). About every fifth also preferred hand wash due to lower electricity costs (Kao, 2010). They used various pre-treatment methods, including stain removal, pre-soaking, pre-rinsing and pre-washing by hand (DuPont, 2015). The average time used on hand washing was rather short, 12% used less than 15 minutes, 63% used 15-30 min, and 25% used 30-60 minutes (DuPont, 2013b). According to Kao (2010), 90% of informants pre-soaked the laundry with dissolved detergent between 5 and 30 minutes. All of the respondents used scrubbing technique with both hands to wash the laundry, but in addition, every fifth used a washboard, and about 12% brushing.

In Mexico, about 55% of households that own a washing machine use mixed methods, where some clothes are soaked, pre-treated or scrubbed before washing in a machine, and inspected after wash to see if additional measures are needed, thus ending up in a modified personalised cleaning process (Hecht and Plata, 2016). A study in Brazil showed that 51% of respondents only used a washing machine, while 11% hand washed only and 38% used a combination of both (DuPont, 2013a).

Not many studies of Western countries document hand washing in detail, but a Finnish consumer study showed that the amount of time used varies considerably. Women washed textiles by hand a couple of times a month, and men once every two months (Aalto, 2003). A survey of young Swedes showed than only 55.9% of them sometimes washed by hand, and it was more common among women than men (Gwozdz et al., 2013). An undated source in Ecolabelling Denmark's (2011) document indicates that hand washing frequency in the UK and Germany is 0.3 washes per week, France 0.2 washes, Spain 0.8 washes, and significantly higher in Italy, 1.6 washes. These constitute, on average, 7% of the laundering times.

Dry-cleaning

Dry-cleaning is a process of cleaning garments with the help of chemical solvents, predominantly volatile organic solvents with perchloroethylene (PERC, C_2Cl_4), which is the most common solvent used in recent years (Troynikov et al., 2016). The dry-cleaning process is typically a three-step process involving washing, extracting and drying.

Troynikov et al. (2016) undertook a systematic review to provide a comprehensive overview of the existing research on cleaning effectiveness and safety of professional apparel cleaning methods and care, focusing on traditional professional dry-cleaning methods, dry-cleaning methods that use solvents other than PERC, and new professional wet-cleaning processes. Effects on the ecosystem and human health of the various solvents used in dry-cleaning were discussed based on state-of-the-art solvent residue trace analysis techniques. As an alternative to dry-cleaning, professional wet-cleaning is the process of removing soiling and stains from garments and other textile products using fresh water and other agents. It is described by The American Association of Textile Chemists and Colorists as "a process for cleaning sensitive textiles (e.g. wool, silk, rayon, linen) in water by professionals using special technology, detergents, and additives to minimize adverse effects". Professional wet-cleaning is considered to be an energy-efficient cleaning process when compared with dry-cleaning processes (Troynikov et al. 2016).

Water is not used in the dry-cleaning process itself, but dry-cleaning facilities can have high water consumption if they use water in cooling processes, washing of the machinery or other related operations. However, in most cases the professional wet-cleaning process has been reported to consume more water than the dry-cleaning process (Keoleian et al., 1997, Sinsheimer et al., 2007).

Over recent decades, an estimated 53% of the world demand for PERC was for dry-cleaning (IARC, 1995) with 513,000 tonnes of PERC estimated to have been used in western Europe, Japan and the USA in 1990. The USA has over 34,000 dry-cleaners with 82% of them estimated to use PERC (EPA, 2006). However, environmental and health hazards associated with PERC have led to the emergence of various alternative solvents and processes that can reduce the impact of dry-cleaning on the environment and human health (Troynikov et al., 2016). There is little doubt that policies to phase out use of PERC in dry-cleaning will be introduced in the near future, at least in developed countries. Effective and viable commercial cleaning alternatives are needed, however gaps exist in understanding the possible health and environmental effects of alternative dry-cleaning solvents.

Wet-cleaning systems appear to be a potential alternative for professional cleaning with lower risks for the environment and health, however more research is needed to fully evaluate the lifetime impacts and cleaning effectiveness for various textiles and garments. This is particularly important for natural fibres such as wool and silk, in order to understand how effectively wet-cleaning can replace traditional dry-cleaning without compromising their unique properties.

Laursen et al. (2007) compared the environmental impacts of dry-cleaning and industrial laundry for cleaning work jackets for Danish consumers. They concluded that changing to dry-cleaning has an overall negative influence on the overall environmental profile of the garments, based on the textile dry-cleaning processes at the time of the assessment. However, it was also indicated that optimizing the dry-cleaning process could reduce some of the environmental indicators. To date, sufficient data for LCA of environmental impacts of the newer professional cleaning methods are not available.

Table 4 Advantages and disadvantages of the wet-cleaning process over traditional dry-cleaning (Keoleian et al., 1997) as cited in Table 3 in Troynikov et al., 2016)

Comparison factors to dry-cleaning	Advantages of wet-cleaning	Disadvantages of wet-cleaning
Effects on clothes	No chemical smells	Shrinkage issue with some garments
	Good for whites	Rare issue of color bleeding
	Water-based stains easier to remove	Grease stains are challenging
Environmental and health effects	Greatly reduced potential for hazardous waste, air pollution, and water & soil contamination	High water consumption
	Chemicals are not persistent or toxic to the aquatic environment	
	Reduced electricity and gas consumption	
	No identified health hazards	
Cost	Significant cost savings in avoided hazardous waste disposal and liability expenses	Increased labour expenses due to pressing and finishing processes
	Economical to establish and operate	
Types of clothes that can be cleaned	Cotton, wool, silk, leather, suede, wedding gowns, highly-decorated beads and sequins	Concerns with some acetate linings, antique satin, gabardine, and highly-structured garments
Other	Easier to establish a new business - fewer environmental/legislative restrictions	

Statistics from the US estimate that on average, each dry-cleaning business has about 800 customers (Gaille, 2016). The average household brings 1-3 garments to their local dry-cleaner, spending only $3 per month on dry-cleaning (Statistics Brain, 2017). The average dry-cleaning cost ranges from $1-$5 depending on what services are provided. Two out of three dry-cleaning customers are women and 65% of them are married (the International Fabricare Institute as cited in Gaille). This indicates that about 100,000 garments are processed every year by one dry-cleaning facility.

A survey among young Swedes showed that only 9.2% sometimes used dry-cleaning, and it was more common among men than women (Gwozdz et al., 2013).

Interviews from seven countries indicated that consumers deem dry-cleaning to be an expensive and inconvenient clothes cleaning option (The Nielsen Company, 2012b). There were differences between the seven countries, with respondents from China and Italy being least likely to use dry-cleaning. Consumers in Japan and Australia report that they may only dry-clean a garment at the end of the cold season, while those in the USA report they will wear a "dry-clean only" garment several times before having it dry-cleaned. In the UK, the consumers did not see the same need to dry-clean woollen garments and thought they could be washed instead. Interviews revealed that the informants mostly only used this method for formal social wear, coats, business attire and specifically tailored suits, pants, skirts and jackets, and some knitwear (The Nielsen Company, 2012b). Similarly, a further survey of the same seven countries revealed that the most common products to dry-clean are suits, overcoats, coats, jackets and blazers (The Nielsen Company, 2012c). This applies both to formal work wear and casual everyday wear, but dry-cleaning formal wear is more common, especially men's formal clothing that often contains wool (Figure 3). To date, sufficient data for LCA of the environmental impacts of the newer professional cleaning methods are not available.

Wool cleaning methods

Interviews with 40 participants from seven countries showed great cultural differences in how wool is perceived and taken care of (The Nielsen Company, 2012a). In the US, many believe that woollen garments have to be dry-cleaned (except for socks), and often regretted if they had hand washed the items instead. They would choose to wear the woollen garments less in order to avoid the hassle and costs of dry-cleaning. They also often believed that the garments needed to be cleaned after one wear. Woollen socks were an exception to the dry-cleaning rule, as they were hand washed with wool detergent. Table 5 shows the main rules of thumb on how the respondents from the seven countries chose the cleaning methods for their garments. However, they would prefer hand washing or machine washing of woollen garments instead of dry-cleaning, which was considered to be a hassle. Table 6 gives some more detailed data on how informants from various countries thought wool should be cleaned.

Table 5 «Rules of thumb» for selection of cleaning methods (Slide 60 of The Nielsen Company, 2012b)

Method	Fabric	Garment category
Machine wash	Cotton, synthetics	Casual social wear, home wear, underwear
Hand wash	Wool, silk	Underwear (some), knitwear (some), smart casual (some)
Dry-clean	Cashmere, wool	Coats, down jackets, suits, work attire (jackets, pants, skirts), knitwear (some)

Table 6 How informants from seven countries take care of wool (Slides 64-66 shortened from the Nielsen Company, 2012b)

Country	Trends in the regular machine wash	Trends in machine wash wool mentioned	Trends in hand wash wool mentioned	Detergents for wool mentioned	Trends in drying wool mentioned
Japan	Machine wash Dried outdoors	'Dry-clean' or 'delicate' wash settings	Lukewarm water in a basin. Wash lightly by hand. Use the washing machine spin cycle for 1-3 minutes after wash	Special detergents for delicate fabrics.	Clothes are dried outdoors - yard or on the balcony. Use special drying nets to keep garment shape
Korea	Machine wash 2-3 times per week, more often in summer. Standard clothes wash cycle. Underwear: boiled in a pot and spin dry in the washing machine. Liquid detergent and softener for all laundry, otherwise bleach powder detergent and synthetic detergent.		Preferred method	Wool detergent called "wool shampoo" is positioned as a substitute for a soap when hand washing and widely used for washing synthetic clothes such as dress shirts and knitwear.	Not reported
Italy	Warm water settings - 40°	Some use	Some use. Colder temperature	Use both heavy duty detergents and specialized ones	Not reported
UK	Separate washing: Casual clothes, mixed colours: 40°. Shirts, tops, socks, underwear: 60°. Delicate items and knitwear: "delicate' setting. Air dried	'Delicate' wash cycle	Use spin cycle on washing machine to wring out prior to air drying	Regular washing powder but smaller amount. Fabric conditioner used by two. One uses soap	All air dry, one by drip dry on an airer over the bath. Dry on indoor and/or outdoor airers depending on weather
Australia	Machine wash bulk of clothes ('daily' /'normal' / 'warm long' wash). Use 1 scoop powder detergent, fabric softener for towels, Napisan for whites. Line dry in warmer climates,	Gentle or delicate setting. One reported using a wash bag	Colder temps in laundry basin	Regular washing powders. One uses a gentle liquid detergent. One uses Wool Wash	Line dried or dried flat

Country	Trends in the regular machine wash	Trends in machine wash wool mentioned	Trends in hand wash wool mentioned	Detergents for wool mentioned	Trends in drying wool mentioned
	tumble dry in cooler climates				
China	Bulk of clothes machine washed. Array of products: liquid detergent, washing powder, soap, stain remover, softener, disinfectant (underwear and sports wear). Prefer to dry in sunshine for quick dry and anti-bacterial. Tumble dry in bad weather	Not used	Preferred method. Will typically soak in water and mild detergent, then wrap in a dry towel and squeeze out water. Use the washing machine spin cycle for 10-15 minutes	Detergent for silk and wool	Dry flat in a air basket hung on the balcony out of direct sunlight Iron when semi-dried
USA	Machine wash. Array of products: liquid detergents, bleach, fabric softeners and stain removers.	Typically dry-clean all woollen garments		Woolite used for washing woollen socks	Socks air dried

The Nielsen survey results (Table 7) show that woollen garments are more likely to be dry-cleaned than cotton or synthetics, especially almost half of men's woollen clothing is dry-cleaned (suits, jackets and other formal wear). Women are more likely to wash clothing by hand than men are, and dry-clean only one quarter of their woollen garments.

Table 7 Main washing methods for clothing made of different materials based on survey in seven countries (The Nielsen company, 2012c)

Washing method	Hand wash		Machine wash		Dry-clean	
Fibre content	**Men**	**Women**	**Men**	**Women**	**Men**	**Women**
Cotton and cotton blends	6%	10%	82%	79%	9%	4%
Wool and wool blends	7%	15%	33%	37%	47%	25%
Synthetics and man-made materials	8%	11%	70%	73%	12%	6%

In Norway, the results from a consumer survey showed that it was more common to wash woollen products in the washing machine (70%) than by hand (19%) (Laitala and Klepp, 2016). Airing has traditionally been a central method in keeping woollen products clean, combined with stain removal and brushing. A survey in Norway showed that airing is still used, and it is more commonly used for woollen products than for other textiles (Figure 5). Respondents over the age of 40 were slightly more likely to air woollen textiles than younger respondents (Laitala and Klepp, 2016). A Dutch consumer survey showed 26% of households said they aired textiles often, and these households washed on average 90 cycles less per year than the households that never or only sometimes aired (Uitdenbogerd et al., 1998). This confirms that airing is likely to reduce laundering frequency.

Figure 5 Airing of woollen and non-woollen textiles in Norway (N=268) (Laitala and Klepp, 2016)

3.1.2 Washing machine programs/cycles

There are variations in which washing programs are available in different types of washing machines. Most machines have a program for washing delicates, but the washing machines used in Europe (horizontal drum) usually have, in addition, their own program for washing wool. In general, the top loading machines commonly used in the US, Australia and Asia do not have a separate program called ‘woollens’ (see for example overview of top loadin machines on the market by Parkinson, 2017).

Only a few studies have reported on the use frequency of various washing machine programs, and most of these show that the wool program (when available) is seldom used. A survey in ten European countries indicates that about 25% of households never used the wool program or did not have a wool program available, indicating that the rest (75%) use it at least occasionally (Figure 6). About 10% reported using it always or often (Schmitz and Stamminger, 2014).

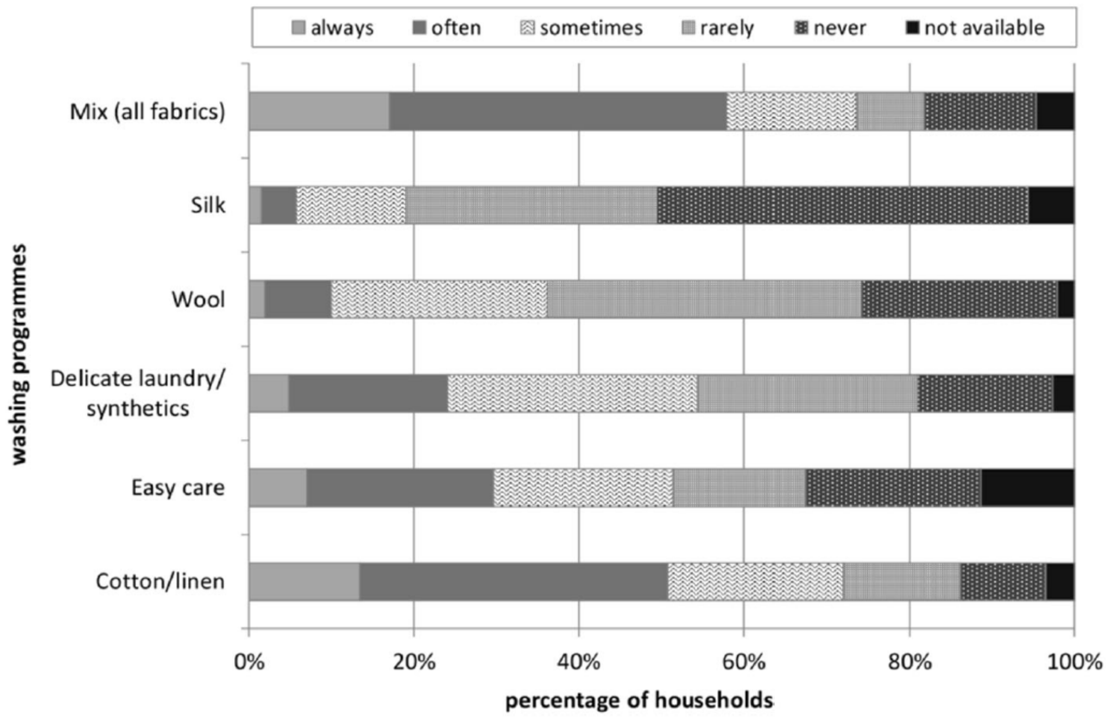

Figure 6 Washing programmes chosen in 2011 in 10 European countries (n=2,290 households) (Figure 10 from Schmitz and Stamminger, 2014)

Laundry diaries in Germany showed that wool wash represented only 1% of the washing cycles (Table 8), indicating that Germans either do not own much wool, wash it using other washing programs or by hand, wash wool very seldom, or dry-clean it. However, the research was conducted between May and November, thus excluding the coldest months when it is more common to use wool (Kruschwitz et al., 2014).

Table 8 Number and percentage of various washing programs used in Germany during a four-weeks period (Kruschwitz et al., 2014)

Washing programme	Number of wash cycles during 4 weeks out of 2867 wash cycles	Percentage of wash cycles
Cotton	1967	68.6%
Synthetics	47	1.6%
Easy care	492	17.2%
Mix	74	2.6%
Wool	31	1.1%
Delicates	151	5.3%

In Norway, the most commonly used washing program was the cotton wash cycle (3.4 washes per week). Use of short programs was the second most popular (1.6 cycles per week) and more common than eco-programs (1.1 per week). Use of wool wash was the fifth most common program with 0.6 cycles per week, right after the synthetics program that was used about 0.7 times in a week. About 7% of washing cycles were washed with the wool/silk program. Wool program use frequency may have been more difficult to estimate, as there is variation between the seasons when it comes to the use of wool (Laitala, Klepp & Boks, 2012; Laitala & Klepp 2016).

For China, studies report different results for the most commonly used washing machine programs. The DuPont (2013b) study states that the most commonly used washing programs are economy wash (49% of machine washing), and the short cycle (19% of machine washing cycles), while Yuan et al. (2016) report that the cotton wash cycle is the most commonly used program. However, both studies indicate that hand washing is more common than washing by machine.

DuPont's (2015) survey in eight countries indicates that consumers sorted laundry mainly in whites (90%), colours (77%), darks (54%), and delicates (49%) (average of eight countries). Country specific results showed that Chinese were most likely to separate underwear in the laundry (81%).

Based on detailed interviews of 104 households in the Netherlands, Uitenbogerd et al., (1998) could estimate the distribution of the washing programmes used (Table 9).

Table 9 Distribution of the use of washing machine programmes over the total number of cycles and percentage of households that use the programme (Table 4-2 from Uitdenbogerd et al., 1998)

Programme	% of cycles	% of households
White/main	33	84
Coloured	39	70
Synthetics	0.5	5
Fine	10	38
Wool	6	39
Hand	9	45
Short	0.03	7
Other	2	2

However, none of the studies report on whether other washing machine programs are used for washing wool, and it is possible that in the German study, for example, some of the delicate wash cycles have been used for wool garments. The same can apply to counties that use mainly top loading machines without specific wool wash program. In general, there is a lack of data regarding use of various washing programs in these countries.

3.1.3 Washing frequency in households

Several studies report the average laundering frequency in different countries. Results from these studies are given in Table 10.

Table 10 Number of washing cycles per household in different regions

Region	Number of washes per week	Number of wash cycles per year	Year, comments and source
European average (23 countries)	3.1	161.2	2014 (A.I.S.E., 2014)
Europe (11 countries)	4.4	228.8	2015 survey (Schmitz et al., 2016)
Europe (10 countries)	4.9	254.8	Survey (Presutto et al. 2007)
Europe	5	260	2014 (Statista, 2015d)
Britain and Ireland (UK, IRL)	3.75	195	2014 (A.I.S.E., 2014)
Scandinavia (DK, FIN, NO, SWE)	2.75	143	2014 (A.I.S.E., 2014)
Central and Eastern Europe (HU, POL, RO, SLK, CZ, BU)	3.05	158.6	2014 (A.I.S.E., 2014)

Region	Number of washes per week	Number of wash cycles per year	Year, comments and source
East Europe	3.3	173	Figure 3 (Pakula and Stamminger, 2010)
Western Europe (BE, NL, FR, DE, AU, CH)	2.9	150.8	2014 (A.I.S.E., 2014)
West Europe	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Southern Europe (GR, IT, POR, ES, TR)	3.15	163.8	2014 (A.I.S.E., 2014)
North America	7	364	2014 (Statista, 2015d)
North America	5.56	289	Figure 3 (Pakula and Stamminger, 2010)
Austria	3.15	164	Figure 3 (Pakula and Stamminger, 2010)
Austria	3.05	158.6	2014 survey 203 respondents (Vandecasteele et al., 2014)
Australia	5	260	Figure 3 (Pakula and Stamminger, 2010)
Belgium	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Belgium	2.7	140.4	2014 survey 210 respondents (Vandecasteele et al., 2014)
Brazil	5.6 (3.5 machine, 2.1 by hand)	291.2	2013 survey 800 respondents DuPont, 2013a
Bulgaria	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Bulgaria	3.4	176.8	2014 survey 211 respondents (Vandecasteele et al., 2014)
Canada	5.6	289	Figure 3 (Pakula and Stamminger, 2010)
Canada	7	364	Surveys (Natural Resources Canada, 2015)
China	1.9 (machine wash only)	100	Figure 3 (Pakula and Stamminger, 2010)
China	2.6 (machine wash only)	133	Survey 1330 respondents (Yuan et al., 2016)
China	7.5 (incl. hand-wash)	390	5 days per week, 1.5 small loads per day (mainly hand wash) (DuPont, 2013b)
Croatia	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Cyprus	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Czech Republic	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Czech Republic	3.2	166.4	2006 (Presutto et al., 2007)
Czech Republic	3.5	182	2011 (Schmitz and Stamminger, 2014)
Czech Republic	2.6	135.2	2014 survey 208 respondents (Vandecasteele et al., 2014)
Denmark	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Denmark	2.5	130	2014 survey 204 respondents (Vandecasteele et al., 2014)
Estonia	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Finland	2.24 (living alone), 5.3 (with children)	116.5 276	Diary study, results separated for those living alone and those living with children (Aalto 2002)
Finland	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Finland	3.9	202.8	2006 (Presutto et al., 2007)
Finland	3.9	202.8	2011 (Schmitz and Stamminger, 2014)
Finland	2.25	117	2014 survey 204 respondents (Vandecasteele et al., 2014)
France	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
France	4.2	218.4	2006 (Presutto et al., 2007)
France	3.5	182	2011 (Schmitz and Stamminger, 2014)
France	4.7	242	Zimmermann et al 2012 (remodece campaign)
France	2.8	145.6	2014 survey 202 respondents (Vandecasteele et al., 2014)
Germany	2.6	135.2	Metering study (Berkholz et al., 2007)
Germany	3.15	164	Figure 3 (Pakula and Stamminger, 2010)
Germany	4.8	249.6	2005 websurvey with 1494 answers (Stamminger and Goerdeler, 2007)
Germany	4.5	234	2004 (Stamminger and Goerdeler, 2005)
Germany	3.8	197.6	2006 (Presutto et al., 2007)
Germany	3.7	192.4	2011 (Schmitz and Stamminger, 2014)
Germany	3.05	158.6	2014 survey 201 respondents (Vandecasteele et al., 2014)
Greece	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Greece	2.85	148.2	2014 survey 212 respondents (Vandecasteele et al., 2014)
Hungary	3.17	165	Figure 3 (Pakula and Stamminger, 2010)

Region	Number of washes per week	Number of wash cycles per year	Year, comments and source
Hungary	4.1	213.2	2006 (Presutto et al., 2007)
Hungary	3.6	187.2	2011 (Schmitz and Stamminger, 2014)
Hungary	3.2	166.4	2014 survey 205 respondents (Vandecasteele et al., 2014)
Iceland	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
India	9.9	514.8	Interviews & observations in 35 households (Honold, 2000)
Ireland	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Ireland	3.65	189.8	2014 survey 205 respondents (Vandecasteele et al., 2014)
Italy	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Italy	5.0	260	2006 (Presutto et al., 2007)
Italy	4.1	213.2	2011 (Schmitz and Stamminger, 2014)
Italy	4.0	208	2014 survey 202 respondents (Vandecasteele et al., 2014)
Japan	10	520	Figure 3 (Pakula and Stamminger, 2010)
Japan	9.2	478.4	(Ishii, 2011)
Japan	7.3	379.6	(Yamaguchi 2011)
Japan	10	520	2014 (Statista, 2015d)
Latvia	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Lithuania	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Luxembourg	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Malta	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Netherlands	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Netherlands	3.0	156	2014 survey 207 respondents (Vandecasteele et al., 2014)
Netherlands	7.2 (large house-holds)	375	1997 survey among families with children (variation from 56 to 1100 cycles, s.d.±189 (Uitdebogerd et al., 1998)
Norway	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Norway	3.45	179.4	2014 survey 211 respondents (Vandecasteele et al., 2014)
Poland	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Poland	3.3	171.6	2006 (Presutto et al., 2007)
Poland	4.1	213.2	2011 (Schmitz and Stamminger, 2014)
Poland	3.25	169	2014 survey 201 respondents (Vandecasteele et al., 2014)
Portugal	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Portugal	2.9	150.8	2014 survey 209 respondents (Vandecasteele et al., 2014)
Romania	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Romania	2.7	140.4	2014 survey 207 respondents (Vandecasteele et al., 2014)
Slovakia	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Slovakia	3.15	163.8	2014 survey 223 respondents (Vandecasteele et al., 2014)
Slovenia	3.4	177	Figure 3 (Pakula and Stamminger, 2010)
Spain	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Spain	4.2	218.4	2006 (Presutto et al., 2007)
Spain	3.8	197.6	2011 (Schmitz and Stamminger, 2014)
Spain	3.15	163.8	2014 survey 202 respondents (Vandecasteele et al., 2014)
South Africa	1.75	91	2008 Handwash (Gordon et al., 2009)
South Korea	4	208	Figure 3 (Pakula and Stamminger, 2010)
Sweden	2.7	140.4	2014 survey 202 respondents (Vandecasteele et al., 2014)
Sweden	2.7	140	Figure 3 (Pakula and Stamminger, 2010)
Sweden	4.1	213.2	2006 (Presutto et al., 2007)
Sweden	3.5	182	2011 (Schmitz and Stamminger, 2014)
Sweden	3.9	204.3	Measured 2005-2008. 250/year in one family houses and 150/year for apartments (Zimmermann 2009)
Switzerland	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
Switzerland	2.9	150.8	2014 survey 207 respondents (Vandecasteele et al., 2014)
Turkey	4	211	Figure 3 (Pakula and Stamminger, 2010)
Turkey	3.0	156	2014 survey 202 respondents (Vandecasteele et al., 2014)
UK	3.2	165	Figure 3 (Pakula and Stamminger, 2010)
UK	4.6	239.2	2006 (Presutto et al., 2007)
UK	4.1	213.2	2011 (Schmitz and Stamminger, 2014)
UK	5.5	284	2011 monitoring + diaries (Zimmermann et al., 2012)
UK	3.85	200.2	2014 survey 202 respondents (Vandecasteele et al., 2014)
USA	6.06	315	Golden et al. 2010 based on previous studies

Region	Number of washes per week	Number of wash cycles per year	Year, comments and source
USA	5.6	289	Figure 3 (Pakula and Stamminger, 2010)
USA	8.5	442	Metering study with 1.21/day (Tomlinson & Rizy, 1998)

A study conducted in 2011 estimates that the average washing frequency in Europe is 3.8 washing cycles per week (based on 10 countries) (Schmitz and Stamminger, 2014). This is higher than the survey results from A.I.S.E. studies, which have shown a reduction in the average cycles per week from 3.4 washes in 2008, 3.2 washes in 2011 and the latest result of 3.1 cycles per week in 2014 (A.I.S.E., 2014). Another study estimates that the average household washes 3.2 wash cycles in the region Germany, Austria and Switzerland, with a distribution of 2.1 wash cycles per week for a single household up to 4.1 wash cycles per week for a four-person household (Rüdenauer and Grießhammer, 2004) (They cite GFK 2001). This figure has been cited many times by other authors, and used further by Pakula & Stamminger (2010). Several other studies also show that the number of washing cycles is very dependent on the size of the household. While the number of washing cycles increases with the number of persons in the household, the average number of washing cycles per person decreases, indicating more efficient filling of the washing machine (Kruschwitz et al., 2014).

It is clear that there are regional variations in laundering frequencies based on climate. In hot and humid countries such as India, laundry does not usually accumulate, but rather washed as soon as it is dirty (Honold, 2000). This causes more frequent laundering with smaller laundry loads. Another aspect affecting laundering frequency is the number of clothing items that are owned. If a person owns only a couple of each type of garment, more frequent washing is necessary.

3.1.4 Number of days in use between washes

The number of days garments are used between washes vary greatly between different types of garments. Some are generally washed after each use, while others are almost never washed.

A consumer survey in the UK showed that only 3% of Brits will never wear anything more than once before laundering it (Gracey & Moon, 2012). That means that the remaining 97% wear at least some clothes more than once before washing. 67% wash a t-shirt/polo shirt after only wearing it once, and 76% will wear a shirt only once before washing it (Figure 7). The most important parameter causing them to use clothes longer between washes, was if clothes smelled fresh for longer (47%) (Gracey & Moon, 2012). Wool has beneficial odour-resistance characteristics (McQueen et al., 2007).

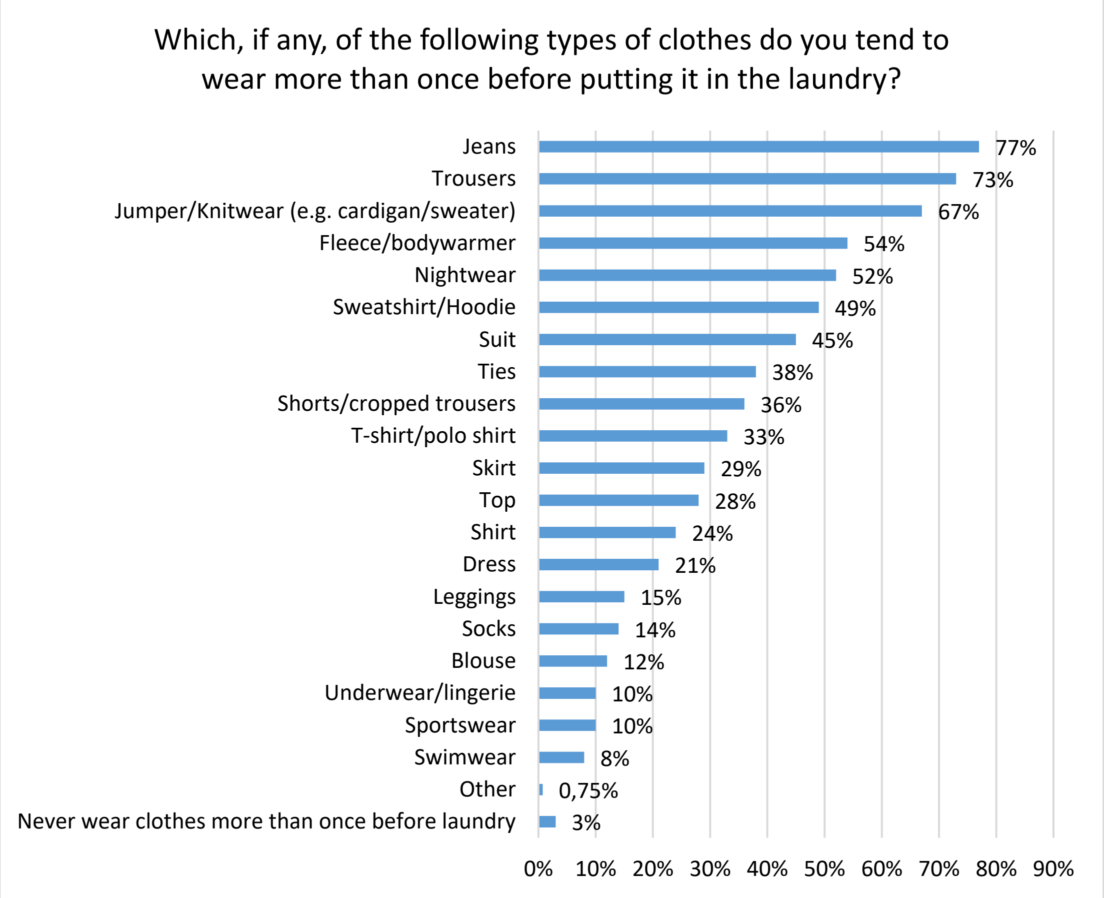

Figure 7 Frequency of clothes wear prior to washing. Which, if any, of the following types of clothes do you tend to wear more than once before laundering? (Figure 26 from Gracey & Moon, 2012)

Two surveys in Norway have asked consumers how many days they wore specified items before they were laundered (Laitala and Klepp, 2016). The results (Table 11) show that most of the respondents wash cotton t-shirts, underpants and synthetic sportswear frequently after one to three days of use. Washing of outerwear, woollen products and jeans is much more varied. Due to the large variations in results, in addition to reporting the mean (average) value, also median (middle value of the data set) and mode (most often-occurring value) results are included in the table. The results indicate that woollen undershirts are on average used about one to two days longer than cotton t-shirts. Woollen sweaters are often used at least 6-10 days and cotton sweaters 2-5 days before washing. This means, as expected, that consumers use woollen products almost twice as long between washes than similar products in cotton. There was also a difference between genders. Men were likely to wear sweaters (both cotton and wool) 2-3 days longer between washes than women. The qualitative data in the study showed that there was a difference in washing habits between consumers that did not own many wool products compared to those who did, both related to how easy they thought taking care of wool is, and the washing frequency.

Table 11 Average numbers of days in use before wash (Laitala and Klepp, 2016) and additional analyses of survey B data, previously unpublished)

Product	Cotton t-shirt		Woollen undershirt		Cotton sweater	Woollen sweater		Underpants (cotton)	Synthetic sportswear	Jeans
Survey source	A	B	A	B	A	A	B	B	B	B
Mean	2.8	2.1	3.9	3.4	4.7	8.9	>7.1	1,2	2.3	>5.7
Median	2	2	3	3	3	5	7	1	2	5
Mode	1	1	1	3	2	10	>10	1	1	>10

An earlier survey conducted in four European countries showed some national differences in laundering frequencies, and that thin woollen sweaters are used longer between washes than synthetic blouses or cotton t-shirts (Arild et al., 2003). Unfortunately, these products are not directly comparable in due to their different use areas (sweaters are more likely to be worn over undershirt than t-shirts or blouses).

Table 12 Average number of days different garments are used before laundering (reanalysed data from European laundry habits survey by Arild et al., 2003)

Garment type	Netherlands	Greece	Norway	Spain
Jeans	3.3	3.0	4.7	3.6
Thin wool sweater	3.2	2.8	4.3	2.7
Synthetic blouse	1.6	2.0	1.9	1.6
Cotton t-shirt	1.4	2.0	1.8	1.5
Bath towels	1.8	2.6	2.7	3.4
Thin socks	1.3	1.4	1.5	1.1
Underpants	1.1	1.2	1.3	1.1

A Dutch consumer survey of 375 respondents indicated that the average number of days between washing was 2.0 days for wearing blouses/shirts, 1.7 days for t-shirts, 4.2 days for jeans, 1.5 days for sports clothing, 10.3 days for woollen jumpers, and 6.9 days for cotton jumpers (Uitdenbogerd et al., 1998, p. 58). Four other studies have reported on washing frequency of jeans, and show the average number of days in use between washes to be 9.5 in Canada (McQueen et al., 2017), 5.4 in Australia (Jack, 2013a), above 8.9 in Sweden (Granello et al., 2015) and 8.24 on average in USA, Germany, Sweden and Poland (Gwozdz et al., 2017). The most recent surveys indicate the longest number of wearings before wash, indicating that the difference may not only be based on geographic variations, but also to changes in general laundering frequency of jeans where several producers have launched campaigns that promote less frequent washing (Nudie Jeans, 2015, O'Connor, 2016). Granello et al. (2015) also report washing frequency of t-shirts to be 2.5 days and dresses 5.1 days. Gwozdz et al., (2017) report washing frequency of t-shirts to be 2.26 days. Slocinski & Fisher (2016) report from a survey in the USA where woollen socks were reported to be used 2.3 days before washing, and woollen next-to-skin garments 3.2 days before washing. However, in their survey the longest interval alternative given between washes was five wears, thus excluding any answers from users that may use these products longer between washes.

A Japanese study states that Japanese consumers are inclined to wash their clothes after one wear, but does not specify which types of clothing are included in this estimation (JSAD 2006).

In general, interviews across seven countries indicated that woollen garments were used a bit longer than other garments between washes. The main reasons given were that they either required dry-cleaning, or did not get as dirty as other garments because formal and winter clothing were less subject to soiling and sweat (The Nielsen Company, 2012a).

The Global Nielsen survey (2012c) included the question “How often do you wash or dry-clean this clothes item or accessory? For seasonal items, please report frequency when item is in use”. This question was asked of respondents concerning for each of the clothing item they owned. These results are given in Figure 8 based on fibre content, and separately for different garment types for men in Figure 9 and for women in Figure 10.

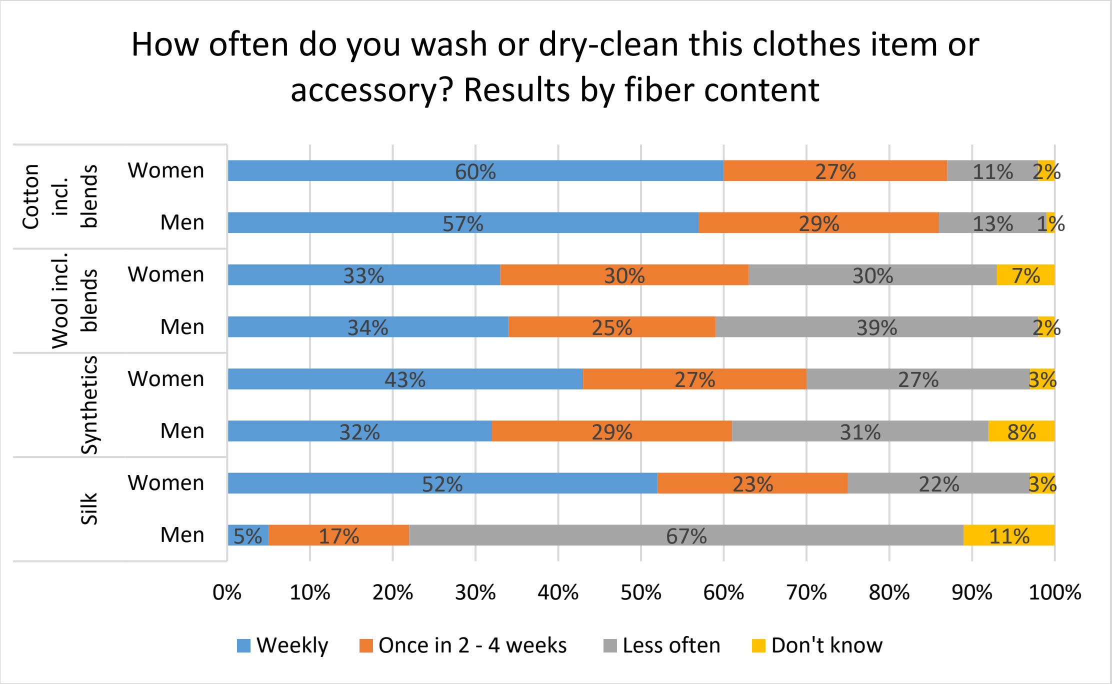

Figure 8 How often do you wash or dry-clean this clothes item or accessory? For seasonal items, please report frequency when item in use (The Nielsen company, 2012c).)

Comparison of wool and cotton products shows that the respondents were likely to use their woollen products about twice as long between washes than their cotton products. The washing frequency of synthetic is close to that of wool, most likely based on types of synthetic products the respondents owned. Both men and women owned synthetic coats, jackets, ski pants, sportswear, but women also had larger share of synthetic bras, formal trousers, dresses, skirts, scarves and chemises.

The difference in washing frequency of silk products between men and women is very large. It is explained by the different products, as men's silk products are mainly ties and some robes and ethnic wear, women own a larger variety of silk garments such as formal wear (blouses, shirts, tops, dresses, and skirts), nightwear, chemises, scarves and ethnic wear.

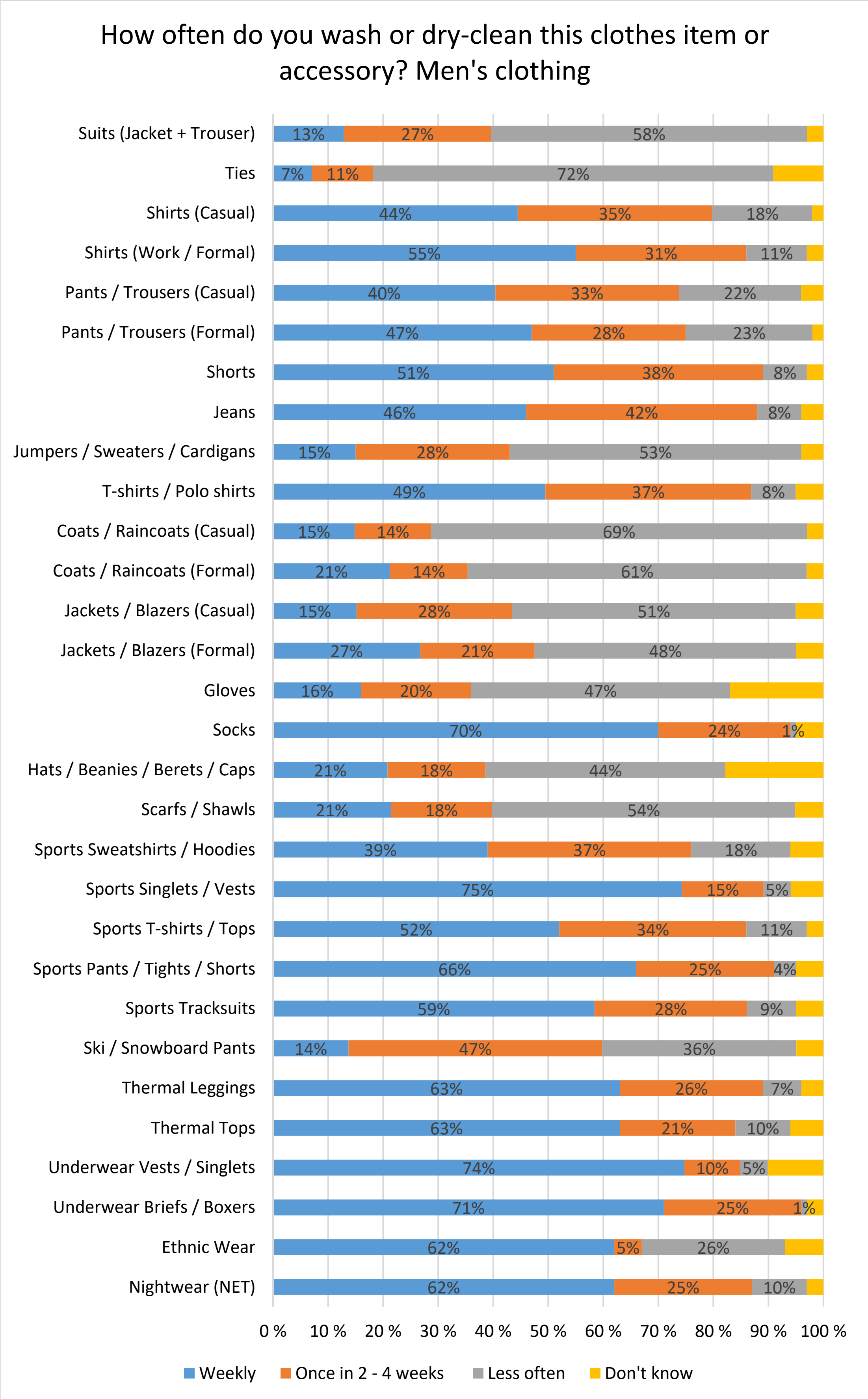

Figure 9 Cleaning frequency of men’s clothing (The Nielsen company, 2012c)

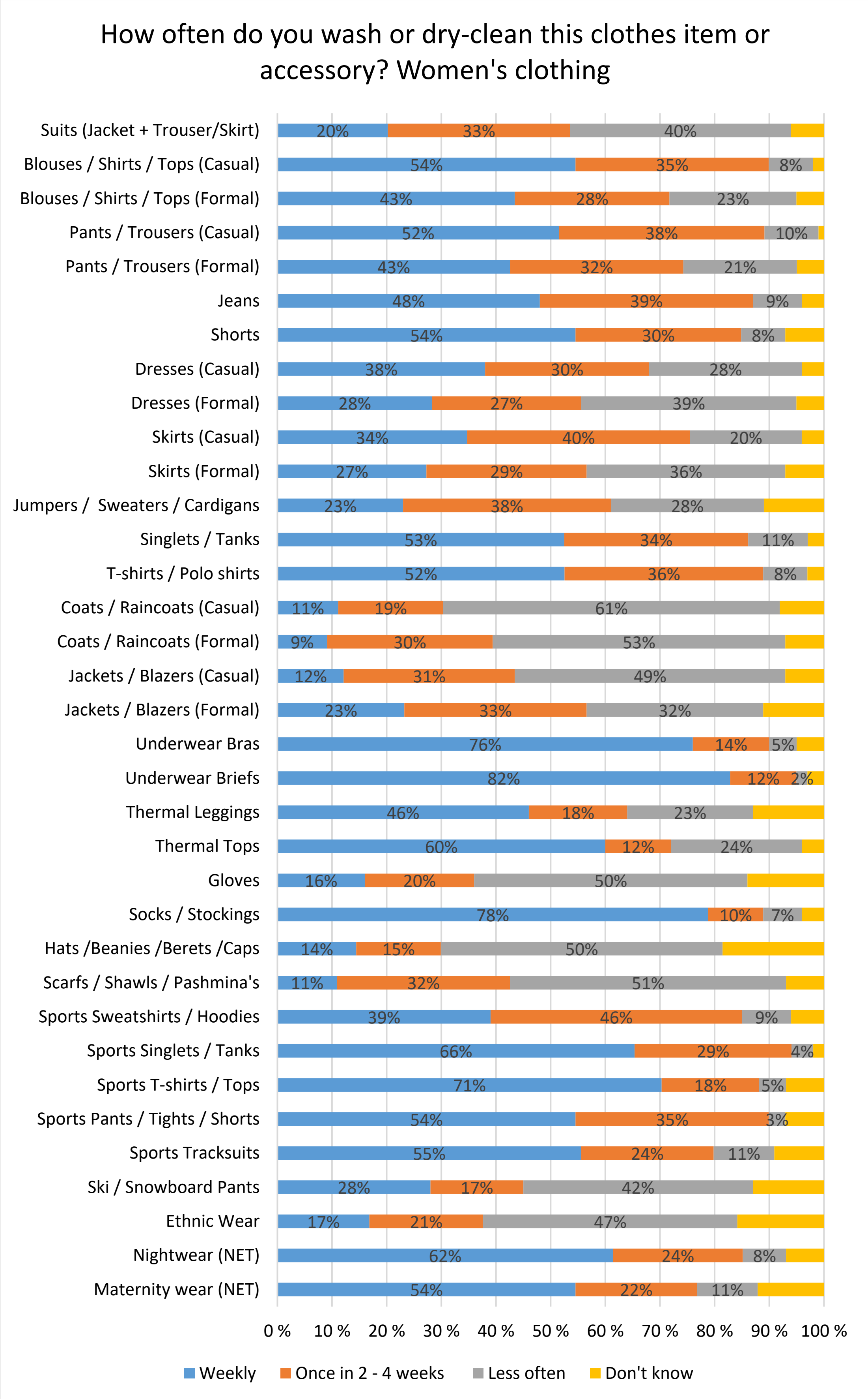

Figure 10 Cleaning frequency of women's clothing (The Nielsen company, 2012c)

Based on these different sources, an average for the number of days in use between washes for some garment types is estimated in Table 13. The studies do not report on whether the wearing occurs on consecutive days or whether the number of wears are spread over a longer period of time, but we assume that the respondents have answered the number of days in use independent of the length of time period between washes.

Table 13 Summary of number of days in use between washes of specific garments based on available studies. Average estimate rounded to closest half day.

	Norway (3 surveys)	Netherlands (1-2 surveys)	Greece	Spain	Other countries	Average estimate
Woollen sweater	8.9 >7.1	10.3				**10**
Cotton sweater	4.7	6.9				**5**
Woollen undershirt or thin sweater	3.4 3.9 4.3	3.2	2.8	2.7	3.2 USA	**3**
Cotton T-shirt	1.8 2.1 2.8	1.4 1.7	2.0	1.5	2.26 USA, Sweden, Germany and Poland	**1.5**
Jeans	4.7 >5.7	3.3 4.2	3.0	3.6	9.5 Canada 5.4 Australia 8.9 Sweden 8.24 USA, Sweden, Germany and Poland	**5.5**
Blouse/shirt	1.9	1.6 2.0	2.0	1.6		**2**
Sports clothing	2.3	1.5				**1.5**
Thin socks	1.5	1.3	1.4	1.1		**1.5**
Wool socks					2.3 USA	**2.5**
Underpants/briefs	1.2 1.3	1.1	1.2	1.1		**1**

Although there are too few data to make regional comparisons, we see that except for jeans, there is little evidence that would suggest regional differences between developed countries for use-days before washing.

3.1.5 Washing temperature

Washing temperature has a great influence on the energy consumption of laundering, but it also affects the cleaning result and is, therefore, important for maintaining clothes and enabling long use. Too high a temperature may damage the clothing, while some soiling may not be removed if the laundering is not efficient. The energy consumption of laundry washing is discussed under section 3.1.11. Average washing temperatures used vary globally. The average European washing temperature was 42.6°C in 2014, but there are several degrees differences between the countries (Table 14).

Table 14 Average washing temperatures for different countries and regions

Country/region	Average washing temperature, all laundry [°C]	Year and source
North America	29	2014 (Statista, 2015a)
European average (23 countries)	42.6 in 2014 41 in 2011	2014 survey 4740 respondents (A.I.S.E., 2014)

Country/region	**Average washing temperature, all laundry [°C]**	**Year and source**
	43 in 2008	
European average (10 countries)	45.8	2006 Presutto et al. 2007
Europe	42	2014 (Statista, 2015a)
Britain and Ireland (UK, IRL)	40.4	2014 survey (A.I.S.E., 2014)
Scandinavia (DK, FIN, NO, SWE)	45.7	2014 survey (A.I.S.E., 2014)
Central and Eastern Europe (HU, POL, RO, SLK, CZ, BU)	43.3	2014 survey (A.I.S.E., 2014)
Western Europe (BE, NL, FR, DE, AU, CH)	42.4	2014 survey (A.I.S.E., 2014)
Southern Europe (GR, IT, POR, ES, TR)	40.7	2014 survey (A.I.S.E., 2014)
Austria	44.0 in 2014 43.0 in 2011 43.9 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Belgium	41.9 in 2014 41.2 in 2011 42.3 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Bulgaria	42.9 in 2014 42.4 in 2011 45.1 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
China	Cold/ambient	(Pakula and Stamminger, 2009)
China	Warm setting on 94% of cycles in washing machine	(DuPont, 2013b)
Czech Republic	49.4	2006 (Presutto et al., 2007)
Czech Republic	46.0	2011 Figure 9 (Schmitz and Stamminger, 2014)
Czech Republic	44.5 in 2014 44.3 in 2011 44.0 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Denmark	44.2 in 2014 43.0 in 2011 43.2 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Finland	46.3 in 2014 45.1 in 2011 44.5 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Finland	46.8	2006 (Presutto et al., 2007)
Finland	46.5	2011 Figure 9 (Schmitz and Stamminger, 2014)
France	42.8	2006 (Presutto et al., 2007)
France	41.8	2011 Figure 9 (Schmitz and Stamminger, 2014)
France	39.8 in 2014 39.7 in 2011 40.8 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Germany	46.8	2006 (Presutto et al., 2007)
Germany	45.0	2011 Figure 9 (Schmitz and Stamminger, 2014)
Germany	43.1 in 2014 42.3 in 2011 43.3 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Greece	42.3 in 2014 41.5 in 2011 41.4 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014)
Greece	41.5	Table 2 (Gooijer and Stamminger, 2016)
Hungary	47.1	2006 (Presutto et al., 2007)
Hungary	46.1	2011 Figure 9 (Schmitz and Stamminger, 2014)
Hungary	42.8 in 2014 41.9 in 2011 42.8 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Ireland	40.2 in 2014 39.7 in 2011 40.1 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)

Country/region	Average washing temperature, all laundry [°C]	Year and source
Italy	45.3	2006 (Presutto et al., 2007)
Italy	42.2	2011 Figure 9 (Schmitz and Stamminger, 2014)
Italy	41.9 in 2014 40.4 in 2011 41.3 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Japan	18 (ambient temperature or used bath water 5-30°C)	(Nakamura, 2010)
Japan	23	2014 (Statista, 2015a)
Netherlands	41.6 in 2014 41.0 in 2011 41.2 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Norway	46.3 in 2014 45.1 in 2011 44.5 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Norway	48.5	2010 survey (Laitala et al., 2012b)
Poland	48.3	2006 (Presutto et al., 2007)
Poland	47.4	2011 Figure 9 (Schmitz and Stamminger, 2014)
Poland	42.8 in 2014 44.1 in 2011 44.6 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Portugal	38.9 in 2014 36.6 in 2011 38.9 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Romania	42.7 in 2014 42.9 in 2011 44.4 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Slovakia	44.2 in 2014 43.5 in 2011 43.9 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
South Korea	Cold/ambient	(Pakula and Stamminger, 2009).
Spain	32.1	2006 (Presutto et al., 2007)
Spain	30.9	2011 Figure 9 (Schmitz and Stamminger, 2014)
Spain	36.6 in 2014 33.9 in 2011 34.2 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Sweden	46.0 in 2014 45.3 in 2011 45.0 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Sweden	48.4	2006 (Presutto et al., 2007)
Sweden	47.3	2011 Figure 9 (Schmitz and Stamminger, 2014)
Switzerland	43.8 in 2014 42.8 in 2011 44.3 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
Turkey	43.9 in 2014 42.5 in 2011 43.9 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
UK	43.7	2006 (Presutto et al., 2007)
UK	40.5	2011 Figure 9 (Schmitz and Stamminger, 2014)
UK	40.7 in 2014 39.1 in 2011 40.1 in 2008	2014 survey A.I.S.E. (Vandecasteele et al., 2014) and 2011 Table 2 (Gooijer & Stamminger, 2016)
USA	31.1	(Golden et al. 2010)

In Europe, the lowest average washing temperatures (under 40°) are found in Spain and Portugal and the highest in Sweden, Norway and Finland (above 46°) (Vandecasteele et al., 2014).

For most of the washing machines in the USA, the user can select the wash and rinse temperatures. In general, the alternatives for wash are hot, warm or cold, and for rinsing either warm or cold temperatures. Measurements of incoming water temperature in Bern, USA, showed that the average hot water inlet temperature was 55.8°C, but it varied between 43.3°C to 75.6°C (Tomlinson & Rizy, 1998). This indicates that the hot water temperature entering in to the machines is not as high as the machines can heat the water in the European counter-parts (up to 90-95°C).

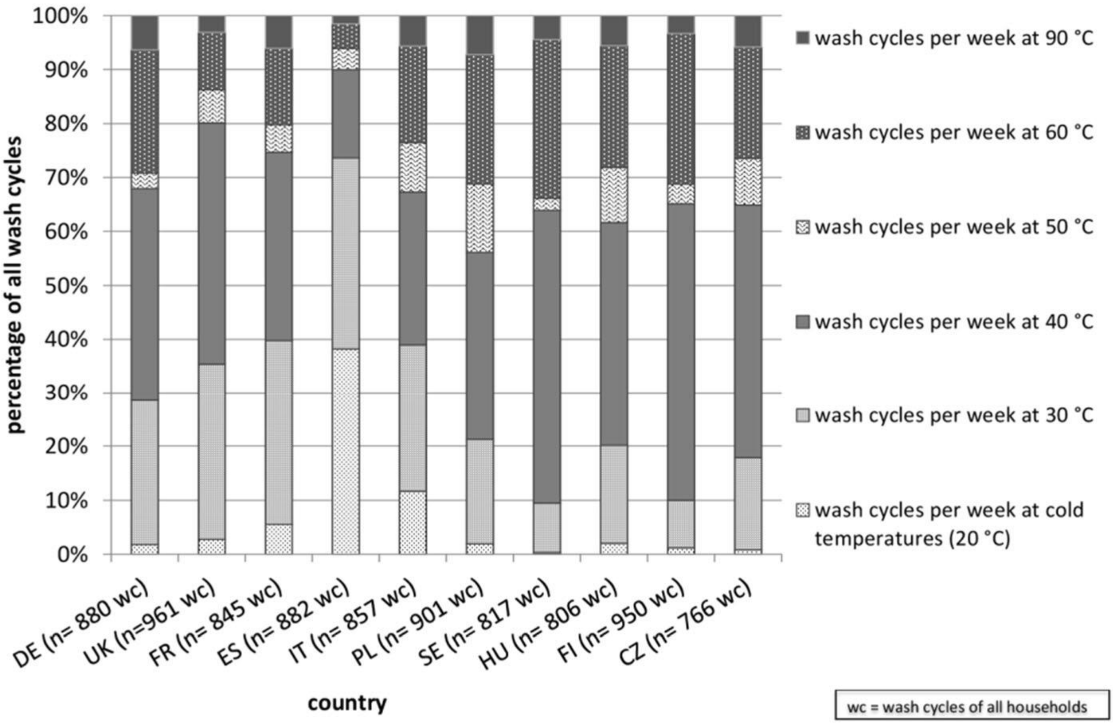

Figure 11 Relative frequency of wash temperatures used in 2011 in different European countries (Figure 8 from Schmitz & Stamminger, 2014)

In Japan, the average temperature for washing is about 18°C. About 58% of the laundry is washed with grey water (used bath water), 36% with ambient temperature tap water, and the remaining 6% is washed with heated water. For the last rinse cycle, 95% use ambient temperature tap water (Nakamura, 2010).

Washing temperature of wool garments

Washing temperatures for various types of garments were studied through a survey in Norway in 2002 and 2010 (Laitala et al., 2012b). The percentage of washes at different temperatures and the average washing temperature for different products made of cotton and wool are given in Figure 12. The average washing temperature of woollen garments was significantly lower than for similar products in cotton in both surveys. Most woollen textiles are washed at 30°C. Products worn against the skin are more often washed at higher temperature than the outer garment layers, such as sweaters.

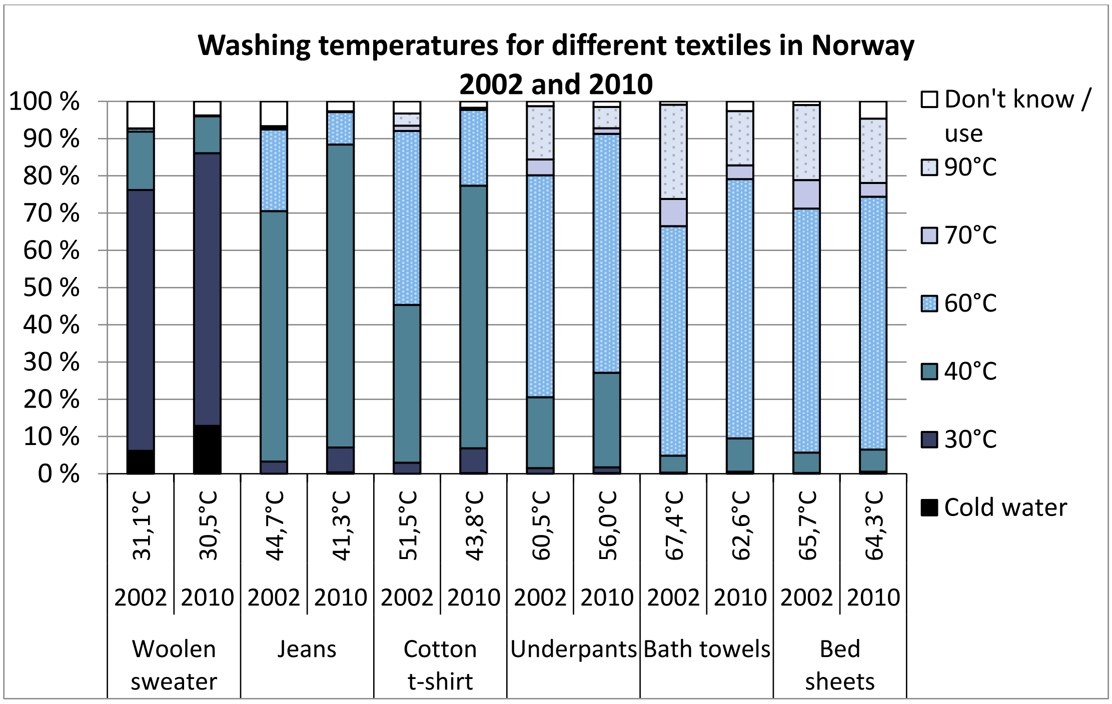

Figure 12 Distribution of washing temperatures for different textile products in 2002 and 2010. Average temperature is given below the pillars. (2002: N= 1008, 2010: N=546) (Laitala, Klepp & Boks, 2012)

A German study showed that the average washing temperature for wool the program was 30.3°C, which is the second lowest of the various washing programs after silk wash, while the average washing temperature of all wash cycles was 44.5°C (Figure 13) (Kruschwitz et al., 2014).

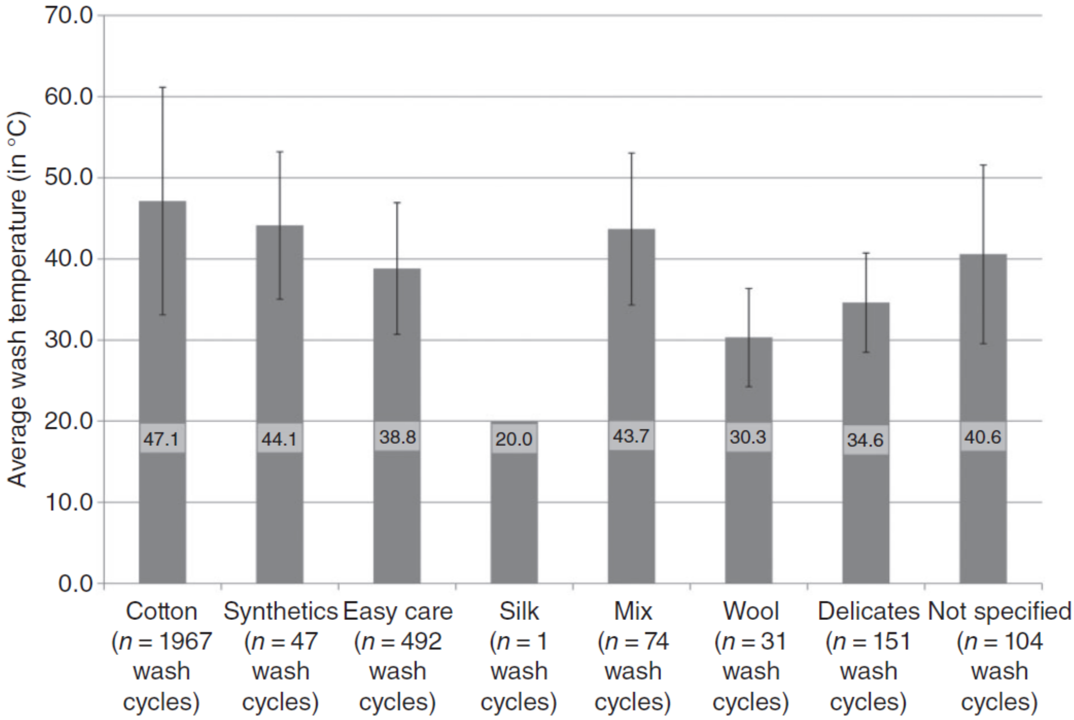

Figure 13 Arithmetic average wash temperature for different washing programs in Germany (n = 2763 wash cycles, with standard deviation). (Figure 8 from Kruschwitz et al., 2014)

3.1.6 Laundry load/volume

The maximum load capacity of washing machines is increasing and is currently about 6.5 kg in Europe (Lasic and Stamminger, 2015, Schmitz et al., 2016), but many studies report that the maximum capacity is seldom used. For example in Europe, consumers estimate that they wash on average 84% of their washing cycles with a full machine (A.I.S.E., 2014). Variations between regions of Europe are given in Table 15, but the differences between the regions are in general small.

Table 15 On average, for normal laundry washes, for what percentage of your washes do you consider that the washing machine is "full"? (A.I.S.E., 2014)

Countries	Washing with a full load
European average (23 countries)	84 %
UK and Ireland (UK, IRL)	83 %
Scandinavia (DK, FIN, NO, SWE)	84 %
Central and Eastern Europe (HU, POL, RO, SLK, CZ, BU)	82 %
Western Europe (BE, NL, FR, DE, AU, CH)	86 %
Southern Europe (GR, IT, POR, ES, TR)	85 %

Many of the new washing machines measure the weight of laundry and adjust the water level accordingly when the machine is less than completely filled, thus also reducing energy use. However, it is still more resource demanding per kg of clothing to wash with an unfilled machine (Laitala, Boks & Klepp, 2011).

Different washing programs have different maximum capacities. For example, the capacity for wool programs is usually around 1/3 of the maximum capacity of the machine. In Germany, measurements of laundry load showed that people often under-loaded the machine when they used the cotton program, but overloaded it slightly when using the wool program (Table 16). The average load size across all washing programs was 3.3 kg. Comparison between what people reported as fully loaded washing machine use and the weighing results showed that the machines were actually not fully loaded. For the majority of consumers, a load factor of 0.73 ± 0.22 was regarded as a maximum load size for a cotton program (Kruschwitz et al., 2014). This means that survey results where consumers report how full the machine is, without weighing the laundry, should be treated cautiously. This applies for example to the results given in Table 15, indicating that the 84% of fully loaded washing cycles is likely to be overestimated to some extent.

Table 16 Measured laundry loads for different washing programs during actual use in Germany (Kruschwitz et al., 2014)

Washing programme	Maximum load for programme as percentage of washing machine capacity based on manuals	Arithmetic average amount of load with standard deviation (in kg per wash cycle)	Average load factor (actual load divided by recommender maximum load)
Cotton	100%	3.4 ± 1.2 kg	0.68
Synthetics	57% - 67%	3.0 ± 1.0 kg	0.99
Easy care	57% - 67%	2.8 ± 1.3 kg	0.93
Mix	67% - 71%	3.7 ± 1.4 kg	1.06
Wool	29% - 40%	2.1 ± 1.1 kg	1.07
Delicates	43% - 60%	2.3 ± 1.2 kg	0.77

Based on detailed interviews of 104 households in the Netherlands, Uitenbogerd et al., (1998) could estimate the average load of the various washing programmes (Table 17).

Table 17 The average load of washing machine programmes (Table 4-2 from Uitdenbogerd et al., 1998)

Programme	Load [kg/cycle]
White/main	3.62
Coloured	3.41
Synthetics	2.64
Fine	2.78
Wool	2.55
Hand	NA
Short	2.35
Other	3.25

Studies of laundry load sizes in various regions show that in Europe, the most common laundry load size is 3-4 kg, which is about 75% of machine capacity. The size is about the same in North-America, as Pakula & Stamminger (2009) report 3-4 kg and Golden et al. (2010) report 3 kg. A laundry project in Bern, USA, where the participants first used traditional top loading v-axis machines and then changed to new front loading h-axis machines, showed that the average load size increased from 3.02 kg to 3.17 kg. However, the researchers observed that this was more related to the change of season (from summer to fall) than the type of washing machine, so average load size was measured to be 3.1 kg (Tomlinson & Rizy, 1998).

In Japan, it is common to have a slightly lower load size. Average values such as 2.6 kg (Yamaguchi et al., 2011), 3 kg (Pakula and Stamminger, 2009) and 3.3 kg (Tsumadori, 2005) as cited in (Gooijer and Stamminger, 2016) have been reported. It is common to use only 50% of the maximum capacity of 6 kg (JSDA, 2002).

The load size is significantly lower in China; 1.3-2 kg (Pakula and Stamminger, 2009), and 60% capacity is the norm (Yuan et al., 2016). Another study in China report that 29% of washing machines loads are at full capacity, and 47% are half full (DuPont, 2013b).

3.1.7 Detergents

Detergents are used in laundering to improve the effectiveness of cleaning. Various types are used, and the different washing methods require their own detergent types, such as hand-washing detergents, and specific types for washing machines with vertical and horizontal axis drums (high degree of tumbling in the front loading h-axis machines require low-sudsing detergents).

Wool should be washed with wool detergents to maintain its properties. There are few large quantitative consumer laundry studies that specify wool detergents as a unique category, but a study in Germany showed that wool detergent was used for about 1.6% of wash cycles, and delicates' detergent for 5.0% of cycles. However, the study period did not include winter months, so the actual proportion of use of wool detergents may be somewhat higher. A total of 44.5% of German households in the study had only one type of detergent for textile care (Kruschwitz et al., 2014). A European survey conducted in 2002 showed that it was more common for Norwegians to own a specific detergent for delicates (82%) compared to Spanish (74%), Dutch (59%) or Greek (59%) respondents (Arild et al., 2003). The distribution of how common it is to use such detergent is given in Figure 14. Qualitative interviews of Norwegian and Swedish consumers showed differences in the level of awareness of the existence of wool detergents, with all the Norwegian informants aware of wool detergents, while this was not the case for Swedes (Laitala and Klepp, 2016). The distribution of ownership of various detergents in Germany is shown in Table 18.

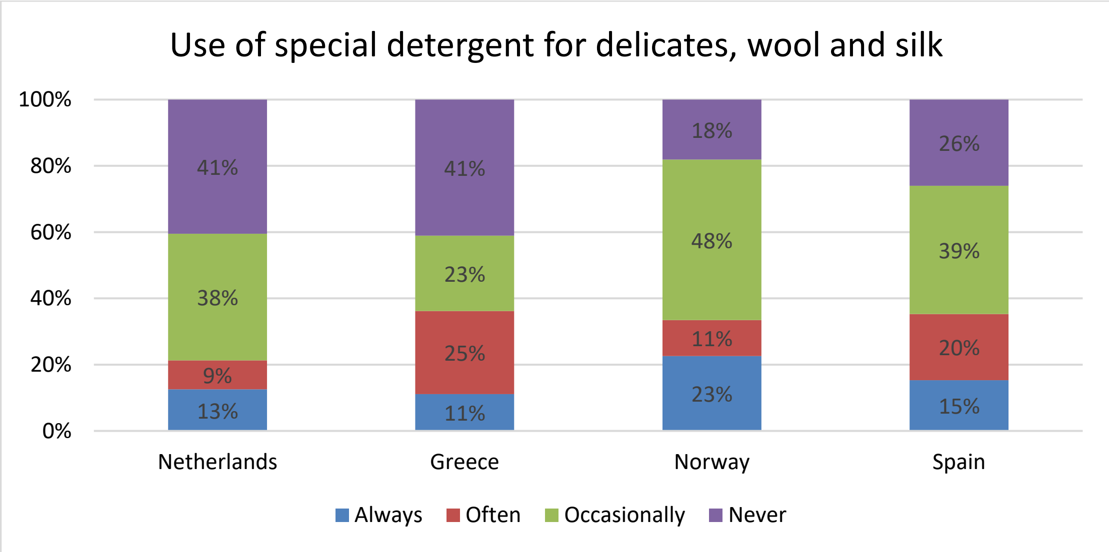

Figure 14 How often special detergent for delicate materials is used (for garments made of wool and silk, also known as gentle or fine wash detergents) (Arild et al. 2003)

Table 18 Types of detergents that German households own (Stamminger and Goerdeler, 2007)

Type of detergents	Percentage of households
One detergent: Universal	13%
One detergent: Colour	6%
Two detergents: universal and colour	25%
Three detergents: universal, colour and fine	33%
Four detergents: universal, colour, fine and special	16%
Modular detergent (with basic detergent, bleach/stain remover and water softener separately)	3%

In the Netherlands, the households report on average use of 3.3 different types of laundry products. For the detergents, 85% of the households have available heavy duty, 57% specialty, 41% colour, and 27% wool/silk detergent (Uitdenbogerd et al., 1998).

In general, wool detergents are liquid. Both liquid and powder detergents are quite commonly used in Europe, as shown by two recent surveys. One of them asked about all detergents used by the household, and these results show that laundry powders are the most used type of detergent in Europe (52%). This is followed by regular liquids/gels in a bottle (47%), concentrated liquids/gels in a bottle (34%), compact powders (20%), liquid tablets/pouches/unit doses (19%) and laundry tablets (16%) (A.I.S.E., 2014, Vandecasteele et al., 2014). Another survey asked which type of detergent was used the most, and showed that liquid detergents were used most (51%), followed by powders (36%) and tablets/caps/pads by 12% (Stamminger 2016).

The studies that document detergent dosing show that overdosing is common (Table 19). However, underdosing also occurs, especially in cases where the water quality is hard and the laundry heavily soiled (Kruschwitz et al., 2014). Paloviita and Järvi (2008) looked into consumers' detergent dosing behaviour in residential laundry facilities in Finland and observed that most of them used some kind of measuring device, but 20% of respondents' measuring activity could be described by the words 'visual', 'careless', 'impressionistic' and so forth. These respondents often poured detergent directly from a package to the detergent chamber. Measurements of the actual detergent dosages showed that about half of these were quite close to the recommended dosage, while 36-43.5% were categorised as "heavy users" that dosed too much detergent. It was more common to overdose in smaller washing machines than the larger ones where maximum capacity was over 5 kg (Paloviita and Järvi, 2008).

Table 19 Average amount of detergent in grams per wash cycle and average dosage factor per type of detergent (n = 2773 wash cycles, with standard deviation) (Table 7 from Kruschwitz et al., 2014)

Type of detergent	Number of wash cycles	Percentage of wash cycles	Arithmetic average amount of detergent with standard deviation (in g per wash cycle)	Arithmetic average dosage factor with standard deviation
Powder	1183	43%	74.6 ± 37.9	1.41 ± 0.91
Compact/pearls	460	17%	64.4 ± 29.5	1.55 ± 0.87
Tabs	100	4%	55.5 ± 25.2	1.38 ± 0.77
Liquid	1030	37%	75.5 ± 34.7	1.38 ± 0.73

Another publication from the same German study where the actual detergent amounts were measured, separates the detergent dosages between heavy-duty detergents (both with and without bleach) and special detergents. These results are given in Table 20. The average laundry load of consumers in that study was 3.3 kg (Kruschwitz et al., 2014). This enables calculation of the average amount of detergent per kg laundry, given in the last column. This estimation does not take into account that the average load sizes for the various detergent types may have been different, as this was not reported in the publications. The report included use of wool detergent in 43 loads, and of these, 74.4% were liquid and 25.6% powder (no tabs or pearls) (Kruschwitz and Stamminger, 2011).

Table 20 Average amount of detergent in grams per wash cycle separate by heavy duty and special detergents types (Kruschwitz & Stamminger, 2011)

Detergent use area	Detergent type	Number of wash cycles	Percentage of wash cycles	Amount of detergent in grams per wash cycle [g/cycle]	Average detergent per kg laundry [g/kg]
Heavy duty	Powder	1154	42 %	75.4	22.8
	Compact/pearls	444	16 %	65.4	19.8
	Tabs	100	4 %	55.5	16.8
	Liquid	893	32 %	77.7	23.5
Special detergents	Powder	29	1 %	44.4	13.5
	Compact/pearls	16	1 %	37.7	11.4
	Liquid	137	5 %	61.5	18.6

Presutto et al. (2007) estimated an average consumption of 139.76 grams of detergent per wash cycle in Europe. With an average load of 3.4 kg, this gives a detergent consumption of 41.1 grams per kilogram of clothes washed. This estimation is higher than reported in most other studies, and the figure is based on standard washing test conditions and may not relate to actual consumer behaviour. It is also likely that the detergents in this study are traditional and not the compact type that are more common in the many Western countries today.

Strand (2015) estimated the use of 15.6 grams of powder detergent per kilogram of textiles in laundry, based on a test of eight Swedish detergents where the average dose for one wash was 39 grams detergent (Testfakta, 2013). An assumption was made that this amount was used for an average wash load of 2.5 kg.

In Japan, the share between liquid and powder detergents is equal, with about 50% each in 2010 (Ishii, 2011). The dose of ultra-compact liquids is about 10 grams per 30 litres wash cycle, while conventional liquids are about twice as much, 20-25 grams per 30 litres wash cycle (Ishii, 2011). Nearly all powder detergents are in concentrated form, and about 40% of them include bleaching agents (JSDA, 2006) In 2010, only about 9% overdosing was estimated (Ishii, 2011).

In China, it is most common to use powder detergent, 67% for washing machines and 54% on handwashing. The next most common type used for machine washing is liquid detergent (34%), and bars for handwashing (34%) (DuPont, 2013b). Another study reported that the average amount of detergent used in China is 15.2 g per wash cycle, and 20.16 kg/year (when counted over 133 wash cycles) (Yuan et al., 2016).

The use of detergents for handwashing is common in India, as 81.8% use detergents suitable for handwashing, only 17.9% use powders for washing machines, and 0.3% use liquids for washing machines (DuPont, 2013c). However, some use handwashing detergents in their washing machines.

In Kenya, the concentrated form of laundry detergents was introduced in 2004, so it is still more common to use regular powder detergents (Euromonitor International, 2011).

In South Africa, the amount of detergent used was estimated to be about 1.5 kg powder detergent per month, resulting in a yearly use of 18 kg (Gordon et al., 2009). Divided by the average of 91 washing times per year (handwashing), about 198 grams are used per wash.

Golsteijn et al. (2015) present and discuss LCAs of two household laundry detergents (powder and tablets). The studies are discussed further in the next section. They identify relevant impact, as well as the detergents' life cycle stages with the largest contribution to the environmental impact. Table 21 shows the generic product formulations of tablet and compact powder laundry detergents for the European market based on information provided by A.I.S.E, and Table 22 the inventory data that Golsteijn et al. (2015) used to model the detergents from the Ecoinvent database. The key assumptions they used in their study for the use phase are given in Table 23.

Table 21 Generic product formulation of detergents (tablet and powder) in Europe (Table S6 from Golsteijn et al., 2015)

Product formulation	Tablet	Powder
Alkalinity sources	15-30%	15-30%
Bleach agents	1-5%	1-5%
Builders	15-30%	15-30%
Enzymes	0.2-0.5%	0.2-0.5%
Fragrances	0.2-0.5%	0.2-0.5%
Optical brighteners	0.2-0.5%	-
Oxidising agents	5-15%	5-15%
Sequestrants	1-5%	1-5%
Surfactant system (anionic – non-ionic)*	5-15%	5-15%
Water	-	5-6%

*The surfactant system modelled here is of a mixed oleochemical (i.e. palm kernel and coconut oil) and petrochemical origin.

Table 22 Ecoinvent data inventory for a tablet powder laundry detergent frame formula. (Tables S7 and S8 from Golsteijn et al., 2015). Dye and fragrances lacked data and were modelled as empty processes.

	Ecoinvent data for **tablet** powder laundry detergent	Ecoinvent data for **powder** solid laundry detergent
Alkalinity sources	GLO: sodium carbonate from ammonium chloride production at plant	GLO: sodium carbonate from ammonium chloride production at plant
Bleach percursors	RER: etylenediamine, at plant RER: layered sodium silicate, SKS-6, powder at plant	RER: etylenediamine, at plant RER: sodium percarbonate, powder at plant RER: layered sodium silicate, SKS-6, powder at plant
Builders	RER: polycarboxylates, 40% active substance, at plant RER: zeolite, powder, at plant RER: sodium sulphate, powder, at plant	RER: polycarboxylates, 40% active substance, at plant RER: zeolite, powder, at plant RER: sodium sulphate, powder, at plant
Auxiliaries	RER: carboxymethyl cellulose, powder at plant Citric acid*	RER: carboxymethyl cellulose, powder at plant Citric acid*

	RER: modified starch, at plant	RER: sodium hydroxide, 50% in H20, production mix RER: sodium chloride, powder at plant
Enzymes	Enzymes**	Enzymes**
Fragrances	Empty process	Empty process
Optical brighteners	Empty process	Empty process
Oxidising agents	Empty process	RER: sulphuric acid, liquid, at plant
Water	RER: water, completely softened, at plant	RER: water, completely softened, at plant
Surfactant system (anionic – non-ionic)	RER: fatty alcohol sulphate mix, at plant*** RER: ethoxylated alcohols, unspecified, at plant****	RER: fatty alcohol sulphate mix, at plant*** RER: ethoxylated alcohols, unspecified, at plant****

*Citric acid LCI data was provided by Unilever
**Enzymes LCI data was provided by Novozymes
*** Alcohol sulphate (AS) C12-18, 25% mix of petrochemical, palm kernel oil, coconut oil, palm oil
**** Alcohol ethoxylates (AE) with two degrees of ethoxylation AE3 and AE7, 1/6 mix of petrochemical, palm kernel oil, coconut oil

Table 23 Key assumptions used in modelling of detergent use phase (Part of table S10 from Golsteijn et al., 2015)

	Reference	Compact powder	Tablet
Functional unit	A.I.S.E.	1 wash	1 wash
Reference flow	A.I.S.E	81.5 g	63.8 g
Use phase	A.I.S.E	40°C (0.70 kWh) electricity 60 l water	40°C (0.70 KWh) electricity 60 l water

As none of the studies reported on the ingredients in wool detergents, we have performed a web search on wool detergents and include the ones where the ingredients and dosage were reported (Table 24).

Table 24 Wool detergent ingredients

Wool detergent	Ingredients	Country of origin	Dosage
IEC 60456 Reference Wool Detergent[2]	78% water, 10% Linear sodium alkyl benzene sulfonate, 50% aqueous solution (Anionic surfactant), 5% Ethoxylated fatty alcohol $C_{13/15}$ (7 EO) (non-ionic surfactant), 1% Anti Foam (fatty acid), 0.5% Phophonate, Sodium Hydroxide (To adjust pH to 8.5), 100 ppm 1,2-Benzisothiazolin-3-on	Europe (Germany)	Reference machine: 70g (for 1 kg test load) Test machine : Formula = 54g + 16g/kg of rated capacity
Milo[3] 	5-15 % Anionic surfactants. Non-ionic surfactants. <5 % Parfum (Butylphenyl methylpropional. Benzyl salicylate. Hexyl cinnamal. Citronellol). Calcium sorbate. Laurylamine dipropylenediamine. Benzisothiazolinone. Methylisothiazolinone.	Norway	50 ml (about 51 grams)

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[2] http://www.testgewebe.de/msds/msds_iecw_en.pdf
[3] https://www.lyreco.com/webshop/P05/product/viewSecuritySheet/000000000006076056?lc=NONO

Wool detergent	Ingredients	Country of origin	Dosage
Woolite® Extra Delicates Care[4] 	15-30% anionic surfactants, <5% amphoteric surfactants, non-ionic surfactants and preservatives Water, Dodecylbenzene Sulfonate (Anionic Surfactant), C12-16 Alcohols Ethoxylated (Nonionic Surfactant), Sodium Laureth Sulfate (Anionic Surfactant), Sodium Hydroxide (pH Adjuster), Coconut Acid (Surfactant), Sodium Chloride (Thickener), Triethanolamine (pH Adjuster), Fragrance/Parfum, BHT (Preservative), Benzisothiazolinone (Preservative), Methylisothiazolinone (Preservative)	USA	One table spoon (11 ml, 12 grams)
Ecover wool wash Delicate[5] 	>30% Water 5-15% Anionic surfactants <5% Non-ionic surfactant 10-15% Liquid soap Perfume (incl. limonene), Preservatives (0,02%): 2-bromo-2-nitropropane-1,3-diol. Natriumclorid Citric acid	Belgium?	45 ml, 45 grams
Nøstebarn detergent for wool and silk[6] 	5-15% non-ionic surfactants *, 5-15% Anionic surfactants *, <5% soap herb extract, <5% Lactic Acid, Water (* Surfactants of vegetable origin)	Norway	1-2 teaspoons for handwash, 1-2 tablespoon to machine wash (about 18 grams)
Sonett wool and silk[7] 	>30% soap derived from olive and rapeseed oils,* -5% sugar surfactant, <1% ethanol (plant derived alcohol), citrate, natural essential lavender oil*, balsamic additives*, rhythmatised water. *Certified organically grown	Germany	60 ml (90 ml if hard water) (about 60 grams)

[4] http://www.woolite.us/products/woolite-delicates/woolite-delicates/ , http://www.rbnainfo.com/productpro/ProductSearch.do?brandId=36&productLineId=592&searchType=PL&template=1

[5] http://www.molevalleyfarmers.com/mvf-static/reports/product/pdf/36016.pdf, http://makelanluomutila.fi/shop/product/ecover-villapesuaine-750-ml

[6] https://nostebarn.no/ullvaskemiddel/ullsape-flytende-250-ml

[7] http://www.sonett.com.au/Sonett-Natural-Cleaning-Products-Olive-Washing-Liquid-for-Wool-or-Silk-1L

Wool detergent	Ingredients	Country of origin	Dosage
Zebla woolwash with lanolin[8] 		Denmark	30-40 ml per kg laundry (assuming 2 kg laundry load, 60-80 g/cycle)
Bio Luvil Wool & Silk[9] 	Water, C12-15 Pareth-7 (Surfactant), Sodium Dodecylbenzenesulfonate (Surfactant), Sodium Laureth Sulfate (Surfactant), Sodium chloride (Viscosity Controlling Agent), Perfume, Sodium Hydrogenated Cocoate (Surfactant) Styrene/Acrylates Copolymer (Opacifier), Vinyl Imidazole/VP Copolymer (Dye Transfer Inhibitor), Sodium sulfate (Process by-product), Benzisothiazolinone (Preservative), Butylphenyl Methylpropional (Fragrance), Sodium hydroxide (pH Adjuster), Benzyl Salicylate (Fragrance), Alpha-Isomethyl Ionone (Fragrance), Geraniol (Fragrance) Sodium Lauryl Sulfate (Surfactant), CI 45100 (Colourant), Methylisothiazolinone (Preservative)	UK (Unilever)	77 ml (about 77 g)
Persil Liquid Silk & Wool 	Water, C12-15 Pareth-7 (Surfactant), Sodium Laureth Sulfate (Surfactant), Propylene glycol (Hydrotrope), Sodium chloride (Viscosity Controlling Agent), Sodium Hydrogenated Cocoate (Surfactant), Parfum (Fragrance), Sodium Diethylenetriamine Pentamethylene Phosphonate (Sequestrant), Sodium sulfate (Process by-product), Limonene (Fragrance), Benzyl Salicylate (Fragrance), Linalool (Fragrance), Butylphenyl Methylpropional (Fragrance), Hexyl Cinnamal (Fragrance), Citronellol (Fragrance), Geraniol (Fragrance), Benzisothiazolinone (Preservative), Sodium hydroxide (pH Adjuster)		50 ml (about 50 g)
Sodasan ecological wool detergent[10] 	Sodium Laurylsulfat <= 9,5% Alkylpolyglycoside < 8% D-Glucopyranose < 5 % Soft Magnolia 0,25% Orangenoil <= 0,15% Ethanol <5%	Germany	Hand wash 20 ml per 10 liters water. Machine wash 30 ml per load. 40 ml if heavy soiling (about 30 g)
Cleanplus woolwash[11]	Alkyl benzene sulphonic acis 1-10% Sodium tripolyphosphate 1-10% Non hazardous ingredients Remainder	Australia	

8 http://www.zebla.dk/uldvask-med-lanolin/?lang=nb
9 https://pioti.unilever.com/pioti/FI/p4.asp?selectCountry=FI&language=FI&productid=3052902
10 http://en.sodasan.com/tl_files/sdb/englisch/Wool%20detergent.pdf
11 http://cleanplus.com.au/test/wp-content/uploads/2013/04/SDS180.pdf , http://cleanplus.com.au/product/wool-wash/

Wool detergent	Ingredients	Country of origin	Dosage
			
Jasol woolwash[12] 	Water 60-100 % Ingredients determined not to be hazardous 0-10 % Non hazardous Surfactants Mixture 10-30 % (Eucalyptus fragrance)	Australia	Add 80 ml to a basin for hand-washing and 80-120 ml to machine (about 100 g)
Kao Light Duty Liquid Detergent (LDLD) with eco-label for fine fabrics application (wool, silk) [13] 	EMAL® 270D Sodium Laureth Sulfate (Anionic surfactant) 12.4% BETADET® HR Cocamidopropyl Betaine (Amphoteric surfactant) 9.0% LEVENOL® F-200 Glycereth - 6 Cocoate (Nonionic sur-factant) 5.7% Coconut Fatty Acid 1.4 KOH (50% solution) 1.8% Citric Acid (50% solution) 1.0% NaCl 1.0% Opacifier 0.3% Fragrance 0.2% Preservative 0.15 % Deionized Water Up to 100%	Japan	45 ml (about 45 g)

To summarize, all of the wool detergents found are liquid and thus contain water, and most of the wool detergents include the following ingredients:

- Anionic surfactants, usually around 5-15%
- Nonionic surfactants, usually around 5%
- Alternatively various soaps (vegetable oil based)
- Preservatives, usually less than 1%
- PH adjusters
- Fragrances

Some of wool detergents also have added lanolin, and the producers of these detergents claim that this addition helps the woollen textile to maintain their properties unchanged.

The dosages vary greatly between products, from 12 to 120 ml per wash cycle. Assuming that one milliliter of the detergent weighs about one gram, the average amount used is 52.3 ± 24.1 grams per cycle. Assuming an average load size of 2.1 kg, laundering wool entails the use of 24.9 ± 11.5 grams of detergent per kg wool, which is higher than the measured value 18.6 g/kg of use of low-duty liquid detergents in Germany (Kruschwitz & Stamminger, 2011).

LCA of detergents

LCAs on detergents show that the use phase has the largest contribution to most of the important environmental impact categories (Van Hoof, Schowanek, & Feijtel, 2003; Golsteijn et

[12] http://huntind.com.au/wp-content/uploads/2013/07/woolwash.pdf
[13] http://www.kaochemicals-eu.com/sites/default/files/formulations/D-163.pdf

al., 2015). It dominates the energy consumption, mainly due to energy required for heating water for washing (Table 25). Use of surfactants of oleo chemical origin, such as palms or coconuts, has a large impact on natural land transformation and agricultural land occupation. Use of builders (water softeners) contributes to marine eutrophication and metal depletion. Figure 15 gives the midpoint results for tablet detergent, and Figure 16 the end point results found in the study by Golsteijn et al. (2015). Results for powder and tablet detergent in this study were quite similar. Unfortunately, no LCA study for wool detergents was found.

Table 25 Total cumulative energy demand of different life cycle stages of tablet and powder detergents (part of table 2 from Golsteijn et al., 2015)

Product category	Total (MJ)	Ingredi-ents	Manufac-ture	Packag-ing	Transport	Use phase	End of life
Tablet laundry deter-gent	13.0	3.70	0.38	0.10	0.19	8.35	0.24
Compact powder laundry detergent	12.2	2.84	0.38	0.15	0.27	8.35	0.24

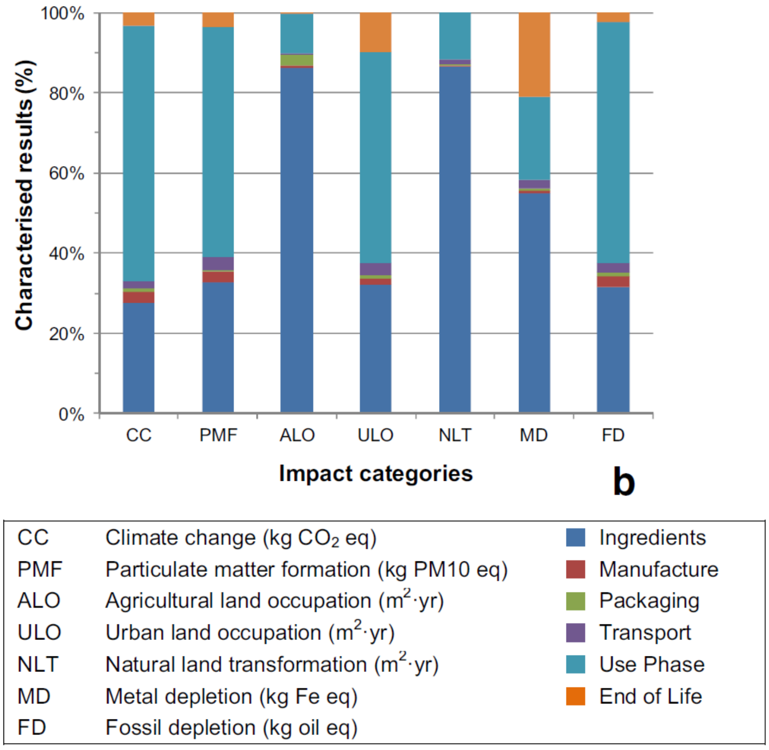

Figure 15 Characterised midpoint results of tablet laundry detergent (Figure 4b from Golsteijn et al., 2015)

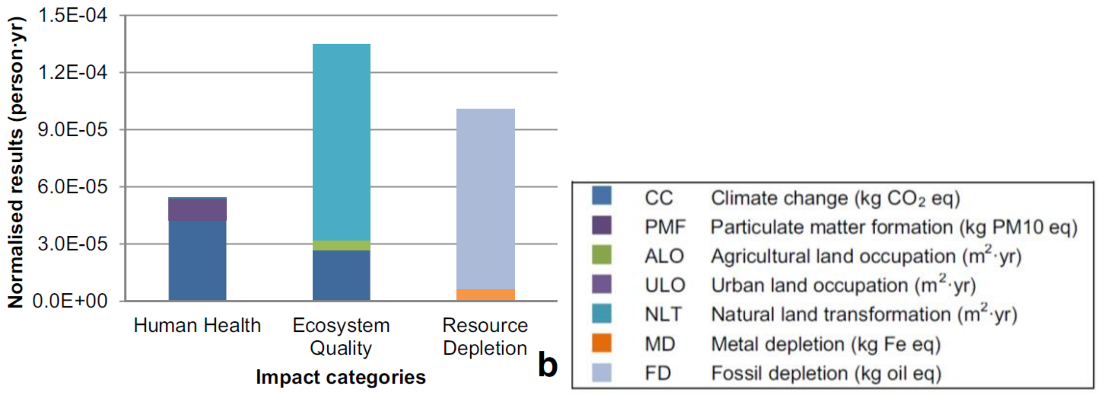

Figure 16 Normalised end point results for tablet laundry detergent (Figure 5b from Golsteijn et al., 2015)

More detailed information for detergents with LCA data can be found in following studies:

- Saouter and van Hoof (2002) have constructed a database for the life-cycle inventory and assessment (LCI and LCA) of Procter & Gamble laundry detergents. Example inventory showed that main energy consumption occurs at the use stage (more than 80%).
- Saouter et al. (2002), Saouter et al. (2001) compared the effect of regular, compact and super compact granular laundry detergent formulations. In part I they conducted an environmental risk assessment and in part II Cradle-to-Grave LCAs based on 1000 wash cycles. The results showed that risk quotients decreased two to five-fold between 1988 and 1998 due to the introduction of compact detergents.
- Van Hoof et al. (2003) presented comparative life-cycle assessment of five Procter & Gamble laundry detergent formulations in the UK in 2001. The study includes regular powder, compact powder, powder tablet, compact liquid and liquid unit-dose system detergents. The results show that compact detergents (both powder and liquid) are environmentally preferable, mainly due to the lower use of chemicals, resulting in benefits on aquatic toxicity, eutrophication, ozone depletion and photochemical smog. The use stage dominates most of the indicators (>70% contribution).
- Ecolabelling Denmark (2011) prepared a background report for revision of ecolabelling criteria for detergents. Because the use phase dominates most of the environmental impacts, they promote products that can be used at low temperature laundering (≤ 30° C). The scope of the ecolabel criteria primarily related to the chemical composition of the products, and thus the impact on the aquatic environment. In addition to laundry detergents, the report includes stain removers and fabric softeners.
- Golsteijn et al. (2015) presented and discussed LCAs of two household laundry detergents (powder and tablets) in Europe. Their selected functional unit was one wash with an average load (5 kg) of normally soiled laundry, using medium hardness water in a 6 kg machine and with a reference wash temperature of 40 °C. The detergent dosage was 81.5 g of compact powder, and 63.8 g of powder tablet.
- Boulay et al. (2015) presented the results of a water impact study for one wash in an ‘average’ French laundry. As a reference, they used 37 g of concentrated laundry liquid detergent. The calculation is for the water impacts as a ‘water footprint’.

3.1.8 Fabric softeners

Fabric softeners (also called fabric conditioners or fabric enhancers) are commonly used consumer products. Fabric softeners consist primarily of cationic surfactants with long hydrophobic hydrocarbon chains that attach to the anionic charged wet fibres and form a layer on the surface (Toedt et al., 2005). Cationic surfactants called esterquats have been used since the 1990s (Braun and Stamminger, 2011). In addition, they contain preservatives (e.g. thiazolinones, bronopol, formaldehyde, benzalkonium chloride etc.), and most also contain colouring agents and fragrances (Ecolabelling Denmark, 2011). Fabric softeners have been documented to improve the fabric hand properties (softness) and to reduce static electricity. Fabric softeners are also claimed to be beneficial for easier ironing, taking care of the clothing by protecting the fibres or colours, and adding scent to textiles. On the negative side, it has been shown that some fabric softeners are associated with increased flammability, reduction of abrasion resistance and strength, and increase in pilling (Laitala et al., 2012a). Fabric softeners are liquid products and are used in amounts varying from app. 30 ml up to 100 ml per wash depending on the concentration of the product (Ecolabelling Denmark, 2011).

There are national differences in how common it is to use fabric softeners. European studies show that in Norway, about 61% of respondents use them often, 19% sometimes and 19% never (Laitala et al., 2012a). In Denmark, consumer surveys show that 60 per cent of the Danish population use fabric softeners (Chapman, 2010). Their use is less common in Germany, where 25.4% of consumers always use fabric softeners, 21.1% sometimes, 16.9% for specific apparel, and 34.6% never use them (Braun and Stamminger, 2011). In the Netherlands, about 31% of households reported to own fabric softener in 1997 (Uitdenbogerd et al. 1998). An international survey conducted in 2002, showed that it was more common for Greek and Spanish respondents to use fabric softeners than for Norwegians or Dutch (Figure 17) (Arild et al., 2003). These results were confirmed by a more recent survey conducted in 2015 (Stamminger 2016), which showed that over 50% of Spanish households use fabric softeners in all wash loads, while in Hungary and Romania only about 5% always use them and about 60% never use them. The average values for EU-28 are that 31% use them in all wash loads, 24% in most of wash loads, 23% in a few loads, and 22% never use them (Stamminger, 2016). These figures are the most recent, include 11 EU countries and are weighted accordingly, and can therefore be used in estimating that softeners are used in about 55% of washing cycles in Europe. This result is also close to the recent survey results of four countries (Germany, Sweden, Poland and USA), that showed that about half of the respondents used softeners when washing jeans and t-shirts (Gwozdz et al. 2017).

A non-representative Swedish survey showed that softener was used in 18.2% of laundry cycles, but most respondents did not use softeners at all (54%) (Granello et al., 2015). They also surveyed to which extent softeners were used related to specific products, with no clear results - except when it came to sportswear and jackets - where softeners were less used. We have not found information of how common the use of fabric softeners is in the USA, but know that they have also commonly used other laundry products, such as dryer sheets. In China, about 31% of respondents reported they used fabric conditioners (DuPont, 2013b).

Unfortunately, none of the studies specify the fibre content in the types of garments that consumers chose to use softeners on, so we do not know whether the frequency of use on wool is different from other materials. However, due to softeners' ability to reduce static electricity, they are more likely to be used on materials prone to this, such as synthetics.

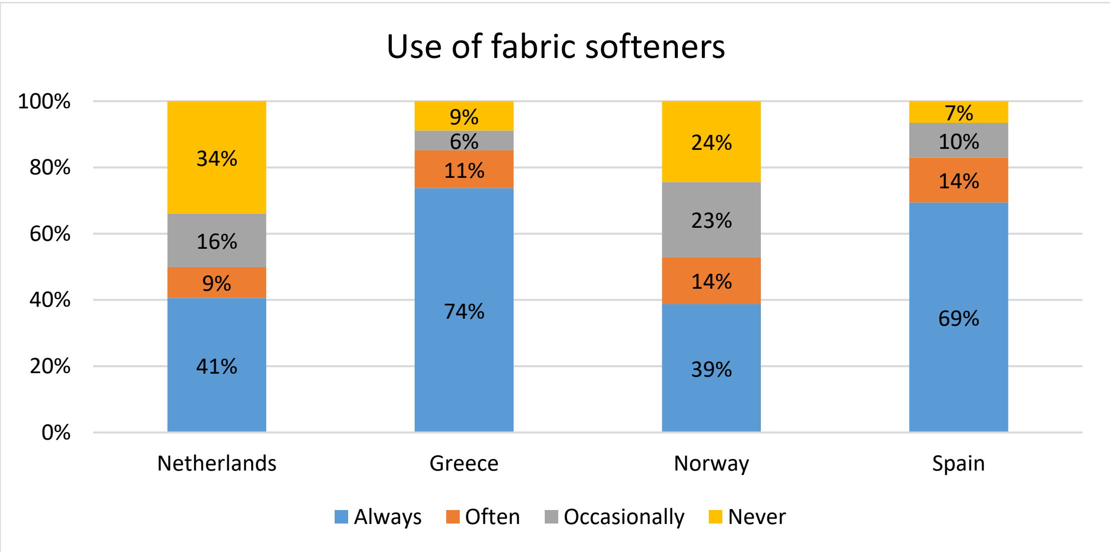

Figure 17 Use of fabric softeners in four European countries (reanalyzed data from Arild et al., 2003)

3.1.9 Drying

Drying wet laundry requires energy that is either “free” when the laundry is dried outdoors or in unheated rooms indoors, but needs to be produced if added heating is required. In general, drying laundry in a dryer uses more energy than washing the laundry. Therefore, this is an important parameter in LCA calculations regarding the use phase. Also drying laundry indoors in heated rooms consumes energy (Schmitz and Stamminger, 2014). Whether this increases the energy consumption of the household is dependent on the heating systems, such as whether a thermostat automatically regulates the temperature up in order to counteract the decrease in room temperature caused by the laundry drying. Additional energy may be required if the room is ventilated extra for airing to control the humidity. Differences in drying methods are likely to result in a difference in energy consumption between wool and many other fibres that are more commonly tumble dried. Line drying could save about 91% of the energy needed to tumble dry a cycle (Uitdenbogerd et al., 1998).

There are several different types of clothes dryers. The traditional vented tumble dryers pump out the warm damp air through a hose outside, condenser tumble dryers condense the warm damp air from laundry into a water tank, and energy effective heat pump dryers are in principle condenser dryers with a heat pump. They use about half of the electricity of a standard energy label[14] C-rated dryer (Zimmermann et al. 2012). Dryers can use electricity or gas, with gas dryers working in the same way as electric vented tumble dryers. In the US, about 80% of dryers are electric, 19% use natural gas and 1% propane/LPG (Statista, 2009a).

The penetration rate of laundry dryers varies between different countries. For example, a survey conducted in 10 European countries (Presutto et al 2007) indicated that 35.8% of the households had a tumble drier. This figure might be higher than in reality due to the selection being restricted to households owning a washing machine. This, and other studies that document ownership of clothes dryers in households in different countries, are summarised in Table 26.

As the overview shows, there are large differences between countries in whether households own a clothes dryer. In addition, studies show that the use rate varies as well. Even though about half of Japanese households own either a laundry dryer or a washer with a dryer, 92% of the owners of these machines state that they never use machine drying (Ishii, 2011, Nakamura, 2010). About 90% of respondents had dried laundry indoors, usually when it is rainy outside. Yamaguchi et al. (2011) estimated that dryers would be used during 99 days of a year, as that is the amount of rainy days in Tokyo and Japanese wash laundry almost daily.

In the USA, registration data from 1998 showed that about 70% of washing loads were dried at least partially in a dryer and 20% on a clothesline (Tomlinson & Rizy, 1998). These results are from a small rural city (Bern), so the results may not be valid for the whole of the USA. More recent survey data showed that about 65% of households use a dryer every time clothes are washed, 12% for some but not all loads, 2% infrequently and 21% did not use a clothes dryer at home (Statista, 2009b). These results fit well with the reported dryer ownership rate in the US.

Similarly, about half of the German respondents reported having a laundry dryer (19.8% venter dryer, 19.8 % condenser, and 9.6% a washer-dryer) but they vary their laundry drying practices based on weather conditions. During summer in good weather, 90% of respondents chose energy saving alternatives for laundry drying (drying outdoors, or in unheated rooms), but the amount decreased to 35% during winter or bad weather conditions (Braun and Stamminger, 2011).

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[14] Many everyday appliences such as washing machines and laundry dryers carry energy labels. In Europe, the energy efficiency of the appliance is rated in terms of a set of energy efficiency classes from A to G on the label, A being the most energy efficient, G the least efficient.

The Swedish study shows how dryers are used differently depending on living conditions (Zimmermann, 2009). The ownership rate is higher in households living in houses (59%) than in apartments (15%), but they use them less often than household apartments, indicating a higher rate of drying outdoors.

A recent survey showed that over 80% of American consumers use a tumble dryer to dry their t-shirts and jeans, while the share in Germany and Sweden was about 20%, and even less in Poland, 12% (Gwozdz et al. 2017).

Table 26 Share of households that own clothes dryer in different countries.

Country	Share of households that own a clothes dryer	Year and source
Australia	55%	2014 (Australian Bureau of Statistics, 2014).
Czech Republic	3%	2011 Table 3 (Schmitz and Stamminger, 2014)
Czech Republic	8%	2007, Figure 3.11 (Presutto et al., 2007)
Europe	32%	Table 4.2 Almeida et al. 2009
Finland	24%	2007, Figure 3.11 (Presutto et al., 2007)
Finland	27%	2011 Table 3 (Schmitz and Stamminger, 2014)
France	51%	2007, Figure 3.11 (Presutto et al., 2007)
France	38%	2011 Table 3 (Schmitz and Stamminger, 2014)
Germany	55%	2007, Figure 3.11 (Presutto et al., 2007)
Germany	49.2%	(Braun and Stamminger, 2011)
Germany	47%	2011 Table 3 (Schmitz and Stamminger, 2014)
Greece	5%	2002 (Arild et al., 2003)
Hungary	17%	2007, Figure 3.11 (Presutto et al., 2007)
Hungary	8%	2011 Table 3 (Schmitz and Stamminger, 2014)
Italy	8%	2011 Table 3 (Schmitz and Stamminger, 2014)
Italy	9%	2007, Figure 3.11 (Presutto et al., 2007)
Japan	50%	(Nakamura, 2010)
The Netherlands	71%	2002 (Arild et al., 2003)
The Netherlands	60%	1997 (Uitdenbogerd et al., 1998)
Norway	47%	2002 (Arild et al., 2003)
Norway	47%	2012 (SSB, 2012)
Poland	34%	2007, Figure 3.11 (Presutto et al., 2007)
Poland	16%	2011 Table 3 (Schmitz and Stamminger, 2014)
Spain	25%	2002 (Arild et al., 2003)
Spain	33%	2011 Table 3 (Schmitz and Stamminger, 2014)
Spain	33%	2007, Figure 3.11 (Presutto et al., 2007)
Sweden	52%	2011 Table 3 (Schmitz and Stamminger, 2014)
Sweden	56%	2007, Figure 3.11 (Presutto et al., 2007)
UK	56%	2014 (Statista, 2015b)
UK	52%	2011 Table 3 (Schmitz and Stamminger, 2014)
UK	62%	2011 (Hulme et al., 2013)
UK	69%	2007, Figure 3.11 (Presutto et al., 2007)
UK	46%	Gracey & Moon, 2012
USA	79%	2005 (Golden et al., 2010)
USA	83.4%	2011 (Siebens, 2013)

A Swedish survey showed that items that were most likely to be either tumble dried or drier in a drying cabinet/room were socks, underwear, and nightwear, while items least likely to be dried with extra energy were dresses, blouses, shirts, jackets, thick jumpers and skirts (Granello et al. 2015).

Schmitz and Stamminger (2014) have made estimations based on a consumer survey with 2290 respondents from 10 European countries. They asked how consumers dried their laundry during summer and winter and the average spin-drying speed at the end of the washing process. The results showed differences between the seasons as well as countries. During summer, the main part of laundry was line dried outdoors (55%) while this portion fell to 18% during winter. During winter, it is most common to dry laundry indoors in heated rooms (51%) in Europe (Figure 18). These results are used further in estimating the energy consumption for drying, presented in section 3.1.11.

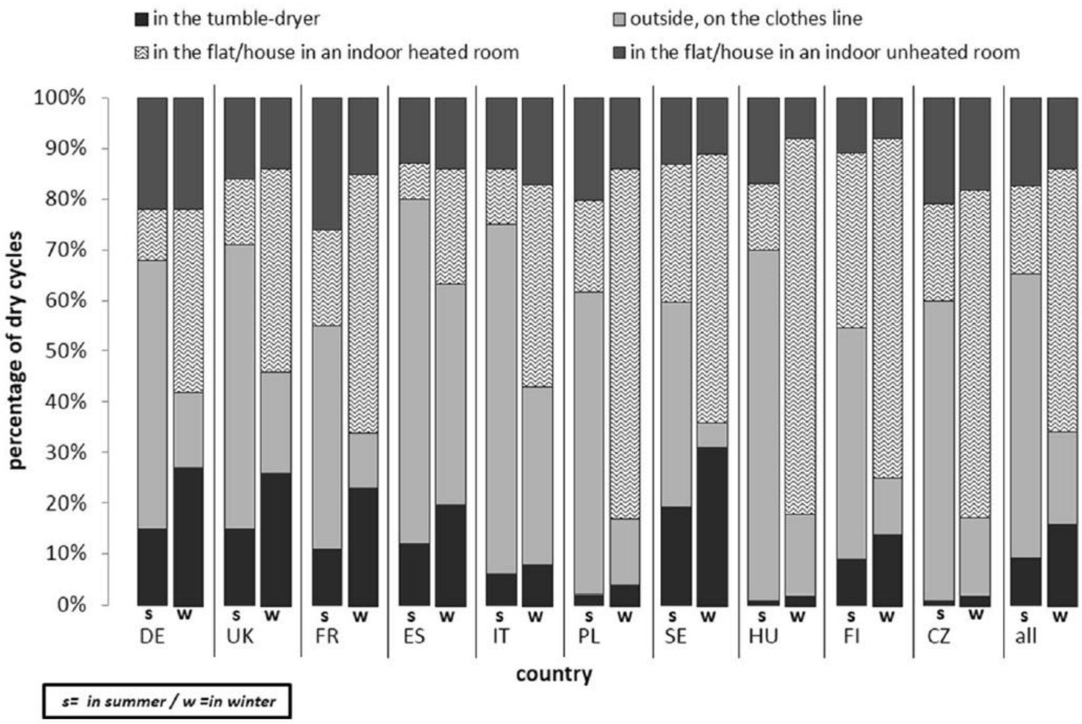

Figure 18 Methods of drying clothes in winter and summer per country in 2011 (Figure 15 from Schmitz & Stamminger, 2014)

Table 27 Usage of tumble drier in winter and summer in ten European countries (table 3 from (Schmitz and Stamminger, 2014)

	DE	UK	FR	ES	IT	PL	SE	HU	FI	CZ
% of drying cycles of all households per country using a tumble dryer (in winter)	27	26	23	20	8	4	31	2	14	2
% of drying cycles of all households per country using a tumble dryer (in summer)	15	15	11	12	6	2	19	1	9	1

On average, 81% of washing cycles were followed by drying cycle in the UK (Zimmermann et al 2012).

In the UK, there is no direct relationship between access to an outdoor area suitable for drying clothes and ownership rate of a tumble drier, even though people with no garden are more likely to own a washer dryer than average (Gracey and Moon, 2012). The alternative drying methods available to consumer in the UK include having an outside clothes line which is available to over two-thirds of adults, a clothes rack (two thirds of consumers) and having an airing cupboard (nearly a half of consumers) (Gracey & Moon, 2012).

Table 28 shows that there are variations in the use of tumble drying during winter and summer. 44% of dryer owners report that they never use it for drying during summer. Surprisingly, 9% report that they never use it during winter either. 6% of respondents use a tumble dryer for drying all of their laundry.

Table 28 Percentage of UK respondents that own a clothes dryer who tumble dry laundry in different seasons (percentage of adults that have at least some responsibility for washing clothes) (part of Figure 25 from Gracey & Moon, 2012)

	Always	More often than not	About half	Less than half	Never	Don't know or N/A
Dry clothes in a tumble dryer in the winter	21%	26%	16%	26%	9%	2%
Dry clothes in a tumble dryer in the summer	6%	7%	9%	32%	44%	3%

3.1.10 Ironing

Clothes can be ironed in order to remove wrinkles either after laundering or during use. In that way, ironing can either increase energy consumption, or decrease water and energy use if it is done instead of laundering to freshen clothing. Ironing practices vary greatly between countries, but also between different types of garments. About 70.6% of the German population own a steam iron and 22.3% a flat iron (Braun and Stamminger, 2011). The respondents who iron, said they used on average two hours per week on ironing. The question of time use was stated openly, and 17% of the respondents did not specify any time, while 4.9% said they ironed for 0 hours per week. Elderly respondents were more likely to give a positive response on ironing. It seems that ironing is even less common in Norway, where about 27% of the population iron regularly. Similarly to the situation in Germany, the time used on ironing varies greatly between respondents of different ages. A larger portion of older respondents iron, and they also use more time on ironing. On average, 16% of women and 30% of men do not iron at all and 28% iron less frequently than monthly (Figure 19). Only 12% iron more than an hour per week. A survey of young Swedes showed than over half of them (56%) ironed their clothes at least sometimes (Gwozdz et al., 2013).

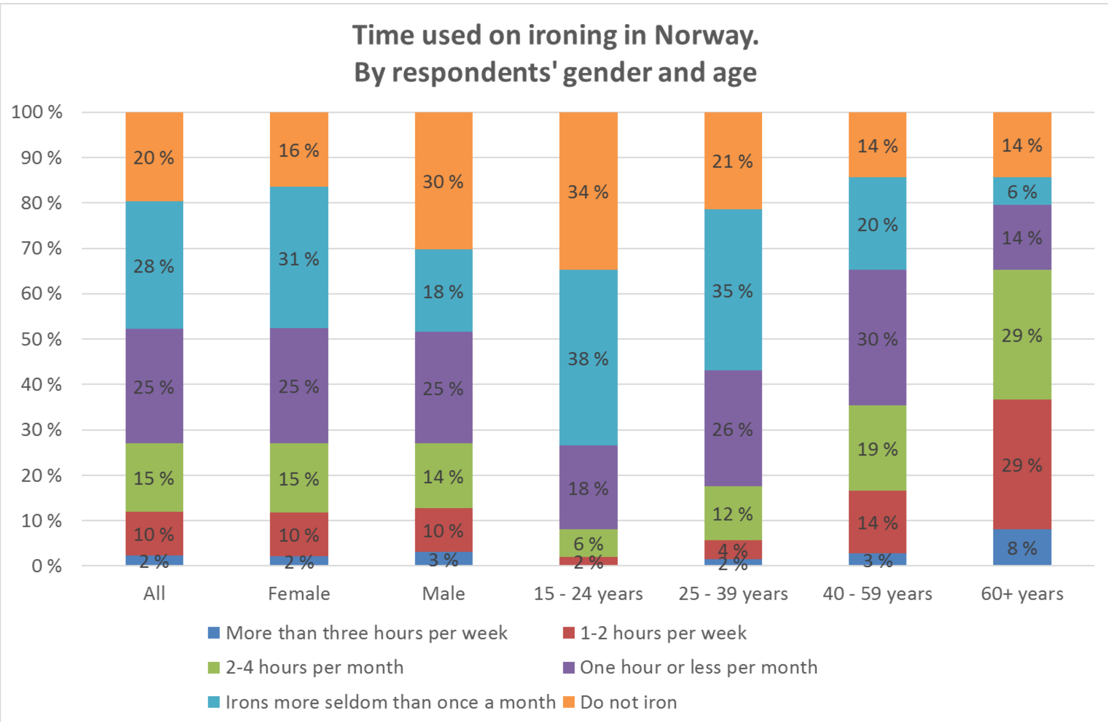

Figure 19 Time used on ironing in Norway by respondents' age and gender (Reanalysed data from textile waste survey, N=545) (Laitala, 2014a)

The UK Office of National Statistics assumes 10% of all clothes washed are ironed. The statistics showed that consumers' opinion on how important ironing is varied. Most UK respondents think it is important that clothes are ironed (30% very important and 33% important), while the remaining 36% do not think it is important (Gracey and Moon, 2012). In Finland, women spend on average 30 minutes per week on ironing, while men use less than three minutes (Aalto, 2003).

A Swedish survey reported on which types of garments were more likely to be ironed than others. Garments more likely to be ironed included skirts, shirts, blouses, dresses and trousers (Granello et al., 2015). Unfortunately the studies did not report in detail on which types of garments are ironed in practice, but there are likely to be differences. For example, suit pants or linen clothing is likely to be ironed, while knitted materials are less likely to be ironed than most woven materials. We did not find information about consumers' use of steam pressing, but assume that it is likely to be used for similar garments as ironing, however is less commonly owned. Therefore we assume it only has a minor contribution to the use phase.

3.1.11 Energy consumption

Here, studies that report energy consumption of washing, drying, ironing and dry-cleaning are presented.

Energy consumption in washing

Washing machines are required to meet changing regulations, and this has led to improvements in energy efficiency and reductions in water use. We have already shown the differences due to the type of washing machine, for example when comparing old top loading machines from the US with new front loading machines. Therefore, the age and type of washing machine is important when estimating the energy consumption. The average age of European washing machines in use is about 5.3 years (Schmitz et al., 2016), and the average lifetime is reported to be over 10 years (Presutto et al., 2007), but even 40 year old machines are still in use (Schmitz et al., 2016).

A test of 50 European washing machines showed that they used on average 0.78 kWh per washing cycle, when tested according to the EU energy labelling standard requirements. This value is the average of seven test rounds, where three are tested with a 60°C cotton program with a full load, two with a 60°C cotton half load, and two with a 40°C cotton half load. When taking into account the maximum load of the different machines, the average consumption is 0.123 kwh/kg load. The measurements also show that reducing the load from full to half for a 60°C cotton program reduces energy consumption by 17%. Reducing the temperature from 60°C to 40°C with half wash load reduces the energy consumption by 23% (Stamminger and Schmitz, 2016). These machines were bought in the time period 2012-2014, and, therefore, this test is most likely offering the most up-to-date data for the European market. Unfortunately, the test did not include a wool wash program. The average figure from the test is also likely to differ from the average real consumption in Europe, because the washing programs used vary more and the average temperature is lower than the 54.3°C in the test. However, the result is only slightly higher than earlier testing, where European energy consumption of program selection was measured to be 0.72 kWh/cycle (Presutto et al., 2007, p. 316).

Berkholz et al. (2007) conducted a metering study in 100 German households. They measured the total electricity consumption for laundry washing in 100 households for one month and found that the average consumption per cycle was 0.89 kWh (average load, 5 kg).

In general, the front loading h-axis drum machines used in Europe have an internal water heater, while most of the top loading machines use pre-heated water for warm washing. These washers consume energy through two main mechanisms: first, energy is needed to produce hot water used by the washer, and secondly, the washer itself uses energy to operate the motor and controls (Tomlinson & Rizy, 1998). Not all studies mention whether both energy consuming stages are included in countries where use of externally heated water is common.

Table 29 Average energy consumption for washing in kWh per average wash cycle, per kg laundry and per household per year (Table 7 from Gooijer & Stamminger (2016) included two different figures for some of the countires)

Country/region	Electricity per wash cycle [kWh]	Electricity per kg laundry [kWh/kg]	Electricity per household per year [kWh]	Comments and source
Australia	0.34		88.4	Table 2 Pakula & Stamminger (2010)
Austria	0.64	0.17		Table 7 (Gooijer and Stamminger, 2016)
Austria	0.87		142.7	Table 2 Pakula & Stamminger (2010)
Belgium	0.62	0.17		Table 7 (Gooijer and Stamminger, 2016)
Belgium	0.92		151.8	Table 2 Pakula & Stamminger (2010)
Bulgaria	0.63	0.17		Table 7 (Gooijer and Stamminger, 2016)
Bulgaria	0.97		160.1	Table 2 Pakula & Stamminger (2010)
Canada	0.43		124.3	Table 2 Pakula & Stamminger (2010)
China	0.10		10.0	Table 2 (Pakula and Stamminger, 2010)
Croatia	0.97		171.7	Table 2 Pakula & Stamminger (2010)
Cyprus	1.35		239.0	Table 2 Pakula & Stamminger (2010)
Czech Republic	0.97		160.1	Table 2 Pakula & Stamminger (2010)
Czech Republic	0.67	0.18		Table 7 (Gooijer and Stamminger, 2016)
Czech Republic	0.71	0.19		Table 7 (Gooijer and Stamminger, 2016)
Czech Re-public			121.9	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Denmark	0.64	0.17		Table 7 (Gooijer and Stamminger, 2016)
Denmark	0.95		156.8	Table 2 Pakula & Stamminger (2010)
Estonia	0.97		160.1	Table 2 Pakula & Stamminger (2010)
Europe			184 (owners) 174 (all house-holds)	Metering study 2008 Table 4.2 Almeida et al., 2009
Finland	0.69	0.19		Table 7 (Gooijer and Stamminger, 2016)
Finland	0.72	0.20		Table 7 (Gooijer and Stamminger, 2016)
Finland			138.6	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Finland	0.89		146.9	Table 2 Pakula & Stamminger (2010)
France	0.94		155.1	Table 2 (Pakula and Stamminger, 2010)
France			106.2	2011 Fig. 17 (Schmitz and Stamminger, 2014)
France	0.57	0.15		Table 7 (Gooijer and Stamminger, 2016)
France	0.62	0.17		Table 2&7 (Gooijer and Stamminger, 2016)
France	0.70		169	Zimmermann et al (2012)
Germany	0.89	0.178	125.46	Metering study of 100 households Berkholz et al. (2007)
Germany	0.63	0.17		Table 7 (Gooijer and Stamminger, 2016)
Germany	0.69	0.19		Table 7 (Gooijer and Stamminger, 2016)
Germany			123.6	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Germany	0.87		142.7	Table 2 Pakula & Stamminger (2010)
Greece	1.35		239.0	Table 2 Pakula & Stamminger (2010)
Greece	0.61	0.17		Table 7 (Gooijer and Stamminger, 2016)
Hungary	0.62	0.17		Table 7 (Gooijer and Stamminger, 2016)
Hungary	0.71	0.19		Table 7 (Gooijer and Stamminger, 2016)
Hungary			123.9	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Hungary	0.97		160.1	Table 2 Pakula & Stamminger (2010)
Iceland	1.03		170.0	Table 2 Pakula & Stamminger (2010)
Ireland	1.13		200.0	Table 2 (Pakula and Stamminger, 2010)
Ireland	0.57	0.15		Table 7 (Gooijer and Stamminger, 2016)

Country/region	Electricity per wash cycle [kWh]	Electricity per kg laundry [kWh/kg]	Electricity per household per year [kWh]	Comments and source
Italy	0.59	0.16		Table 7 (Gooijer and Stamminger, 2016)
Italy	0.63	0.17		Table 7 (Gooijer and Stamminger, 2016)
Italy			127.4	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Italy	1.05		173.3	Table 2 Pakula & Stamminger (2010)
Japan	0.10	0.03	52.0	Table 2 (Pakula and Stamminger, 2010) (3.3 kg load)
Latvia	0.97		171.7	Table 2 Pakula & Stamminger (2010)
Lithuania	0.97		160.1	Table 2 Pakula & Stamminger (2010)
Luxembourg	0.93		153.5	Table 2 Pakula & Stamminger (2010)
Malta	0.97		171.7	Table 2 Pakula & Stamminger (2010)
Netherlands	0.60	0.16		Table 7 Gooijer & Stamminger (2016)
Netherlands	0.88		145.2	Table 2 Pakula & Stamminger (2010)
Norway	0.69	0.19		Table 7 Gooijer & Stamminger (2016)
Norway	1.04		171.6	Table 2 (Pakula and Stamminger, 2010)
Poland	0.67	0.18		Table 7 Gooijer & Stamminger (2016)
Poland	0.74	0.20		Table 7 (Gooijer and Stamminger, 2016)
Poland			146.7	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Poland	0.97		171.7	Table 2 (Pakula and Stamminger, 2010)
Portugal	0.50	0.13		Table 7 Gooijer & Stamminger (2016)
Portugal	0.89		157.5	Table 2 Pakula & Stamminger (2010)
Romania	0.97		171.7	Table 2 Pakula & Stamminger (2010)
Romania	0.64	0.17		Table 7 Gooijer & Stamminger (2016)
Slovakia	0.97		171.7	Table 2 Pakula & Stamminger (2010)
Slovakia	0.66	0.18		Table 7 Gooijer & Stamminger (2016)
Slovenia	0.97		171.7	Table 2 Pakula & Stamminger (2010)
South Korea	0.37		77.0	Table 2 Pakula & Stamminger (2010)
Spain	0.59		97.4	Table 2 Pakula & Stamminger (2010)
Spain	0.44	0.12		Table 7 Gooijer & Stamminger (2016)
Spain	0.44	0.12		Table 7 Gooijer & Stamminger (2016)
Spain			74.1	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Sweden	0.95		133.0	Table 2 Pakula & Stamminger (2010)
Sweden	0.70	0.19		Table 7 Gooijer & Stamminger (2016)
Sweden	0.74	0.20		Table 7 Gooijer & Stamminger (2016)
Sweden			126.4	2011 Fig. 17 (Schmitz and Stamminger, 2014)
Sweden	0.84 1.09		209 163	Measured 2005-2008 Zimmermann 2009. The fisrt figure is for houses, the second for apartments
Switzerland	0.64	0.17		Table 7 Gooijer & Stamminger (2016)
Switzerland	0.99		163.4	Table 2 Pakula & Stamminger (2010)
Turkey	1.35		284.9	Table 2 Pakula & Stamminger (2010)
Turkey	0.63	0.17		Table 7 Gooijer & Stamminger (2016)
UK	0.56	0.15		Table 7 Gooijer & Stamminger (2016)
UK	0.59	0.17		Table 7 Gooijer & Stamminger (2016)
UK	0.58		166	Table 3 Zimmermann et al (2012)
UK			116.7	2011 Fig. 17 (Schmitz and Stamminger, 2014)
UK	1.14		188.1	Table 2 Pakula & Stamminger (2010)
USA	0.43		124.3	Table 2 Pakula & Stamminger (2010)
USA	2.7			(Tsumadori, 2005) as cited in table 10 Gooijer &stamminger 2016
USA	Top load: 2.26 (washer 0.23) Front load: 0.96 (washer 0.11)	Top: 0.75 Front: 0.30	Top load 999 Front load 406.6	Metering study that separates between external water heater and the washing machine energy consumption. 442 loads per year Tomlinson & Rizy, 1998

A metering study in Bern, USA, showed that a front loading h-axis washers used 57.6% less energy than the standard top-loading v-axis models (Tomlinzon & Rizy, 1998). More detailed results of the energy consumption of the different stages of laundry in USA are included in Table 30 (Golden et al., 2010).

Table 30 Comparison of findings for the electricity consumed in each step of the residential laundry process (per load). (Table 4 from Golden et al., 2010)

Literature	Type of washer	Water supply, conveyance, treatment and distribution [kWh]	Water heating [kWh]	Clothes washing [kWh]	Waste water treatment and dis-charge [kWh]	Clothes drying [kWh]	Total [kWh]
Experimental re-sults Golden et al. 2010	v-axis	0.49	1.03	0.21	0.09	4.49	6.32
	h-axis	0.19	0.30	0.10	0.04	4.17	4.80
(Tomlinson and Rizy, 1998)	v-axis	-	2.03	0.22	-	-	2.25
	h-axis	-	0.85	0.10	-	-	0.95
(Sabaliunas et al., 2006)	v-axis	-	1.24	0.26	-	-	1.50
	h-axis	-	0.46	0.20	-	-	0.66
(EIA, 2001) (RECS)	v-axis	-	-	0.33	-	4.10	4.43
	h-axis	0.003*	0.10	0.19	-	3.00	3.29

Kim et al. (2015) have compared the energy efficiency of drum and impeller type machines from different countries (Table 31). The study is based on existing literature, but in addition, they performed laboratory trials to find optimal washing conditions.

Table 31 Electricity consumption of different types of washing machines (Kim et al., 2015) (estimated values based on a diagrams in the article, exact numbers not available.)

Area	Europe			China					USA	South Korea	
Machine type	Drum	Drum	Drum	Drum	Drum	Drum	Impeller	Impeller	Drum	Drum	Impeller
Maximum ca-pacity kg	7	8	9.75	6.1	7 kg	8.1	6.21	7.22	7.95 kg	12.5	14.25
Electricity con-sumption per cycle kWh/cycle	0.8	0.85	1.05	0.55	0.6	0.7	0.05	0.08	0.35	0.4	0.1
Electricity con-sumption per cycle per kg ca-pacity kWh/cy-cle/kg	0.117	0.105	0.105	0.09	0.085	0.085	0.007	0.007	0.04	0.03	0.005
Electricity con-sumption per year kWh/year	160	160	205	50	55	65	5	5	90	80	20

Experiments on the relationship between laundry load and energy, and water consumption, have shown that even when the washing machine has a fuzzy logic control that reduces the amount of water (and hence energy) when the machine is less than completely filled, it was still more resource-demanding per kg of clothing to wash with an unfilled machine. When the machine was only half filled, it still used 94% of the energy and 74% of the water compared with a full machine. Washing only one garment (about 0.5 kg) at a time is even more resource-consuming per kg as the machine still used 69% of the energy and 50% of water of a full machine (Laitala, Boks & Klepp, 2011).

Energy consumption of different wash programmes

We have found three European studies that compared the energy consumption of different washing programmes in the washing machine and included a wool program. Table 32 presents data based on a metering study in 100 German households (Berkholz et al., 2007).

Table 32 Energy consumption as a function of washing programmes based on data from Germany (Berkholz et al., 2007; as cited in Table 3 in Gooijer & Stamminger, 2016).

Type	Temperature [°C]	Load user [kg /cycle]	Energy use per load [kWh /cycle]	Energy use per kg laundry [kWh /kg]
Cotton	49.7	3.18	1.02	0.32
Mix	42.2	2.64	0.66	0.25
Easy care	39.3	2.8	0.67	0.24
Delicate	36.5	2.36	0.76	0.32
Wool	25	2.46	0.56	0.23

Table 33 indicates average EU values of the SAVE II study based on several sources such as consumer organisations, test institutes, research organisations, and AISE (Uitdenbogerd, 2001).

Table 33 Share of wash programmes in total EU energy consumption for washing (SAVE II, 2001) (Table 1 from Uitdenbogerd, 2001)

Wash programme	Frequency EU 1996 (a)	Installed in 1996 kWh/cycle (b)	Share in total energy requirement (a*b) in %
Cotton 95 °C (>61 °C)	7.3%	2.32	17.8%
Cotton 60 °C (41 -> 60 °C)	24.6%	1.45	37.6%
Cotton 40 °C	26.9%	0.76	21.5%
Cotton 30 °C	20.0%	0.44	9.3%
Subtotal cotton	78.8%		86.1%
Easy care 60 °C	2.7%	1.45	4.2%
Easy care 50 °C	2.5%	0.76	2.0%
Easy care 40 °C	10.8%	0.44	5.0%
Subtotal easy care	16.1%		11.2%
Other 40 °C	0.3%	0.76	0.2%
Other 30 °C	1.1%	0.44	0.5%
Wool 30 °C	4.2%	0.44	1.9%
Subtotal wool & other	5.6%		2.7%
TOTAL	100.0%		100.0%

Table 34 presents energy consumption data based on randomly selected user manuals of 31 different washing machines from 14 producers available on the Norwegian market (Laitala & Vereide, 2010). The washing machine capacities varied between 5 and 7 kg. All were horizontal drum type, but 18 were front loading and 13 top loading machines. Table 34 lists the energy use of three washing programmes; cotton, synthetics and wool. The cotton programme selection includes all cotton programmes that allow full washing load, such as eco cotton, coloureds and whites. The different temperatures that are available for each programme are given separately. The "N" column indicates how many information inputs for the washing programmes were available for the calculation. A small N value indicates that only some programmes had information of the consumption values, and therefore these average values are less reliable than the values that have a large number of programmes as basis for the calculation.

An average cotton washing programme uses more energy per washing than the synthetics or wool programme. This is mainly caused by the higher washing temperature and larger wash load capacity. However, if the programmes are compared at the same washing temperature, the difference in energy consumption is lower. The cotton washing load capacity is double that for the synthetics programme and about three times that for the wool programme and, therefore, the difference in energy consumption measured as kWh/kg laundry is of interest. The results show that for the same temperature, the wool programme can use more energy per kg laundry than cotton and synthetic programmes. However, when interpreting the results, one should take into account that woollen garments are in general washed at lower temperatures, and are usually used longer between washes, thus reducing the energy and water use calculated per day of use. The German study showed that people were likely to overload when washing wool and underload when washing cotton.

Table 34 Energy use values of different washing programmes and temperatures (part of Table 2 from Laitala & Vereide, 2010)

Programme and temperature	Average load [kg]	Energy [kWh/cycle]			Energy kWh/kg laundry with maximum load
		Average	Variation	N	
Cotton	5.9	1.20	0.31-2.30	87	0.202
30 °C		0.48	0.31-0.55	4	0.076
40 °C		0.68	0.50-1.40	20	0.113
60 °C		1.09	0.73-2.30	40	0.183
90-95 °C		1.95	1.50-2.20	23	0.329
Synthetics/ easy iron[15]	2.6	0.57	0.10-1.00	31	0.218
Cold		NG	NG	0	NG
30 °C		0.35	0.35-0.35	1	0.175
40 °C		0.46	0.30-0.55	18	0.178
60 °C		0.76	0.10-1.00	12	0.282
Wool[16]	1.6	0.30	0.10-0.50	24	0.186
Cold		0.10	0.10-0.10	3	0.05
20 °C		NG	NG	0	NG
30 °C		0.22	0.17-0.30	11	0.114
40 °C		0.44	0.32-0.50	10	0.366

Some of the manuals had information on energy consumption for the same washing programme with different temperatures. Energy reduction for a 10°C temperature decrease was calculated and the results are given in Table 35. Lowering the washing temperature of the cotton programme by 10 °C led to a reduction on average of 0.23 kWh of energy per load. However, this number varied greatly, from 0.12 to 0.37 kWh, depending on the machine model. The effect was less on other programmes that have smaller washing loads. For the synthetics programme, the 10 °C reduction led to a 0.18 kWh reduction and for wool wash to a 0.09 kWh reduction.

Table 35 Energy saving for a 10 °C temperature reduction (Laitala and Vereide, 2010)

Washing programme	Average	Minimum	Maximum
Cotton programme	0.230 kWh (18%)	0.120 kWh	0.367 kWh
Synthetics programme	0.177 kWh (21 %)	0.150 kWh	0.205 kWh
Delicate, wool or hand wash	0.089 kWh (30 %)[17]	0.050 kWh	0.200 kWh

The average energy consumption values for wool programme vary slightly between the three studies, from 0.30 to 0.56 kWh per cycle and 0.186 to 0.23 kWh/kg laundry.

[15] Synthetic: No information available for cold wash and only one program for washing at 30°C
[16] Wool: No information was available for washing at 20 °C
[17] Includes calculations of reductions from 30 °C to cold wash, where it is assumed that cold wash is 12°C.

Energy consumption in drying

Energy consumption for drying laundry is a less studied topic than energy consumption for washing, but some sources of data were available. Presutto et al (2007) studied the energy consumption of tumble drying cotton laundry that had been spun dried at different speeds and therefore had various amounts of residual moisture. Spin-drying at the end of the washing cycle removes water from the laundered garments. Efficient spin-drying reduces the energy needed for drying the laundry afterwards. Table 36 shows the effect of changing the spinning speed and the resulting moisture content in cotton laundry.

Table 36 Spin drying speed and the resulting average moisture content in laundry and the energy required for dying it in tumble dyer (Presutto et al., 2009and table 5 from Schmitz & Stamminger, 2014)

Spin drying speed [rpm]	Residual moisture content in cotton [%]	Energy needed for drying the laundry in tumble dryer with "cotton dry" program [kwh/kg]
200	154	1.754
400	118	1.346
600	92	1.046
800	72	0.800
1000	62	0.700
1200	56	0.640
1400	52	0.600
1600	49	0.570

It is estimated that the nominal energy factor for a clothes dryer in the US is 1.1 kWh (Yun et al., 2017). This is the amount of energy needed to remove 1 kg of moisture from wet laundry during drying. However, the actual energy consumption is likely to be higher due to uneven drying that requires partial over drying. The authors measured the actual energy consumption for drying to be 2.649 kWh when the nominal calculated energy consumption under the same conditions would have been 2.208 kWh (cotton load, high spin speed, medium drying temperature, normal drying level). Spin drying tests for cotton, polyester and blend-materials showed that the residual moisture content varied greatly based on the material (Table 37) (Yun et al., 2017). The tests were performed with two different spinning speeds, where the high speed is often the default for laundry programmes and, therefore, is the most commonly used by consumers. Unfortunately they do not give the actual speed in revolutions per minute.

Table 37 Remaining water content after spinning and energy consumption calculated with nominal energy factor to bone-dry fabrics (Figure 1 from Yun et al., 2017)

	Remaining water content [%]		Electric energy needed to dry fabrics [kWh]	
	High spin speed	Maximum spin speed	High spin speed	Maximum Spin speed
Cotton, weight 102 g/m²	66.9	61.7	2.208	2.035
Polyester/cotton 50/50, weight 104 g/m²	43.6	39.3	1.440	1.297
Polyester/cotton 65/35, weight 82 g/m²	35.0	30.8	1.156	1.017
Polyester, weight 106 g/m²	8.6	7.0	0.282	0.233
Polyester/spandex 92/8, quick dry, weight 203 g/m²	17.9	15.5	0.590	0.510

One study documents residual moisture after spin-drying wool (Laitala & Eilertsen, 2009). It showed a significant reduction in residual moisture content by increased spin speed (Table 38). In addition to spin drying speed in revolutions per minute (rpm), the residual moisture content is dependent on the performance efficiency of the specific washing machine, as well as the materials in the laundry. In general, natural fibres have higher moisture uptake than synthetic fibres.

Table 38 Residual moisture content in wool samples after wash and spin drying with different speeds (Table 6 from Laitala and Eilertsen, 2009)

Spinning speed [rpm]	Residual moisture
400	47.0%
900	29.2%
1400	24%

The average spin drying speed at the end of the washing cycles used in Europe was calculated to be 941 rpm, varying between 743 rpm in Italy to 1118 rpm in Sweden (Schmitz and Stamminger, 2014).

The wool wash programmes often have a lower spin drying speed than the other washing programmes, but studies have shown that wool tolerates spin drying at high speed as long as there is no mechanical action that could cause the fibres to become entangled, felt and shrink. Therefore, the acceleration and slowing-down phases of the spin drying programme have to be rapid, so that the centrifugal forces will keep the garments trapped in place against the walls of the drum.

A metering study in Bern, USA, showed that the moisture content of a damp load from a front loading machine was on average 7% lower than the moisture content of laundry from top loading machines. This saves on the energy needed for drying clothes (Tomlinzon & Rizy, 1998).

Schmitz and Stamminger (2014) have made estimations of the energy consumption for drying laundry based on a consumer survey with 2290 respondents from 10 European countries. They asked how consumers dried their laundry during summer and winter and the average spin drying speed at the end of the washing process. Based on these figures, they estimated the electricity needed for using tumble driers as well as the heat energy required for evaporating the water from wet laundry in indoor heated rooms to be 2260 kJ/kg water, equal to 0.628 kWh/kg (Table 39). The amount of water in the laundry was estimated based on measurements of residual moisture in the cotton laundry that was spun dried at different speeds (Table 36), combined with data on the spinning speeds the survey respondents reported they used. However, their estimations for energy needed for line drying clothes indoors seem rather high, especially during summer as heating is usually not required. The energy required for evaporation of water was multiplied by two to include heat loss due to opening windows for reducing humidity from the damp air.

Table 39 Average annual energy consumption per method of drying and season (n=2,290 households) (Table 6 from Schmitz and Stamminger, 2014)

Type of energy consumption per household per year	Average energy consumption per year [kWh/year]
Electric drying—in summer	24.8
Electric drying—in winter	44.6
Thermal drying—in summer	49.9
Thermal drying—in winter	156.3
Total drying (elec. + therm. winter and summer)	275.6

Table 40 Average energy consumption for drying annually and per kg laundry including thermal and electric drying. (Table 8 Gooijer & Stamminger 2016 and Figure 19 Schmitz & Stamminger 2014).

Country	Energy per household per year [kWh]	Energy per kg laundry [kWh/kg]
France	283.7	0.42
Germany	227.2	0.32
Italy	227.3	0.29
Spain	207.8	0.31
Czech republic	243.5	0.36
Hungary	273.9	0.40
Poland	324.1	0.41
Finland	315.9	0.49
Sweden	293.5	0.44
UK	296.7	0.37

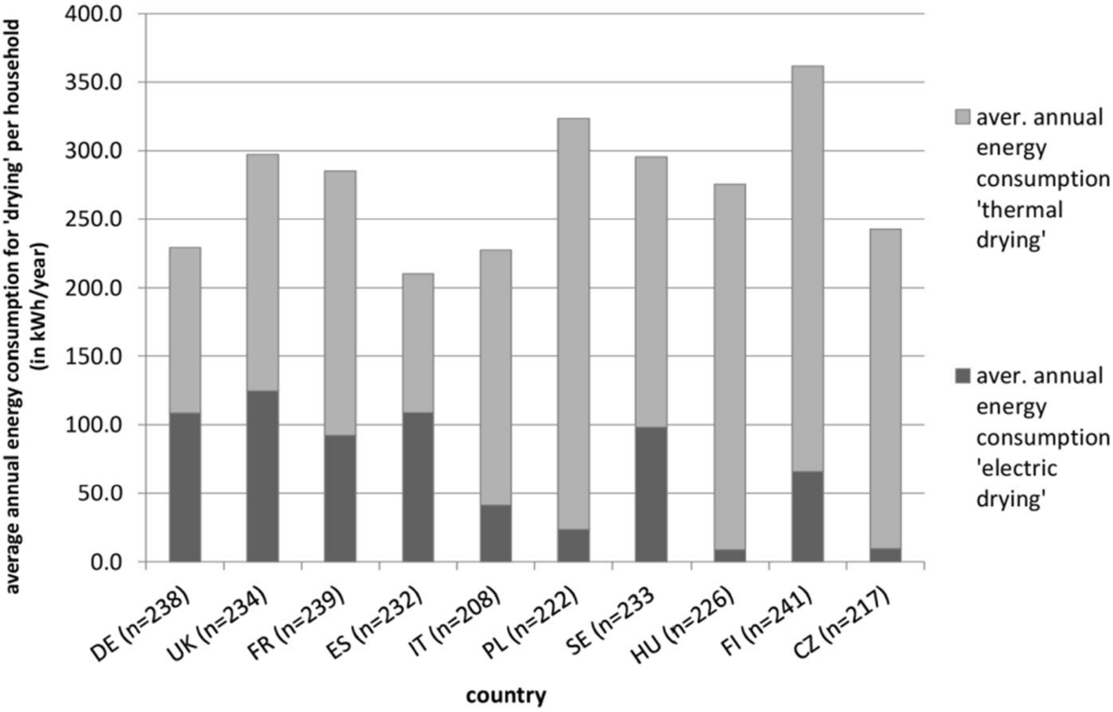

Figure 20 Average annual energy consumption per method of drying and country in 2011 (Figure 19 from (Schmitz and Stamminger, 2014) (Electric drying means use of clothes dryer, while thermal drying means drying indoors in heated room)

Another German study has compared the environmental effects of various forms of drying laundry (Rüdenauer et al., 2008). Different clothes dryers are compared in Table 41, and drying indoors in heated rooms in Table 42.

Table 41 Specific energy consumption of the clothes dryers under consideration in the defined usage modes under standard conditions kwh/kg cited (Table 7 from BSH, 2008)

	Dryer program "Cotton cupboard dry", full load [kwh/kg]	Dryer program "Cotton cupboard dry", half load [kwh/kg]	Dryer program "Delicates", half load [kwh/kg]
Conventional vented exhaust air dryer (energy efficiency class C)	0.59	0.73	0.37
Conventional condensation dryer (energy efficiency class B)	0.6	0.68	0.4
Heat pump dryer alt. 1 (competing company)	0.34	0.41	0.23
Heat pump dryer alt. 2 (from BSH)	0.28	0.33	0.19

Table 42 Additional heating required for the line drying average laundry on four different days during the heating period (Based on table 23 from Rüdenauer et al. 2008)

	Best case [kWh/kg]	Worst case [kWh/kg]
Winter day	0,45	1,80
Transition day, dry	0,60	0,68
Transition day, moist	0,67	1,08
Transitional day, very moist	0,95	0,75

Golden et al. (2010) measured energy consumption in drying after laundry is washed in different washing machines, and hence with different moisture contents (Table 43).

Table 43 Comparison of electricity consumed in drying after washed with different machines (per load). (Part of Table 4 from Golden et al., 2010)

Literature	Type of washer	Clothes drying [kWh]
Experimental results Golden et al. 2010	v-axis	4.49
	h-axis	4.17
(EIA, 2001) (RECS)	v-axis	4.10
	h-axis	3.00

Energy consumption in dry-cleaning

Dry-cleaning also consumes energy (Table 44). Processes with PERC use 0.586 kWh/kg textiles. When comparing this to regular laundering with the average values in Europe which requires about 0.18 kWh/kg, we see that dry-cleaning requires more than three times the amount of energy. Professional wet-cleaning is more energy efficient.

Table 44 Estimated electricity usage of dry-cleaning and wet-cleaning processes/solvents (Fong et al., 2006, as cited in table 6 in Troynikov et al., 2016)

Cleaning process/solvent	Electricity usage (KWh/100 kg) of textile materials
GreenEarth®	119.5
Hydrocarbon	78.3
LCO_2	68.1
PERC	58.6
Wet-cleaning	20.5

Energy consumption for ironing

A report by WRAP (Thomas et al. 2012) provides a table of iron times for different garments. The typical ironing times are presented weighted by the mass of each garment and the assumed proportion of washes where the garment is ironed. The assumption of which garments are ironed is based on the European IMPRO report (Beton et al., 2014), which gives a rather unrealistic assumption that most garments are ironed every time they are washed. These weighted ironing times multiplied by the typical power rating of an iron (e.g. 0.75 kW for the UK) can be used to give the energy demand for ironing (Bain et al., 2009; Thomas et al., 2012).

Table 45 Ironing time per garment (Table 14 from Thomas et al., 2012)

Garment type	Ironing time [hours per garment]	Ironing time [hours per kg of garment]	Proportion of washes where garment is ironed (simplified estimation)	Weighted ironing time [hours per kg of garment]
Tops	0.043	0.017	100%	0.017
Underwear, nightwear and hosiery	0.057	0.007	0%	0.000
Bottoms	0.072	0.041	100%	0.041
Jackets	0.040	0.032	100%	0.032
Dresses	0.075	0.064	100%	0.084
Suits and ensembles	0.050	0.046	0%	0.000
Gloves	0.000	0.000	0%	0.000
Sportswear	0.033	0.016	100%	0.016
Swimwear	0.000	0.000	0%	0.000
Scarves, shawls ties, etc.	0.033	0.003	0%	0.000

Based on this data, Thomas et al (2012) estimate further that the average weighted ironing duration of clothing is 0.022 hours per kg of washed clothing.

3.1.12 Water use

The use of water in washing machines is highly dependent on the type of machine (vertical top loading machines use a lot more than drum types), the age of the machine (new machines are more efficient due to stricter energy labelling requirements and improved automatic water level adjustment to fit the amount of laundry), maximum capacity of the machine, and the selected programme.

In addition to machine washing, other laundering processes such as pre-soaking consume water. The use of pre-soaking varies greatly between different countries. In Brazil, for example, 30% of respondents reported that they soaked their laundry before washing "all the time" (DuPont, 2013a). Various pre-treatments are common in China in combination with washing by hand (DuPont, 2015). Additional steps that require more water include additional rinsing cycles after washing, but as we have not found studies that report on this, we assume that it is not a common practice.

Testing of European washing machines showed that they used 47.5 litres per washing cycle when full-loaded with a 60°C cotton programme (Stamminger & Schmitz 2016). Under EU energy labelling standard conditions, the water use is slightly less, on average 41.9 litres per washing cycle. This value is an average of seven test rounds, where three are tested with a 60°C cotton programme with a full load, two with a setting for 60°C cotton and a half load, and two with a setting for 40°C cotton and a half load. When taking into account the maximum load of the different machines, the average use is 7.53 litres per kg laundry at 60°C and a full loaded cotton program, and 6.65 litres per kg of load under standard test conditions. The measurements show also that reducing the load from full to half for a 60°C cotton programme reduces water use by 21.2%. However, there were large variations. Some machines reduced the water use by half, while some did not reduce water use at all. In most cases, reducing the temperature from 60°C to 40°C with a half wash load does not reduce the water use, and actually, on average it increases by 3% (Stamminger & Schmitz 2016). These machines were bought between 2012-2014, and therefore this test provides recent and relevant data for the European market. Unfortunately, the study did not include a wool wash programme. Another older study showed that the average water use for programme selection in Europe is 46.3 l/cycle (Presutto et al., 2007).

The largest difference between regions is due to the type of washing machines, as front loading machines use significantly less water. Gooijer & Stamminger (2016) comment that the water use data for Japan differs significantly from source to source, because several types of washing machines are in use there, and because of the increasing practice of using grey water (reused bath water) in the first laundering cycles (Nakamura, 2010, Tsumadori, 2005, Yamaguchi et al., 2011). In 2010, 58% of the total water used in the washing cycle was re-used bath water, while in 1991 this was less than 20% (Nakamura, 2010). Tap water is usually used for final rinsing (Ishii, 2011). In Mexico, the rinse solution was reused in 30% of the cases, and the wash solution 9% of times. The wash solution was reused twice on average (Hecht and Plata, 2016).

Table 46 Overview of water use in domestic laundering worldwide. Figures given in litres per washing cycle and litres per dry weight of the laundry, as well as yearly consumption, when available.

Country or region	Water use per wash cycle in litres [L]	Water use per kg laundry [L/kg]	Water use for clothes washing per household per year [m^3]	Source
Austria	60		9.8	Table 2 Pakula & Stamminger, (2010)
Australia	106		27.6	Table 2 Pakula & Stamminger, (2010)
Belgium	60		9.9	Table 2 Pakula & Stamminger, (2010)
Bulgaria	60		9.9	Table 2 Pakula & Stamminger, (2010)
Canada	144		41.6	(Table 2 from Pakula and Stamminger, 2010) (Table 6 Gooijer & Stamminger 2016)
China	99		9.9	Table 2 Pakula & Stamminger, (2010) (Table 6 Gooijer & Stamminger 2016)
China	66.4		8.8	(Yuan et al., 2016)
Croatia	60		10.6	Table 2 Pakula & Stamminger, (2010)
Czech Republic	60		9.9	Table 2 Pakula & Stamminger, (2010)
Denmark	60		9.9	Table 2 Pakula & Stamminger, (2010)
Estonia	60		9.9	Table 2 Pakula & Stamminger, (2010)
Europe	40.8-45.1	11.0-12.2		Table 9 (Gooijer & Stamminger, 2016)
Europe	75	20.3		Table 9 (Gooijer & Stamminger, 2016)
Finland	60		9.9	Table 2 Pakula & Stamminger, (2010)
France	60		9.9	Table 2 Pakula & Stamminger, (2010)
Germany	60		9.8	Table 2 Pakula & Stamminger, (2010)
Germany	44	11.9		Table 6 (Gooijer and Stamminger, 2016)
Greece	60		10.6	Table 2 Pakula & Stamminger, (2010)
Hungary	60		9.9	Table 2 Pakula & Stamminger, (2010)
Iceland	60		9.9	Table 2 Pakula & Stamminger, (2010)
Italy	60		9.9	Table 2 Pakula & Stamminger, (2010)
Japan	120	36.4	62.4	(Table 2 from Pakula and Stamminger, 2010) (Table 6 Gooijer & Stamminger 2016)
Japan	110	33.3		(Tsumadori, 2005) as cited in Table 6 (Gooijer and Stamminger, 2016)
Japan	50.4	16.8	24.2	(JSDA, 2002)[18]
Korea	140		29.1	(Table 2 from Pakula and Stamminger, 2010) (Table 6 Gooijer & Stamminger 2016)
Latvia	60		10.6	Table 2 Pakula & Stamminger (2010)
Lithuania	60		9.9	Table 2 Pakula & Stamminger (2010)
Luxembourg	60		9.9	Table 2 Pakula & Stamminger (2010)
Netherlands	60		9.9	Table 2 Pakula & Stamminger (2010)
Norway	60		9.9	Table 2 Pakula & Stamminger (2010)
Poland	60		10.6	Table 2 Pakula & Stamminger (2010)

[18] The average water use in 2000 was 16.8 liters pr kg textiles in wash cycle in Japan (JSDA, 2002). The average laundry load was 3 kg, therefore 50.4 liters per wash cycle. With 478.4 cycles per year and 50.5 liters per wash, 24 159 liters=24,2 m3 per year.

Country or region	Water use per wash cycle in litres [L]	Water use per kg laundry [L/kg]	Water use for clothes washing per household per year [m³]	Source
Portugal	60		10.6	Table 2 Pakula & Stamminger (2010)
Romania	60		10.6	Table 2 Pakula & Stamminger (2010)
Slovenia	60		10.6	Table 2 Pakula & Stamminger (2010)
Spain	60		9.9	Table 2 Pakula & Stamminger (2010)
Sweden	60		8.4	Table 2 Pakula & Stamminger (2010)
Switzerland	60		9.9	Table 2 Pakula & Stamminger (2010)
Turkey	60			Table 2 Pakula & Stamminger (2010) (Table 6 Gooijer & Stamminger 2016)
USA	144		41.6	Table 2 Pakula & Stamminger (2010) (Table 6&10 Gooijer & Stamminger 2016)
USA	157			(Hustvedt, 2011) (Table 6&10 Gooijer & Stamminger 2016)
USA	160			(Tsumadori, 2005) as cited in Table 6&10 (Gooijer and Stamminger, 2016)
USA	123			(Hustvedt, 2011) Calculated from: Front load: 26.5liters (22.7% adoption reate), Top load: 151.4 liters (77.3%)
USA	Top load: 151.4 Front load: 93.4			Hustvedt 2013
USA	Top load: 157 Front load: 98			Metering study in Bern, Tomlinson & Rizy, 1998

The metering study from Bern, USA, showed that changing to the h-axis washer reduced the average water consumption from 157 litres/load to 97.7 litres/load – a water savings of about 38% (Tomlinzon & Rizy, 1998). Also the remaining moisture content of damp loads removed from the h-axis washers was, on average, 7% lower, which will later save energy in laundry drying.

Table 47 Comparison of water consumption of 18 front loading and 19 top loading washing machines on the market in Australia (Choice, 2008)

Maximum load capacity of washing machine	Water consumption in «normal» wash cycle, liters		Difference	
	Top loading	Front loading	Liters	Percentage
Capacity 5-7 kg	105.2	57.2	48.0	46 %
Capacity 7.5 kg and higher	124.2	66.75	57.5	46 %

Table 48 shows water use for 31 different horizontal drum type washing machines available on the Norwegian market (Laitala and Vereide, 2010). The water use for three washing programmes, cotton, synthetics and wool, are given. The “N” column indicates how many sources of washing programme information were available for the calculation. As the maximum washing load with a cotton programme is twice as large as the synthetics programme and about three times more than the wool programme, the difference in water use measured as litres/kg laundry is also calculated. The results show that the wool programme uses more water per kg laundry than cotton and synthetic programmes, if the maximum capacity of the programme is used (Laitala & Vereide, 2010). However, when using these results, one should take in to account that consumers often underload the cotton programme, and overload the wool programme (Kruschwitz et al., 2014), thus evening out the water use between the two washes. In addition, woollen garments are often used longer between washes, thus reducing the water use when calculated for one day of use.

Table 48 Water use values of different washing programs and temperatures (part of table 2 from Laitala & Vereide, 2010)

Program and temperature	**Average load** [kg]	**Water use [L/cycle]**			**Water use [L/kg laundry]**		
		Average	Variation	N	Average	Variation	St. Dev.
Cotton	5.9	54	39-74	87	9.18	6.5-12.2	1.1
30 °C		57	54-60	4			
40 °C		55	45-72	20			
60 °C		51	39-74	40			
90-95 °C		58	47-65	23			
Synthetics/ easy iron[19]	2.6	49	30-69	31	18.56	8.6-60	8.4
Cold		NA	NA	0			
30 °C		69	NA	1			
40 °C		46	30-60	18			
60 °C		51	43-62	12			
Wool[20]	1.6	46	35-60	24	28.5	17.5-60	13.7
Cold		39	39-39	3			
20 °C		NA	NA	0			
30 °C		43	35-54	11			
40 °C		52	42-60	10			

Kim et al. (2015) have compared the drum and impeller type machines from different countries based on existing literature (Table 49).

Table 49 Water use of different types of washing machines (Kim et al., 2015) (estimated values based on a diagrams in the article, exact numbers not available.)

Area	**Europe**			**China**					**USA**	**South Korea**	
Machine type	Drum	Drum	Drum	Drum	Drum	Drum	Impeller	Impeller	Drum	Drum	Impeller
Maximum capacity kg	7	8	9.75	6.1	7 kg	8.1	6.21	7.22	7.95 kg	12.5	14.25
Water use per cycle L/cycle	40	45	50	40	45	50	85	100	50	110	190
Water use per cycle per kg capacity L/cycle/kg	6	5.7	5.5	6.5	6	6	14.2	14	6	9	13
Water use per year L/year	9000	10000	10500	3000	3100	3300	8000	10000	13000	22000	39000

We have only found one study that documents water consumption in hand laundering. Based on interviews and observations in China, Kao (2010 a, b) measured that the informants used on average 23 liters of water per load, 90% which was used for rinsing the laundry. Informants rinsed on average four times, until the detergent suds disappeared completely. Rinsing was mainly done with stored water. The daily hand wash was sorted into two loads, and these loads were rather small, mainly socks, underwear and some other next-to-skin items, but no exact weight in kg was given. Based on frequent laundering and small clothing items laundered, we can assume the loads size to around 1 kg per wash or less, depending on the household size.

[19] Synthetic: No information available for cold wash and only one program for washing at 30°C
[20] Wool: No information was available for washing at 20 °C

3.2 Micro-fibres

Awareness of problems related to plastics in marine environments has increased rapidly over the past two decades. Laundering textiles is one of the important contributors to microplastic pollution (Browne et al., 2011). Henry, Laitala and Klepp (2018) have conducted a comprehensive review of current understanding of microplastic pollution and its impacts on ecosystems and potentially on human health. The report has a focus on the contribution of textile microfibres and discusses the data and methodological needs for inclusion in LCA of textiles and clothing. An introduction to the topic and summary of some findings are included here.

Microplastics, including the sub-category known as microsynthetic fibres or microfibres, are now ubiquitous in aquatic and terrestrial ecosystems globally. Their abundance is set to increase as consumption of plastics and the use of synthetic fibres in clothing continues to expand with population growth and the culture of 'fast fashion' spreads to countries with growing economic wealth. Banning of synthetic clothing is not feasible due to their role in providing affordable garments to meet the current and growing global demands of consumers. This makes the management of microfibre pollution a great challenge for the apparel and textile industries.

There is well-established evidence of ingestion of microplastic fibres by marine and freshwater organisms and concern regarding the physical and chemical impacts that occur once in the digestive system and following transfer along the food chain (Wright et al., 2013). There is also evidence of microfibre intake in human diets through consumption of seafood, particularly shellfish (Van Cauwenberghe and Janssen, 2014). Chemical impacts occur due to release of compounds from microscopic plastic fibres and from sorbed compounds. Microfibres have a relatively large surface area for potential sorption of harmful chemicals such as persistent organic pollutants (PoPs). Physical impacts such as blockages of the digestive tract are exacerbated in fibrous microplastics because their tendency for entanglement leads to a lower likelihood of their being passed easily from the organism. Hence the risk of eventual starvation of marine organisms is greater. Experimental testing and hydrological models are beginning to provide some information on levels and fate of microfibre emissions in marine and freshwater systems (Woodall et al., 2014).

While sufficiently sensitive detection and measurement is still evolving, experimental results are starting to quantify microfibre loss during washing of synthetic clothing and the factors affecting the abundance of fibres in washing machine effluent (Browne et al., 2011, Bruce et al., 2016, Napper and Thompson, 2016). Factors tested include the type and quality of the fabric, garment age, type of washing machine (top-loading vs front-loading), and temperature and detergent used. Some work has also looked at filter and sewage waste-water treatment plant effectiveness. A study by the Bren group for Patagonia stressed the need for "further research on shedding characteristics of apparel and the development of mitigation measures by producers, consumers, waste managers, and policy makers towards addressing the issue of microfibre pollution." Another fundamental need is the development of agreed statistically relevant protocols for quantifying and monitoring microplastic prevalence in habitats and impacts on ecosystem and human health. The growing evidence of the prevalence and risk of microfibre pollution highlights the importance of developing an agreed method of including an indicator for the environmental impact of microplastic pollution in LCA studies of textile and footwear products. Potential methods and indicators are explored in the accompanying report, but further research is needed to identify suitable indicator(s) for measuring environmental impacts. The links between physical and chemical harm to ecosystems or human health and microfibre mass, number and dimensions are not well understood. For example, mass, number and prevalence will likely determine exposure and effects in different ways and the dimensions of fibres (length and diameter) will influence the surface area for sorption of toxic chemicals in solution. Developing scientifically robust methods for measuring and monitoring impacts of microfibres from clothing is a high priority, however strategies to manage the risks are an immediate need.

Potential microfibre mitigation strategies can be grouped into three categories:

1. *Reducing production and consumption of clothing*: The current 'fast fashion' trend results in an enormous volume of waste textiles in landfill. Because synthetics make up the highest proportion, this waste is a growing source of secondary microplastic pollution as garments gradually break down to micro-sized plastic particles;

2. *Improving consumer practices in the use phase of synthetic garments*: In the use phase, the abrasive action of washing clothing and other textiles is a primary source of microfibre contamination of the environment, with preliminary evidence that man-made cellulosic fibres may also contribute to persistent microfibre pollution. Practices recommended to reduce microfibre shedding from textiles include:
    i. less frequent washing over the life of a garment;
    ii. gentler, lower chemical use washing; and
    iii. extending the life of the garment.

    These recommendations not only reduce microplastic pollution but are shown in this review to reduce other environmental impacts and resource use (e.g. energy and water use).

    Textile brands as well as researchers are already developing and recommending practices for consumers to reduce microfibre pollution from clothing. Various laundry filters are being developed, but their effectivity is yet to be determined. Beginning in 2017, the US outdoor brand, Patagonia, will provide all customers who purchase a Patagonia synthetic item with information about how to care for any synthetic garment to limit the shedding of microfibres in the wash and keeping what does shed out of the ocean. Napper and Thompson (2016) describe a set of criteria that synthetic garment manufacturers should consider during design and manufacture stages: (1) performance in service, giving a long lasting product; (2) minimal release of non-degradable synthetic fibres; and (3) a product that is compatible with end of life recycling.

3. *Avoiding microplastic fibre pollution through increased use of natural fibres:* The most effective strategy for consumers to reduce their contribution to microfibre pollution would be to choose garments made from natural fibres. Natural fibres are biodegradable in terrestrial and aquatic environments (Brown 1994) and do not contribute to the build-up of microfibres or plastics in the environment. The recommended practices to reduce shedding from synthetic garments such as less frequent, gentler washing are already commonly used for wool garments as shown in surveys reported in this review. Through choosing natural rather than synthetic fibre clothing, consumers achieve additional environmental benefits, in addition to avoiding microplastic pollution.

3.3 Clothing lifespan

The length of clothing use period is usually referred to as clothing lifespan or lifetime and often expressed in years, or sometimes as number of wears, or number of washes. Effective lifetime refers to time the clothing is in active use, and can be shorter than the total use period when clothing is inactive and stored for periods of time. Also the term "duration of service" has become more common lately. There are some differences in the way these terms are used, and measuring them is difficult.

The length of clothing lifespans has been discussed in some studies, but very little information is available on actual lifetimes and use times for clothing. Beton et al. (2014) have estimated in an EU report that all garments have a lifespan of 1-3 years, but they refer only to their own and others' estimates that are not based on actual research with references. Similarly, the estimates of lifetime of clothing items varied from ten up to 104 uses in two separate studies (Birtwistle and Moore, 2007, Collins and Aumônier, 2002). A Dutch study estimated that the average lifespan of trousers was 6.2 years, skirts and dresses 15.2 years , jumpers 7.1 years, blouses 7.2 years, t-shirts 6.8 years, blazers 11.5 years and coats 11.6 years (Uitdenbogerd et al., 1998, p. 127). The lifespan of a skirt was thus estimated to be twice as long as that of a pair of pants. The calculation was based on the number of garments in 16 households and correlated with how much was purchased. In her PhD study, Uitdenbogerd also asked survey respondents about how long they used two different garments before they were disposed of, and the result for cotton trousers was 2.45 years, and for wool sweaters, 6.17 years (Uitdenbogerd, 2007, p. 281). The differences between the results of these studies by the same researcher are quite substantial, and confirm how uncertain such indirect ways of estimating garment lifetimes are. Literature, which has some detailed information based on consumer studies, is included here.

A comprehensive online survey with 467 respondents from seven countries (Australia, China, Italy, Japan, Korea, UK, and USA) focused on all of the clothing items the respondents owned (The Nielsen Company, 2012c). They answered the question “When did you buy this clothes item or accessory?” for each of their owned clothing items. The results are divided by different categories for fibre content and type of apparel. Results for different fibre types are given in Figure 21. The results show that respondents reported that garments made of wool blends were bought the longest time ago (3.9 years), followed by synthetics (3.7 years). The total lifespans would then be about twice as long as the current average.

The same study included interviews with a smaller number of informants (The Nielsen Company, 2012a, b). Respondents from the US and Italy said the average lifespan of their clothing was 2-3 years. In US, the exception was outerwear which was kept longer. Respondents believed their cotton clothing had longer lifespans than synthetics, and that wool may even be longer. Similarly, in Japan the respondents used cotton summer clothes for about 2-3 seasons, woollen winter coats for 5-8 years, and other winter jackets for 3-5 years. Trendy clothes were only used for one season. In the UK, the respondents most frequently wore clothing that was purchased 0.5-2 years ago. In Korea, wool garments were estimated to last 5 years, which is longer than garments made of synthetics (3-4 years) or cotton (2-3 years). In general, formal wear and work suits were reported to last longer than other garments.

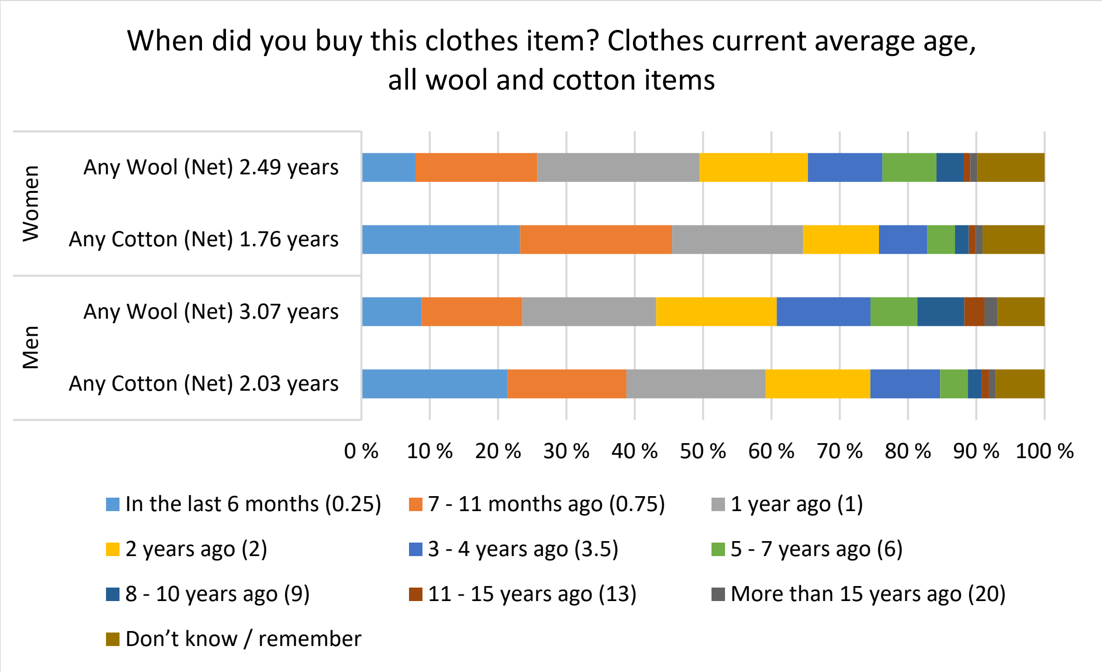

Figure 21 Response to the question ‘When did you buy this clothes item or accessory?’. Answers are disaggregated by main fibre and gender (The Nielsen Company, 2012c)

Men in the youngest age group 18-24 years report the shortest average clothing lifespan (1.35 years). Men between 25-39 years report about half a year longer clothing lifespan (1.82 years), and men above 40 years almost two years longer, 3.25 years.

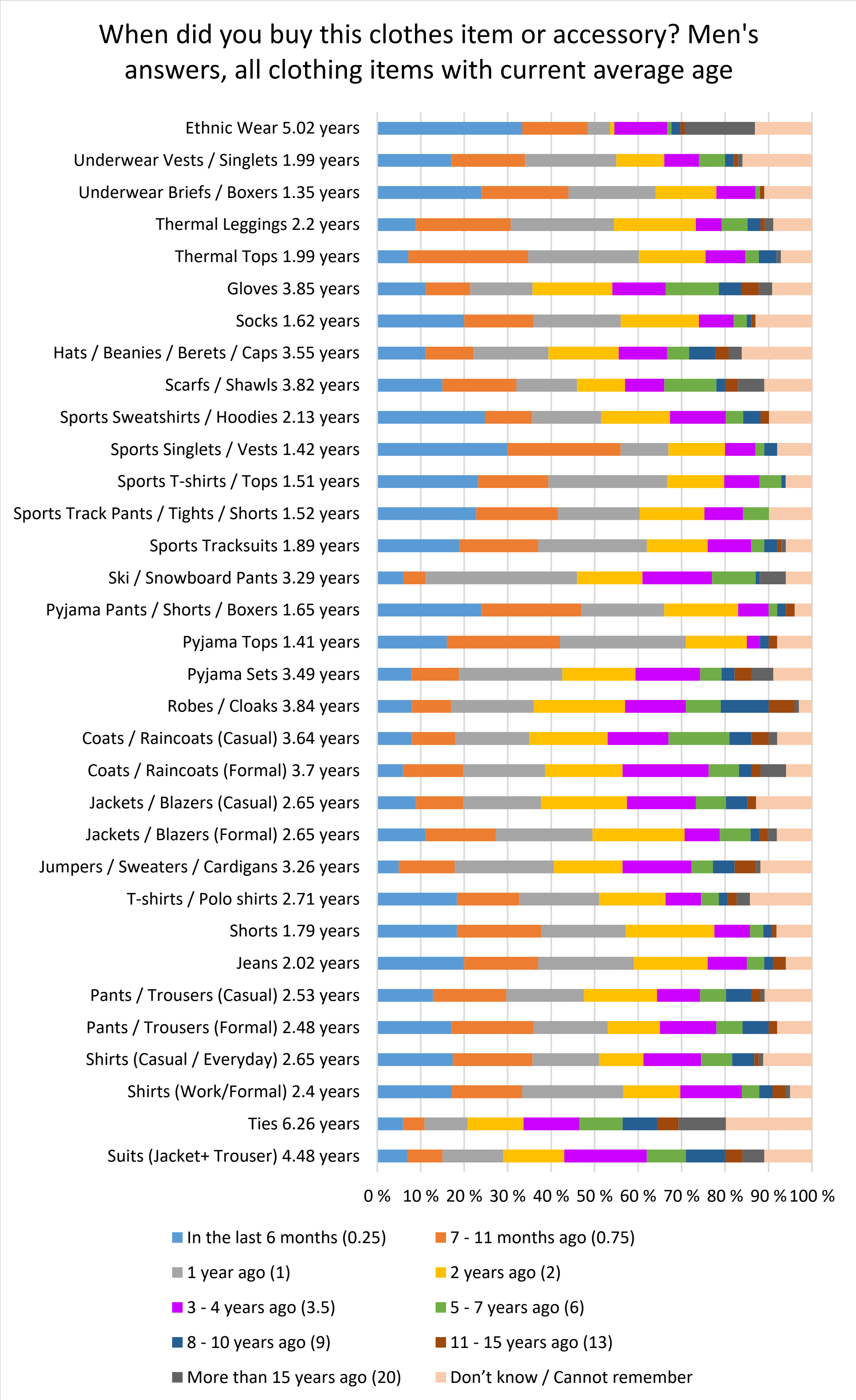

Figure 22 Current average age of men’s clothing (The Nielsen Company, 2012c)

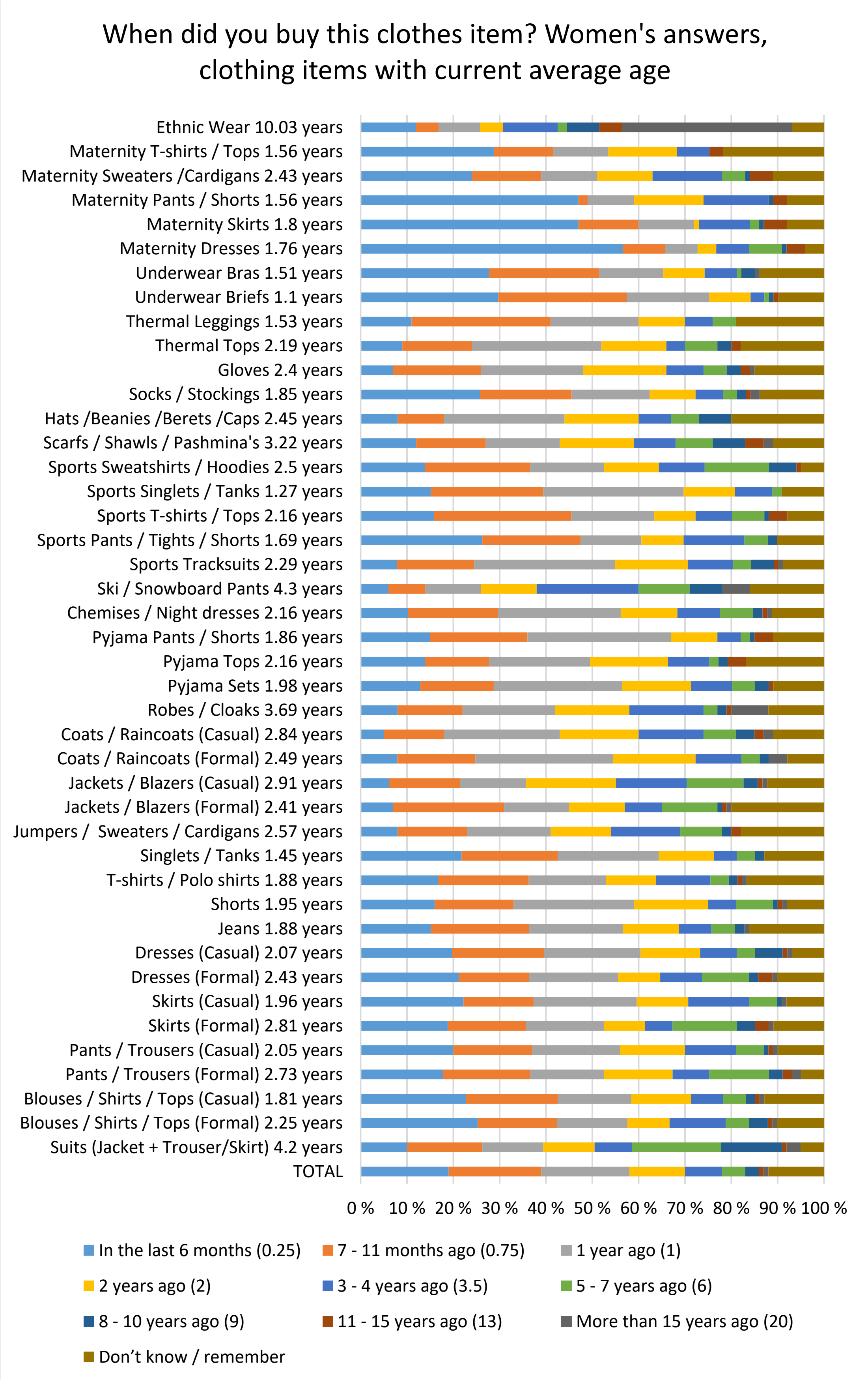

Figure 23 Current average age of women's clothing (The Nielsen company, 2012c)

Table 50 Current average age of men's clothing by fibre content (The Nielsen Company, 2012c)

Garment type	Average	Cotton and blends	Synthetics and man made	Wool and blends	Silk
Suits - Jacket + Trouser	4.5	3.8	2.7	5.1	
Ties	6.3	4.8	6.4	4.6	7.3
Shirts (Work / Formal)	2.4	2.2	3.1	1.9	
Shirts (Casual / Everyday)	2.7	2.2	3.9	3.6	6.7
Pants / Trousers (Work / Formal)	2.5	2.0	3.9	3.2	
Pants / Trousers (Casual / Everyday)	2.5	2.4	2.2	3.5	
Jeans	2.0	1.7		0.9	
Shorts	1.8	1.7	1.8	2.2	
T-shirts / Polo shirts	2.7	2.3	2.0	1.5	
Jumpers / Pullovers / Sweaters / Cardigans	3.3	3.3	3.0	3.5	
Jackets / Blazers (Work / Formal)	2.7	2.3		2.7	
Jackets / Blazers (Casual / Everyday)	2.7	2.0	3.2	2.9	
Overcoats / Coats / Raincoats (Work / Formal)	3.7	3.0	2.5	4.0	
Overcoats / Coats / Raincoats (Casual / Everyday)	3.6	3.1	4.8	2.7	
Robes / Cloaks	3.8	4.1		2.7	
Pyjama Sets	3.5	3.9		2.2	
Pyjama Tops	1.4	0.9		2.4	
Pyjama Pants / Shorts / Boxers	1.7	1.6		1.9	
Ski / Snowboard Pants	3.3			1.6	
Sports Tracksuits	1.9	1.2	2.9	1.4	
Sports Track Pants / Tights / Shorts	1.5	1.1	2.8	1.6	
Sports T-shirts / Tops	1.5	1.5	2.1	0.8	
Sports Singlets / Vests	1.4	1.2		2.1	
Sports Sweatshirts / Hoodies	2.1	2.0	4.2		
Scarves / Shawls	3.8	2.2		4.0	
Hats / Beanies / Berets / Caps	3.6	1.9	5.3	2.1	
Socks	1.6	1.5	2.8	2.8	1.9
Gloves	3.9	2.3	7.3	3.2	
Thermal Tops	2.0	1.9	2.4	1.8	
Thermal Leggings	2.2	1.7	3.2	1.4	
Underwear Briefs / Trunks / Boxers	1.4	1.3	1.7	1.1	2.0
Underwear Vests / Singlets	2.0	2.0		1.6	
Ethnic Clothing / Ethnic Wear (e.g. kurta, hakama, jeogori, paji, uwagi etc)	5.02				

Table 51 Current average age of women's clothing by fibre content (The Nielsen Company, 2012c)

	Average	Cotton and blends	Synthetics and man made	Wool and blends	Silk
Suits - Jacket + Trouser / Skirt	4.2	3.3	3.8	4.6	
Blouses / Shirts / Tops (Work / Formal)	2.3	1.9	3.4	1.9	1.3
Blouses / Shirts / Tops (Casual / Everyday)	1.8	1.6	2.3	2.4	1.8
Pants / Trousers (Work / Formal)	2.7	1.8	3.6	2.7	
Pants / Trousers (Casual / Everyday)	2.1	1.8	2.9	1.3	
Skirts (Work / Formal)	2.8	2.4	3.8	3.6	0.9
Skirts (Casual / Everyday)	2.0	1.8	2.3	2.2	0.8
Dresses (Work / Formal)	2.4	1.3	4.5	1.5	1.9
Dresses (Casual / Everyday)	2.1	1.9	2.2	1.9	1.8
Jeans	1.9	1.7	4.7	1.8	
Shorts	2.0	2.0	2.0	2.1	
T-shirts / Polo shirts	1.9	1.9	2.1	1.7	

Singlets / Tanks	1.5	1.5	1.1	1.3	1.5
Jumpers / Pullovers / Sweaters / Cardigans	2.6	2.3	3.5	2.5	
Jackets / Blazers (Work / Formal)	2.4	2.0	2.4	3.0	
Jackets / Blazers (Casual / Everyday)	2.9	3.0	3.4	2.2	
Overcoats / Coats / Raincoats (Work / Formal)	2.5	2.3	3.1	2.5	
Overcoats / Coats / Raincoats (Casual / Everyday)	2.8	2.6	3.6	2.6	
Robes / Cloaks	3.7	5.1	2.6	2.2	
Pyjama Sets	2.0	1.9	1.6	2.0	2.9
Pyjama Tops	2.2	2.1	3.0	2.8	3.2
Pyjama Pants / Shorts	1.9	1.9	1.6	2.8	1.0
Chemises / Baby dolls / Night dresses	2.2	1.9	2.6	1.2	2.7
Ski / Snowboard Pants	4.3	4.3	4.7		
Sports Tracksuits	2.3	1.8	3.8	1.5	
Sports Track Pants / Tights / Shorts	1.7	1.3	2.1		
Sports T-shirts / Tops	2.2	2.0	2.1		
Sports Singlets / Tanks	1.3	1.2			
Sports Sweatshirts / Hoodies	2.5	2.5	1.9	1.4	
Scarves / Shawls / Pashminas / Stoles	3.2	1.8	5.8	3.1	3.8
Hats / Beanies / Berets / Caps	2.5	2.3	2.7	2.3	
Socks / Stockings	1.9	1.8	1.5	2.7	2.4
Gloves	2.4	2.2	3.7	2.1	
Thermal Tops	2.2	1.8	3.1	3.0	
Thermal Leggings	1.5	1.3	1.3	2.0	
Underwear Briefs	1.1	0.9	1.5	2.8	1.5
Underwear Bras	1.5	1.2	2.2	1.8	2.2
Ethnic Clothing / Ethnic Wear (e.g. kimono, hanbok, chima jeogori, sari etc)	10.0	5.8	1.1		12.8

In the UK, the Waste and Resources Action Program (WRAP) has focused on clothing sustainability through their Sustainable Clothing Action Plan (SCAP) including clothing longevity. They surveyed 3244 respondents online in the UK to study how long people keep and regularly wear their clothes for (active use of clothing). In this study, the expected clothing active use was calculated as "a sum of the amount of time since respondents acquired a clothing item and the anticipated amount of time they will continue to wear it" (Langley et al., 2013, p. 3). Based on this, the average active use of clothing was determined to be 3.3 years (averaged across all types of clothing and six different purposes for wearing). They also showed that some consumer groups are more likely to keep their clothing longer than average, including men, older people, people on low incomes, and people in higher social classes. In addition, ownership of large number of items of clothing as well as a high number of clothes that are not in active use were associated with longer clothing lifespans. Also, people who said they buy clothes that are meant to last longer, reported longer use (Langley et al., 2013). Figure 24 shows the variations in estimated lifespans by garment type. It shows that socks, tights and stockings, as well as knickers and underpants, have the shortest expected lifespans, while swimwear, jackets, blazers and coats have the longest expected lifespans. The study also indicates that consumers estimated the length of future use of garments to be longer than past use, which seems a bit unrealistic, as most likely the average should be in the middle of the use period.

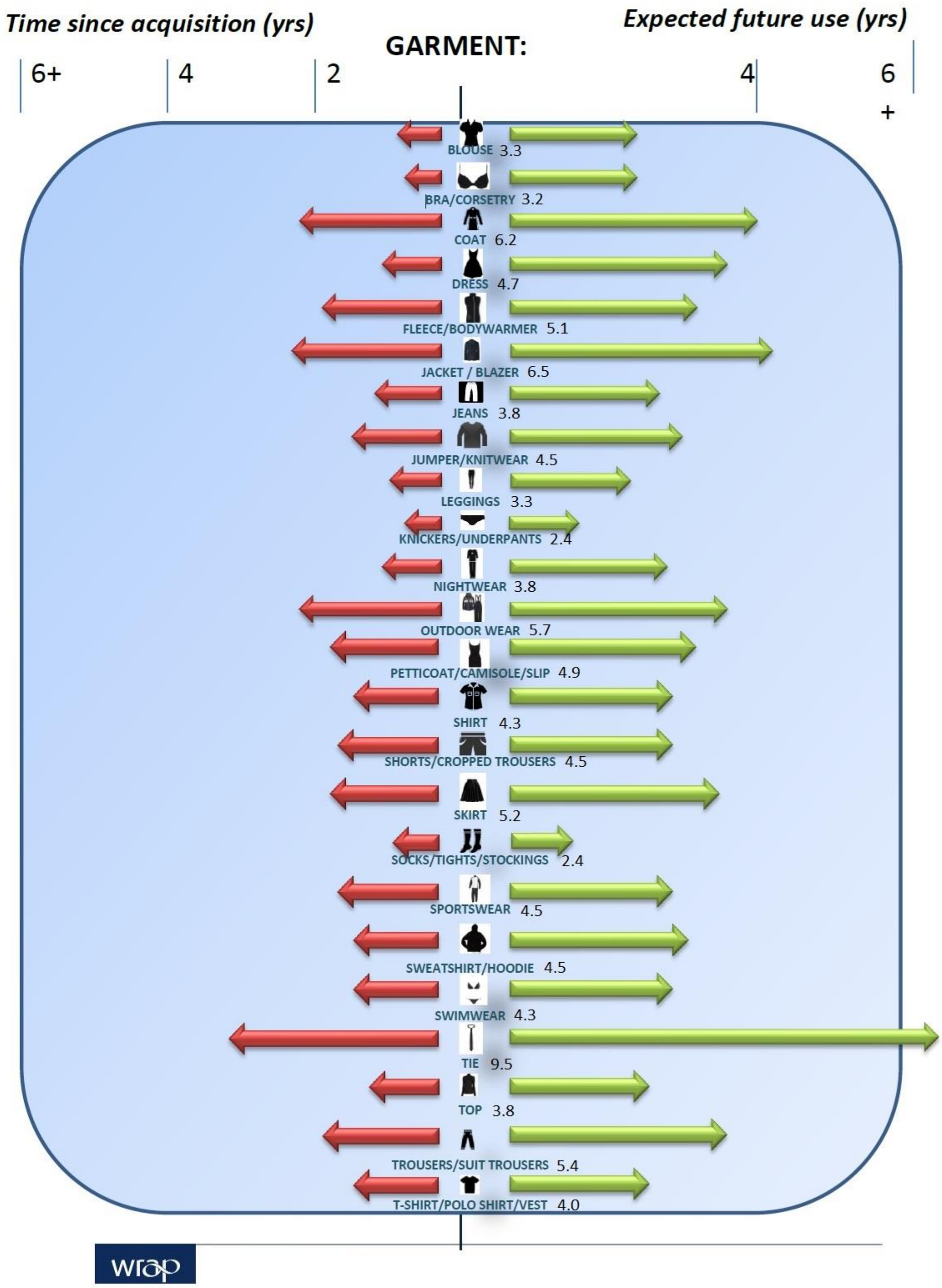

Figure 24 Survey results on time since acquisition of clothing, and expected length of future use (Figure 2 from (Langley et al., 2013). Estimated total length of lifetime in years added later based n length of arrows in figure.

Two Norwegian projects have had a focus on clothing going out of use and studied reasons for the household's disposal and the lifespans of garments. In both studies, all garments that went out of use during six months, were registered. The clothes that went out of use in 2010 had an average total life of 5.4 years, and had been with the current owner for the past four years. The average difference of 1.4 years shows that many of the clothes were inherited or purchased as used items. However, the assumption related to the length of use during the previous owner was a best guess based on the appearance of the clothing item, and any other information that the latest owner was able to provide. The total lifetime ranged from brand new to about 50-year-old garments.

A study by Klepp (2001) included 329 clothing items going out of use from 24 women who were 35-45 years old. The average lifespan of clothing was 7.14 years, but they were not in active use during the whole period. On average, they were stored for over a year before the final disposal decision was made (Klepp, 2001).

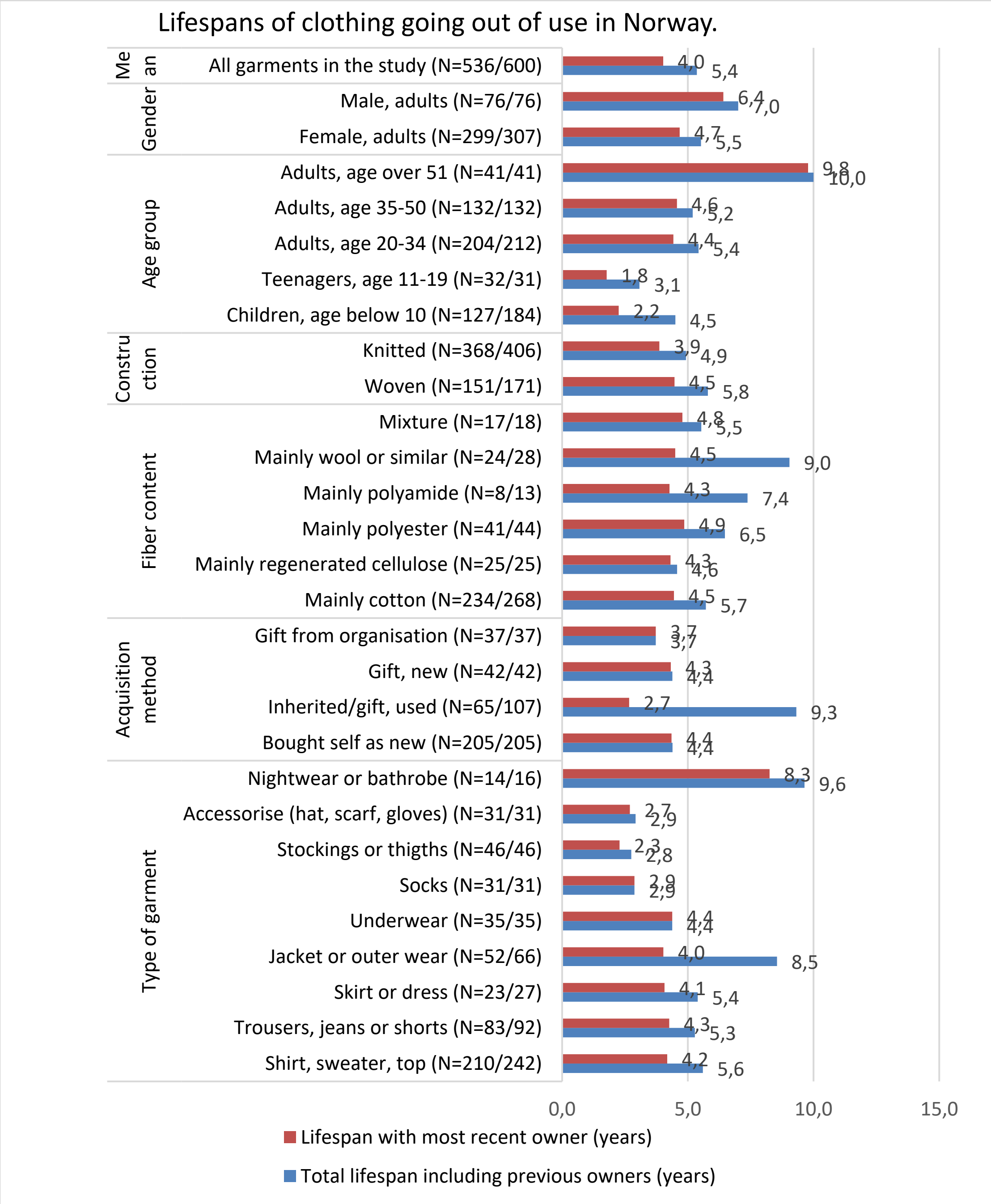

Figure 25 Lifespans of clothing that went out of use from 16 Norwegian households grouped according to user's gender and age, garment structure, fibre content and type, and how it was acquired (reanalysed data).

A Norwegian survey from 2012 included questions about clothing lifespans as well as consumers' expectations of clothing lifespans (Klepp and Laitala, 2016). The respondents were asked the age of the oldest garment they were still using, and what that garment was. The results show that the oldest garment still in use, was on average 11.7 years, with a median value of 9 years and maximum of 90 years. Some respondents also said the oldest garment was less than a year old, and 5.6% answered they did not know. The most common answer to the nature of the oldest garment in use was coats, jackets, different tops such as sweaters and t-shirts, followed by trousers. Quite a lot of the answers specified that the garments were made of wool, but unfortunately, it is not possible to quantify how large the proportion of the oldest garments that were wool. The median answer for both men and women was 9 years, but the average lifespan of the oldest garment was higher for women (12.7 years) than for men (10.7 years).

In addition, we asked the age of the top (blouse, sweater or shirt) that the informant was wearing at the moment, the age of the woollen sweater the informant wore most during the past winter (if they wore one), the age of trousers the informant wore most during winter, and the age of the winter jacket/coat that was most used. Of these four garments, woollen sweaters were the oldest (average 5.4 years), but there were also many respondents who did not own such garments or had not used such a garment during past winter (16 % of respondents). Winter coats were the next oldest (3.2 years), followed by the sweater/shirt worn currently (2.8 years). The trousers had the lowest average age (2.2 years). The differences in age of garments in use in general did not vary much between genders (Figure 26), but the younger respondents wore newer clothing more often than the older respondents (Figure 27) (Klepp and Laitala, 2016).

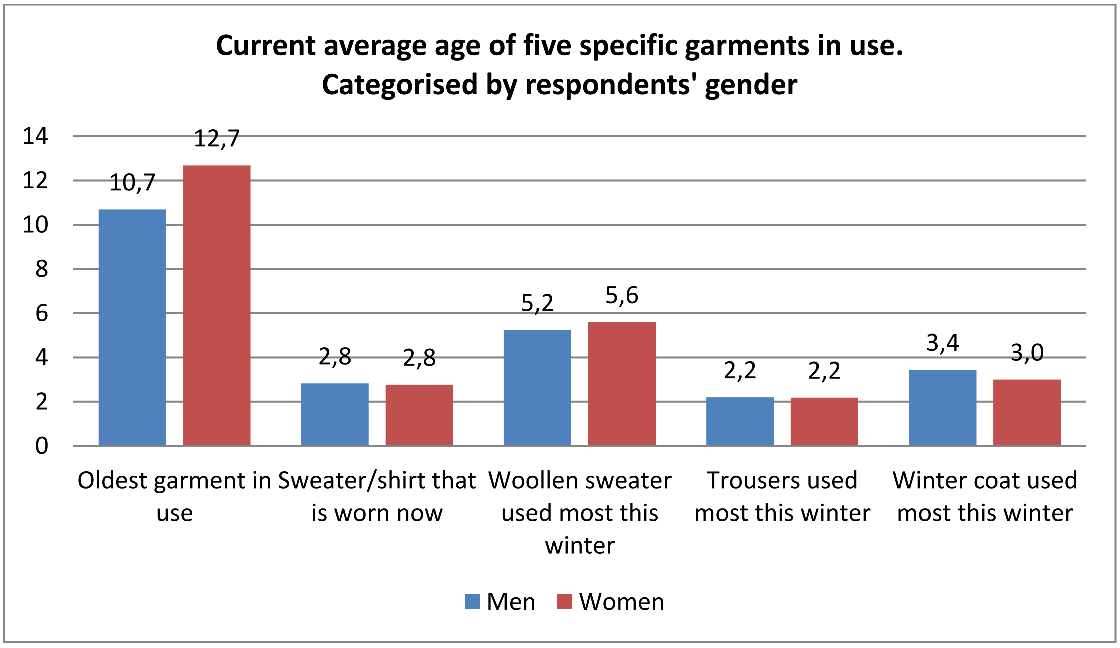

Figure 26 Average age of five garments in use categorised by gender

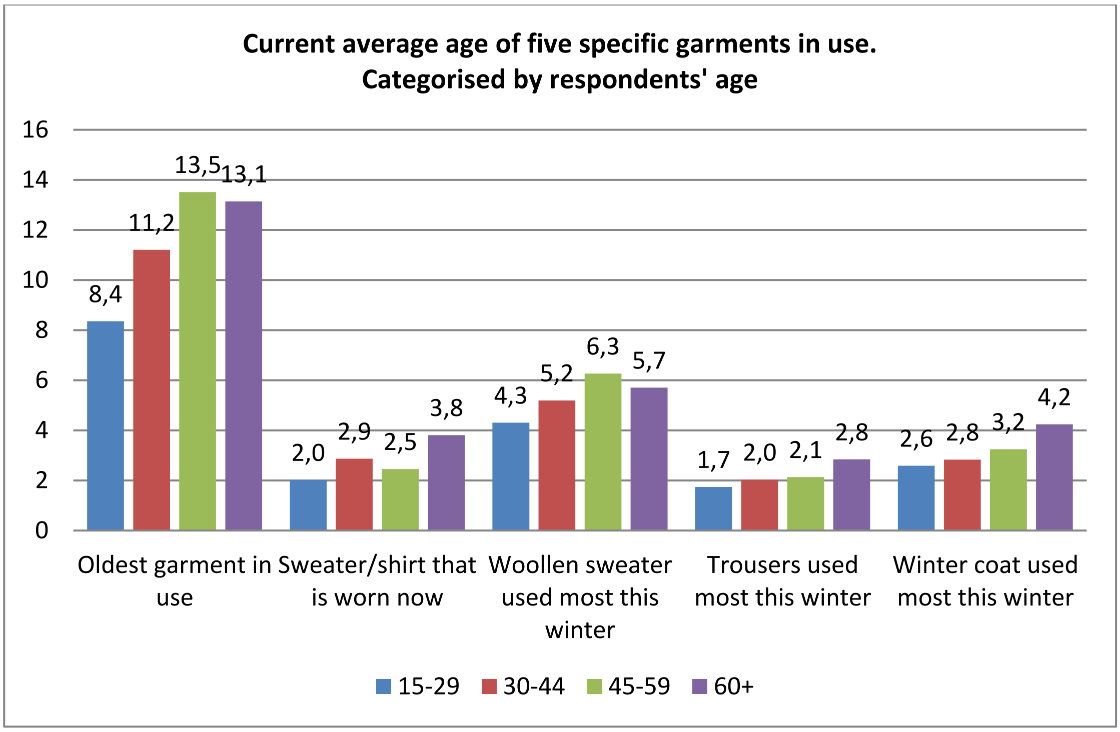

Figure 27 Average age of five garments in use categorised by respondent's age

However, these statistics on current garment age are not the same as the total lifespan. Some respondents wore brand new items, while others were likely to wear something they would soon dispose of. We therefore assumed that the total lifespan is about double the average age of garments currently in use. This estimation may be lower than reality, as the total lifespan includes the time that the informants gave (current age), to which is added an estimate of future active use period that is likely to be as long as the average of current age. In addition, garments are likely to have an inactive period where they are stored while the user considers what to do with it (see discussion of this in Laitala et al. (2015)). This gives average lifespans of 5.6 years for sweaters/shirts, 10.8 years for woollen sweaters, 6.4 years for winter coats and 4.2 years for pants/trousers.

We also wanted to know more about the expectations consumers have for clothing lifespans, and asked "How many years do you think it should be possible to use the following garments before they get worn out?" The answers are given in Table 52.

Table 52 How long should it be possible to use the garment (SIFO surveys 2012 and 2013)

Type of garment	Average	Median	Mode
Wool coat	10.0	8	10
Woollen sweater	8.8	6	5
"All weather jacket" (jackets that are wind- and waterproof, but that "breath", for example Gore tex)	7.5	5	5
Winter coat of good quality	6.9	5	5
Down jacket	6.6	5	5
Woollen underwear	5.2	5	5
Jeans	4.7	4	5
Cotton sweater	4.3	3	5
T-shirt	3.6	3	2

Women expected these products to last 0.9 years longer on average than men did. Of the given garment types, the respondents thought that woollen coats should last the longest, 10 years, while they had the lowest expectations for the lifespan of a T-shirt, 3.6 years. The median values are a bit lower than the average. This indicates that it was more common to answer a higher expected lifespan, than a very short one. When comparing these expectations to the real reported lifespans of garments in use, we see that the average expected use time of woollen sweaters, 8.8 years, is lower than the estimated lifespan of 10.8 years. The same is valid for the expectations for cotton sweaters (4.3 years) and T-shirts (3.6 years) which are lower than then estimated lifespan of 5.6 years for the sweaters/shirts the respondents were wearing.

On the other hand, the average expected use time for jeans, 4.7 years, is a bit higher than the age of trousers respondents wore (4.2 years). However, trousers are a more varied clothing category than jeans, and include different materials, as well as type of use. Denim is a rather strong material, and the use differs socially from that of some trousers, so jeans are allowed to look more worn than, for example, suit trousers, before they are considered to be at the end of their useful life.

Expectations for the lifespan for different winter jackets varied from 6.6 to 10 years, which is a bit higher than the estimated lifespan of 6.4 years. These results do not differ very much from wardrobe studies where the lifespan was 4 years, but ranged up to 8.5 years when the use by one or more previous owners was included (Klepp and Laitala, 2016).

A consumer survey conducted in four countries (USA, Germany, Sweden and Poland), showed that the respondents estimated they kept jeans and T-shirt for about 3-4 years (Gwozdz et al. 2017).

A web based survey in Finland with 1060 respondents included questions about clothing lifespans and disposal habits (Aalto, 2014). The survey is non-representative as 93% of respondents were women and they were above-average interested in the topic. However, the large number of respondents merits its inclusion in this review. The results for women's clothing lifespans are given in Figure 28 and for men's clothing in Figure 29.

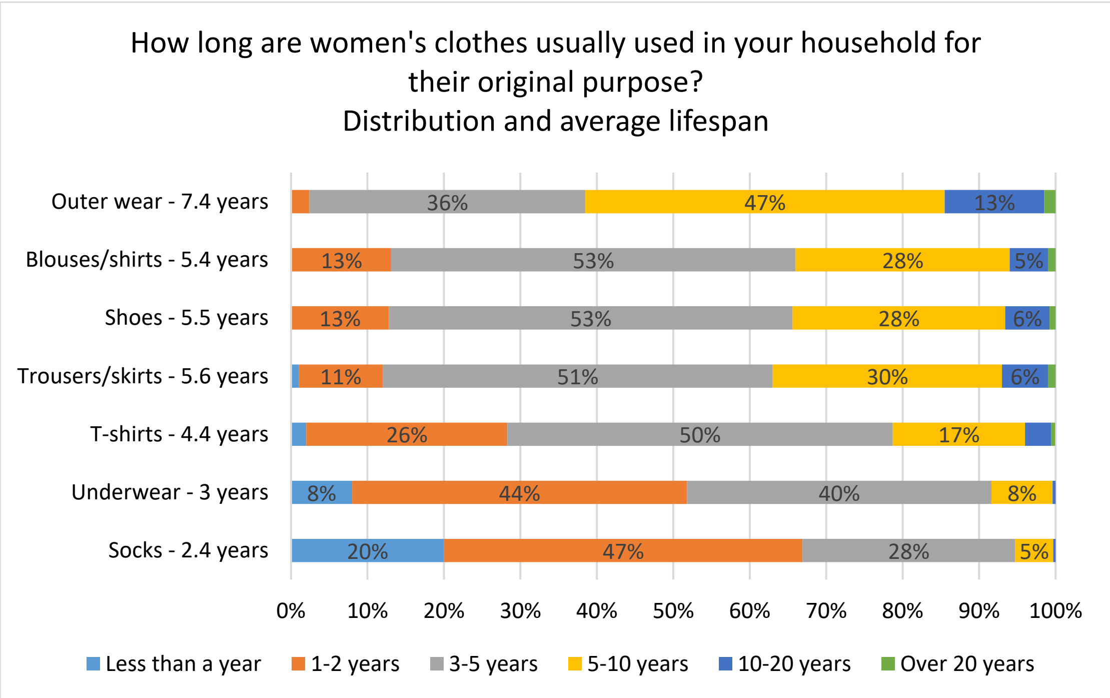

Figure 28 Average lifespans of women's clothing (N=981, translated Table 2 and Figure 7 from Aalto, 2014)

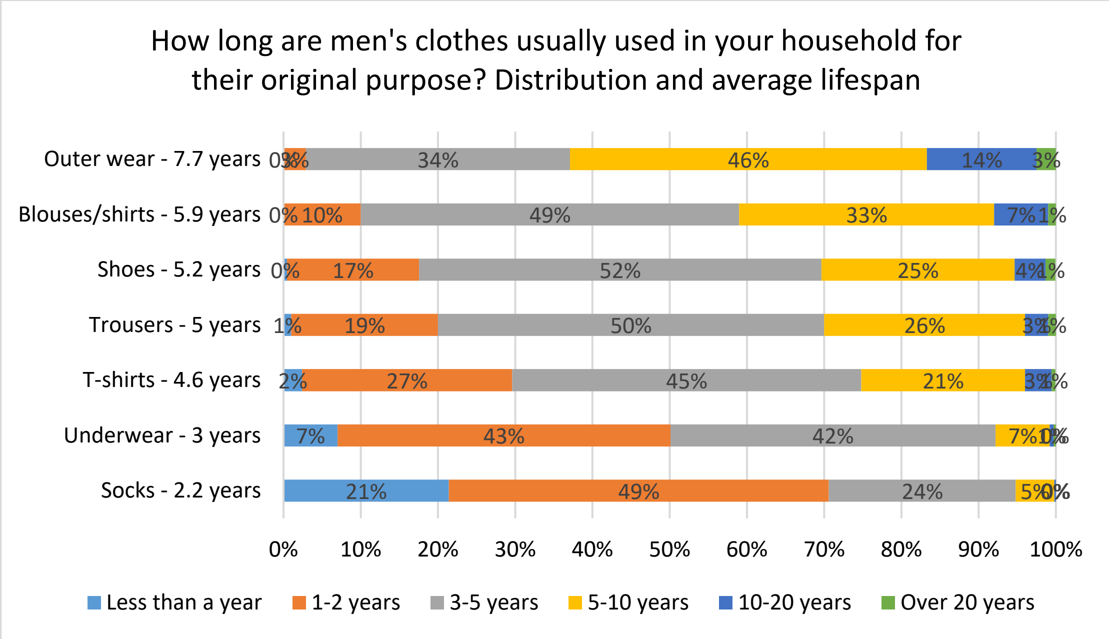

Figure 29 Average lifespans of men's clothing (N=69, translated Table 2 and Figure 8 from Aalto, 2014).

Another Finnish study by Niinimäki (2011) included a survey where she asked the lifespan of clothes that had either the shortest or the longest lifespans. 66% of women and 78% of men reported that their oldest clothes were over 5 years, while the shortest use periods were below three months (31% of women and 12% of men) (Niinimäki 2011).

The International Fabricare Institute has published a table of the "Average Life Expectancy of Textile Items in Years" to guide Fair Claims within the cleaning industry. The table indicates the expected length of use phase (based on durability only). The assessments are made by the cleaning industry and are, therefore, likely to be conservative because they relate to liability for complaints to the dry-cleaning industry. The important feature is the relative life of different materials/garments rather than the 'minimum' expected life. It includes a wide range of different garments and interior textiles and has a global perspective (Drycleaning Institute of Australia Ltd, 2015).

Table 53 Textile Life Expectancy Rates in Years (this excludes garments of leather, suede and fur, as well as household furnishings). Part of Table I from Drycleaning Institute of Australia Ltd, 2015, page 23)

MEN'S AND WOMEN'S WEAR		Years
1. Bathing Suit		2
2. Blouses, (Dress and Sports)		
	white cotton	3
	coloured, cotton, silk & synthetic	2
3. Choir & Religious Robe		5
4. Coats, Jackets and Blazers		
	cloth (dress and sport)	4
	pile	3
	fur (imitation)	3
	leather and suede	5
	imitation suede	3
	wool	4
	cotton and blends	3
	plastics	2
	flocked or coated	2
5. Denim		
	Jackets	3

MEN'S AND WOMEN'S WEAR		**Years**
	jeans or skirts	2
	bleached or stonewashed	3
6. Dresses		
	Casuals	1
	Fancy	2
	Evening	3
	high fashion	2
	imitation suede	3
	wedding (See Section 6)	
7. Dressing Gowns		
	Wool	3
	Lightweight	1
	quilted and heavy	3
	silk	2
	other	2
8. Formal Wear		5
9. Gloves		
	Fabric	1
	Leather	3
10. Hats		
	felt and straw	2
	fur	5
	fabric	2
11. Jumpers and cardigans		
	Wool	4
	wool blends	3
	synthetics	3
12. Neckties		1
13. Plastics Apparel		2
14. Rainwear and Windbreakers (Anoraks)		
	film and plastics coated	2
	fabric	3
	rubber (wash only) and plastic	3
15. Scarves		2
16. Shirts		
	Plain	2
	wool or silk	2
	casual cotton blend	3
	other	2
17. Ski Jackets		
	Fabric	3
	Quilted	2
	rubber and plastic	2
18. Skirts		
	Wool	4
	Cotton	2
	Leather	5
	Other	2
19. Suits		
	summer weight	3
	wool or wool blends	3
	cotton and synthetic	2
	winter weight wool	4
	wash suits	2
	imitation suede	2
20. Trousers, Slacks & Shorts		
	wool or wool blends	4
	cotton blends	2
21. Underwear		
	Socks	1
	foundation garments	1

MEN'S AND WOMEN'S WEAR		Years
	underpants	1
	lingerie	2
22. Vests		2
23. Windjackets (see #14)		
24. Work Uniforms		1
CHILDREN'S WEAR		**Years**
1. Coats & baby sets		2
2. Dresses		2
3. Suits		2
4. Playclothes		1

The clothing longevity protocol supports companies that wish to produce clothing with potential for longer lifespans than current practice of quality assurance throughout the production chain and garment performance testing (Cooper et al., 2014). In their work, they have estimated the current lifetimes of various types of clothing, and suggest a target lifetime that is one third longer than the current practice (see section 4.3 on best practice). They also estimate the average days and hours of wear for which the garments are used, wash frequency and average number of washes for the target lifetime. These estimates are given in Table 54.

Table 54 Garment longevity wash and wear examples (Figure 2 from Cooper et al., 2014)

Row	Longevity factors	Knitwear	Shirt	Jeans	Socks	T-shirt
A	Current lifetime estimate based on WRAP data (years)	3.7	3.6	3.1	1.8	3.3
B	Target lifetime: increase of one third (years)	5	5	4	2.5	4.5
C	Average wear days per year[21]	30	16	75	50	25
D	Implied wear days per month[22]	2.5	1.3	6.2	4.2	2.1
E	Total days of wear for the target lifetime[23]	150	80	300	125	112.5
F	Hours of wear for the target lifetime[24]	1,800	960	3,600	1,500	1,350
G	Assumed days of wear per wash[25]	5	2	10	2	2
H	Hours of wear per wash[26]	60	24	120	24	24
I	Average number of washes for the target lifetime[27]	30	40	30	62	56

The UK Waste and Resources Action Programme (WRAP) guide for design for clothing longevity suggests that natural fibres such as wool, or silk or linen blends, are better choices for fabric longevity than synthetics because they resist dirt and breathe better compared to synthetics that are more likely to retain body odour (McQueen et al., 2008). However, they suggest using blend materials with polyester to improve abrasion resistance and shape retention (Cooper et al., 2013, p. 32). This seems to agree with the findings from the Nielsen study (The Nielsen Company, 2012c), where garments of wool blends were reported to be somewhat older than pure wool products.

Effect of lifespan on clothing impacts

These studies show that clothing lifespan varies greatly in length depending on garment type and type of use, as well as fibre content and user related aspects such as the age, gender, income and area of living. They also show that empirical data is really difficult to obtain, as most of

[21] Working assumption (validated by industry interviews)
[22] Row C / 12
[23] Row B x Row C
[24] Row E x 12 (assumed average 12 hours wear per day)
[25] Working assumption (validated by industry interviews)
[26] Row G x 12
[27] Row F / Row H

the studies are based on consumers’ own reported behaviour, and they may not know or be aware of how old all their garments are, especially elderly consumers who may have items that are several decades old among their clothing. In addition, estimating the lifespans of pre-owned and second-hand clothing is really challenging.

Most Western consumers own a large amount of clothing, and do not necessarily remember when each item was acquired. Garments are not labelled with year of production, and therefore acquiring information is difficult in general, and especially challenging when it comes to second-hand clothing. The variations are great between garments, as some are used intensively over long periods of time, and others are barely used during the time they are owned. In addition, the active use period is often much shorter than the period over which the clothing is owned. A wardrobe study of disposed clothing showed that the average time from when a garment was last used until disposal was 1.4 years. The estimates based on wardrobe studies and on questions of the age of the garment being worn by respondents, gave longer estimates of lifespan than many other studies. This is likely connected to the fact that consumers own a lot of clothing. The more clothing we own, the less each item is used on average. Clothing does not get worn out by being stored in the wardrobe. Results from various studies on clothing lifespans are collected in Table 55, including the average and the range of values. It shows that the lowest estimate was often (but not always) for the UK and the highest for Holland, but this may reflect the method used in the study, rather than real differences.

Table 55 Summary of garment lifespan from various studies and estimated average lifespan based on these data (only the period with one current owner is used, not the total age of preowned clothes)

<table>
<tr><th>Garment type</th><th>Seven countries Nielsen 2012c</th><th>Norway (textile waste)</th><th>Norway survey Klepp & Laitala 2016</th><th>UK Langley et al., 2013</th><th>UK Cooper et al 2014</th><th>Holland Uitdenbogerd et al 1998</th><th>Holland Uitdenbogerd 2007</th><th>Four countries Gwozdz et al. 2017</th><th>Finland Aalto 2014</th><th>Total lifespan, average and range</th></tr>
<tr><td>T-shirts</td><td>4.6</td><td rowspan="3">4.2</td><td></td><td>4.0</td><td>3.3</td><td>6.8</td><td></td><td>3-4 years</td><td>4.5</td><td>4.6 (3.3-6.8)</td></tr>
<tr><td>Blouses / shirts</td><td>4.6</td><td>5.6</td><td>3.3 / 4.3</td><td>3.6</td><td>7.2</td><td></td><td></td><td>5.7</td><td>4.8 (3.3-7.2)</td></tr>
<tr><td>Jumpers / sweaters</td><td>5.8</td><td>10.8 (wool)</td><td>4.5</td><td>3.7</td><td>7.1</td><td>6.17 (wool)</td><td></td><td></td><td>6.0 (3.7-10.8)</td></tr>
<tr><td>Suits</td><td>8.7</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>8.7</td></tr>
<tr><td>Jeans</td><td>3.9</td><td rowspan="2">4.3</td><td></td><td>3.8</td><td>3.1</td><td></td><td rowspan="2">2.45 (cot-ton)</td><td>3-4 years</td><td></td><td>3.5 (2.5-4.3)</td></tr>
<tr><td>Trousers / pants</td><td>4.9</td><td>4.4</td><td>5.4</td><td></td><td>6.2</td><td></td><td rowspan="2">5.3</td><td>4.7 (2.5-6.2)</td></tr>
<tr><td>Skirts</td><td>4.8</td><td rowspan="2">4.1</td><td></td><td>5.2</td><td></td><td rowspan="2">15.2</td><td></td><td></td><td>6.9 (4.1-15.2)</td></tr>
<tr><td>Dresses</td><td>4.5</td><td></td><td>4.7</td><td></td><td></td><td></td><td></td><td>7.1 (4.1-15.2)</td></tr>
<tr><td>Jackets / Blazers</td><td>5.3</td><td rowspan="2">4.0</td><td></td><td>6.5</td><td></td><td>11.5</td><td></td><td></td><td></td><td>6.8 (4.0-11.5)</td></tr>
<tr><td>Coats</td><td>6.3</td><td>6.4</td><td>6.2</td><td></td><td>11.6</td><td></td><td></td><td>7.6</td><td>7.0 (4.0-11.6)</td></tr>
<tr><td>Underwear briefs / boxers</td><td>2.5</td><td rowspan="2">4.4</td><td></td><td>2.4</td><td></td><td></td><td></td><td></td><td rowspan="2">3</td><td>3.1 (2.4-4.4)</td></tr>
<tr><td>Bras</td><td>3.0</td><td></td><td></td><td></td><td></td><td></td><td></td><td>3.5 (3.0-4.4)</td></tr>
<tr><td>Socks</td><td>3.6 (incl. stock-ings)</td><td>2.9</td><td></td><td>2.4</td><td>1.8</td><td></td><td></td><td></td><td>2.3</td><td>2.6 (1.8-3.6)</td></tr>
</table>

When comparing garments of each type made of different fibres, the Nielsen survey showed that woollen garments on average had a 55% longer lifespan than cotton garments (6.2 years as opposed to 4.0 years). Similarly, the Textile waste garment registrations showed that even though the life with the current owner had a similar length (4 years), the difference in total lifespan including previous owners was 58% longer for woollen garments than for cotton garments (9.0 years compared to 5.7 years).

3.3.1 Number of clothing items owned

We are interested in the amount of clothing each consumer has access to. Usually, this is referred to as clothing they "own". This does not take into account that studies show that people also use clothes they do not own themselves, either because they borrow, share, rent or use clothing owned by others, such as their employer (Klepp & Laitala, In press). We disregard this question and use "owned" to cover the clothing consumers have access to. Studies of clothing ownership can be based on various forms of inventories or audits, that is, counting the items, or surveys where the consumers estimate the number of items they own. There are also other ways to estimate the amount of clothing based on top-down methods where statistics on clothing purchases, import, export and waste are used to estimate the over-all numbers (Klepp & Laitala, 2015). The number of clothing items owned affects how much they are worn on average.

Most of other studies on wardrobe sizes are based on surveys where the respondents are asked to estimate the number of clothing items. According to a global wardrobe audit conducted by the Nielsen Company in seven countries in 2012, male respondents estimated that they own on average 114 items of clothing. The Chinese reported having the least amount of items, 69 garments, while the Americans reported to have the most, 124 garments. Women reported owning on average 131 items of clothing. The British have the most clothes, 155 items, whereas the Chinese have the least, 90 items of clothing.

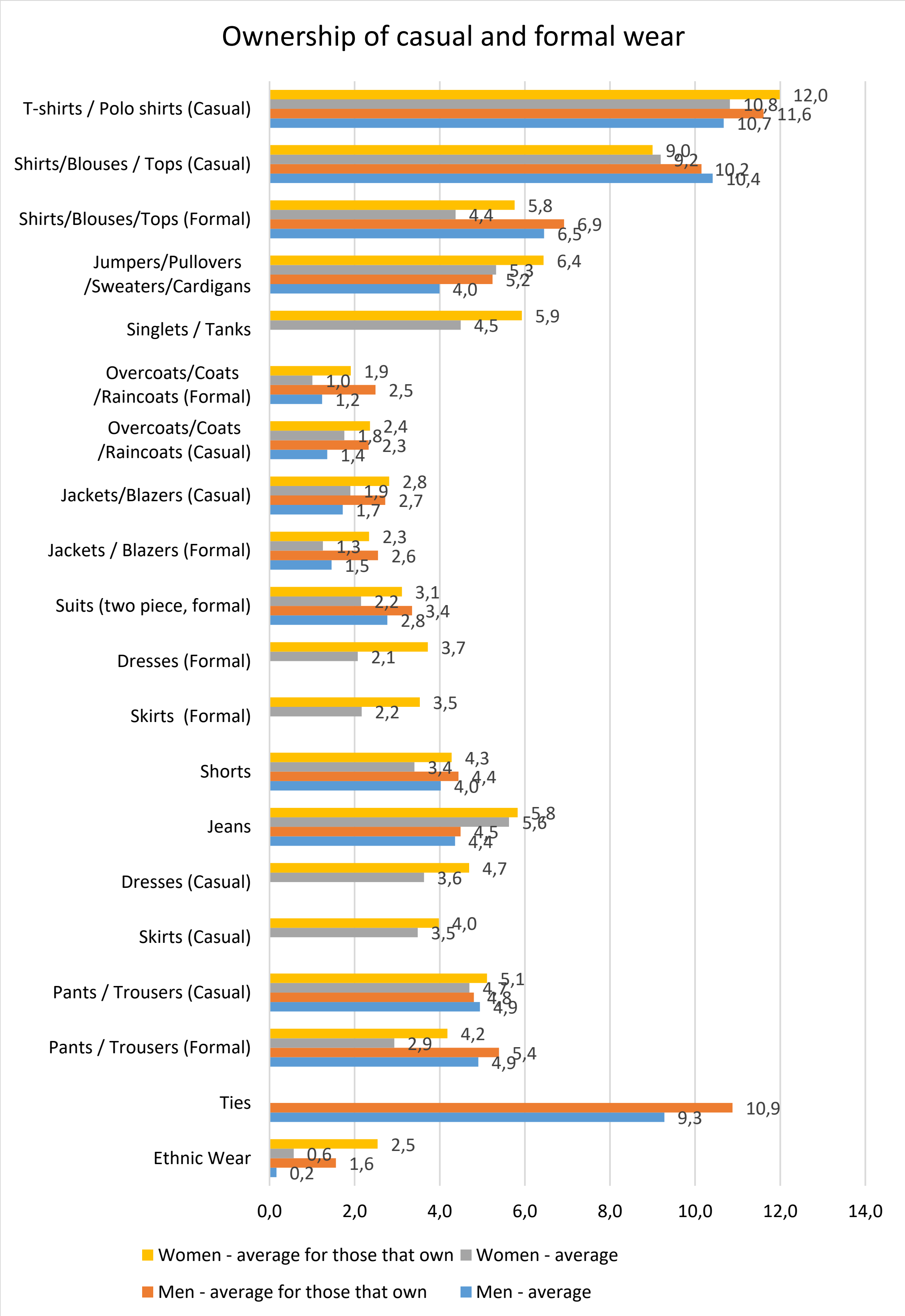

Figure 30 Number of garments of each type (e.g. shirts/blouses) in casual everyday wear or formal work wear categories, averaged across all respondents and across respondents owning that item. Data for men and women presented separately. (The Nielsen Company, 2012)

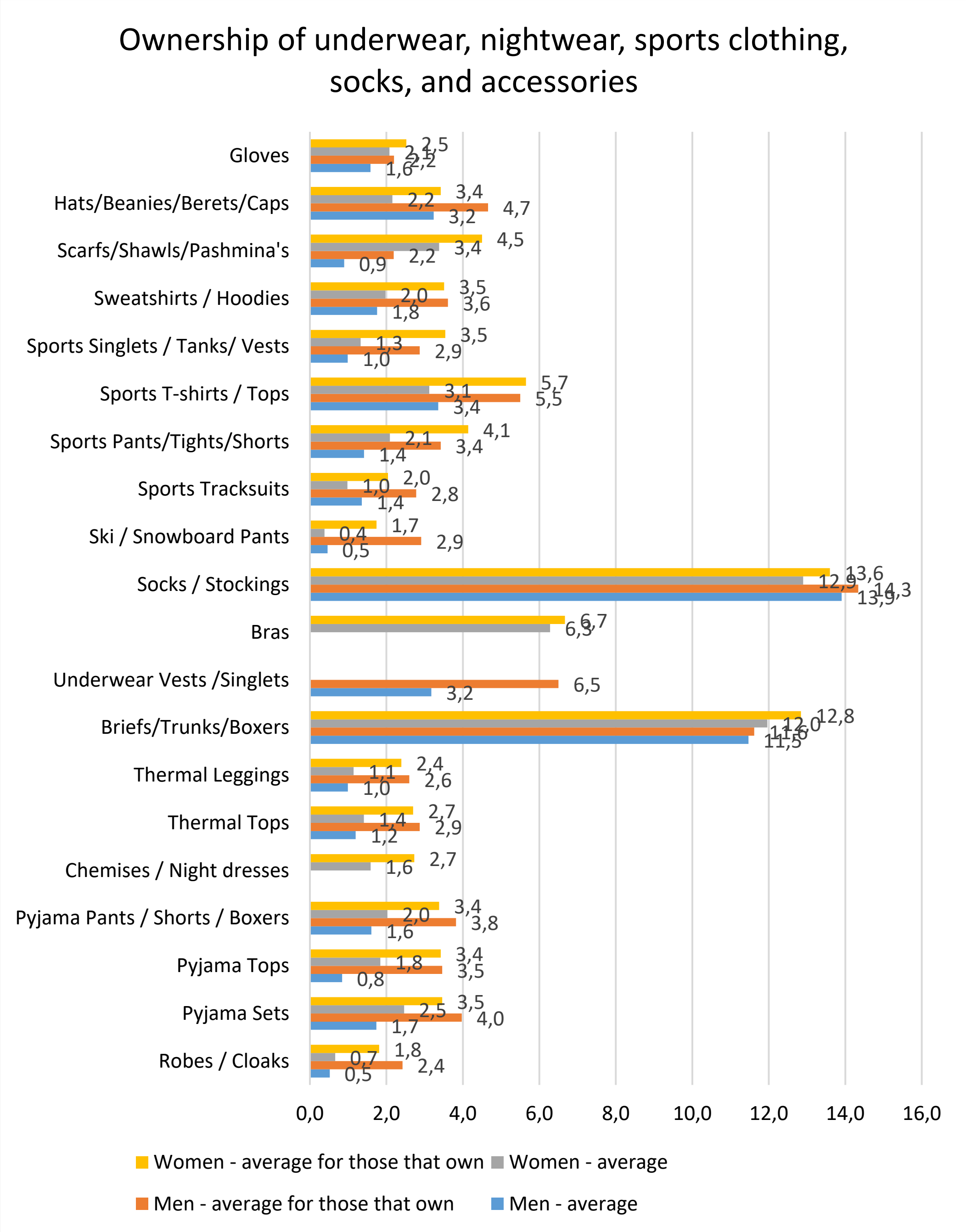

Figure 31 Number of garments of each type (e.g. underwear, nightwear, sports clothing, socks, and accessories), averaged across all respondents and across respondents owning that item. Data for men and women presented separately (The Nielsen Company, 2012)

Other studies conducted in the UK have shown that respondents on average claim to have from 115 items of clothing (Gracey & Moon, 2012) to 127 items (Langley et al., 2013) in their wardrobe (excluding footwear and accessories).

Wardrobe studies of 50 adults in the Netherlands showed that they had on average 130 clothing items (excluding socks and underwear but including shoes and accessories). Based on sales statistics, the number of socks and underwear was estimated to be 43 sets, resulting in a total wardrobe size of 173 clothing items (Maldini et al., 2017). The respondents were asked to estimate the number of items they owned before they were counted, and they had on average 22.7 items (21%) more than they thought they had. The estimation would likely have been even more difficult if socks and underwear were included in the count. The largest wardrobes were around 300 items, and the smallest 40 items (excluding socks and underwear). Similar wardrobe study of fifty people in Germany showed that they owned on average 29 clothing items more than the Dutch; 159 items excluding socks and underwear (Maldini et al., 2017).

Table 56 Average number of clothes owned in the Netherlands (Maldini et al. 2017).

Garment category	Average number of garments per person
Coats and jackets (including rain jackets and sport jackets)	5.7
Shoes and boots (pairs)	9.6
Bags (only bags used as clothing accessories)	4.6
Scarves and shawls	5.1
Hats	3.3
Gloves (pairs)	2.2
Suits	1.1
Trousers	9.5
Jeans	8.2
Shorts (including sportswear)	5.5
Sweaters and cardigans	14.1
Short-sleeve T-shirts	25.6
Long-sleeve T-shirts	11.7
Blouses and shirts	11.5
Dresses	3.9
Jumpsuits	1.0
Skirts	3.0
Other	4.5
Total	**130.0**

A British survey of 7950 respondents included a question of how many clothing items they owned in different categories, and how many of those they had not worn in the last 12 months (Gracey & Moon, 2012). Figure 32 gives the average result for each category. Some of these garments are more gender specific, such as ties, and it is therefore likely that men own more of the items, and women less, than the average value indicates. The results show that about 30% of clothing items owned are inactive and have not been in use during the past year, which is a larger number than in the studies presented in 3.3.2.

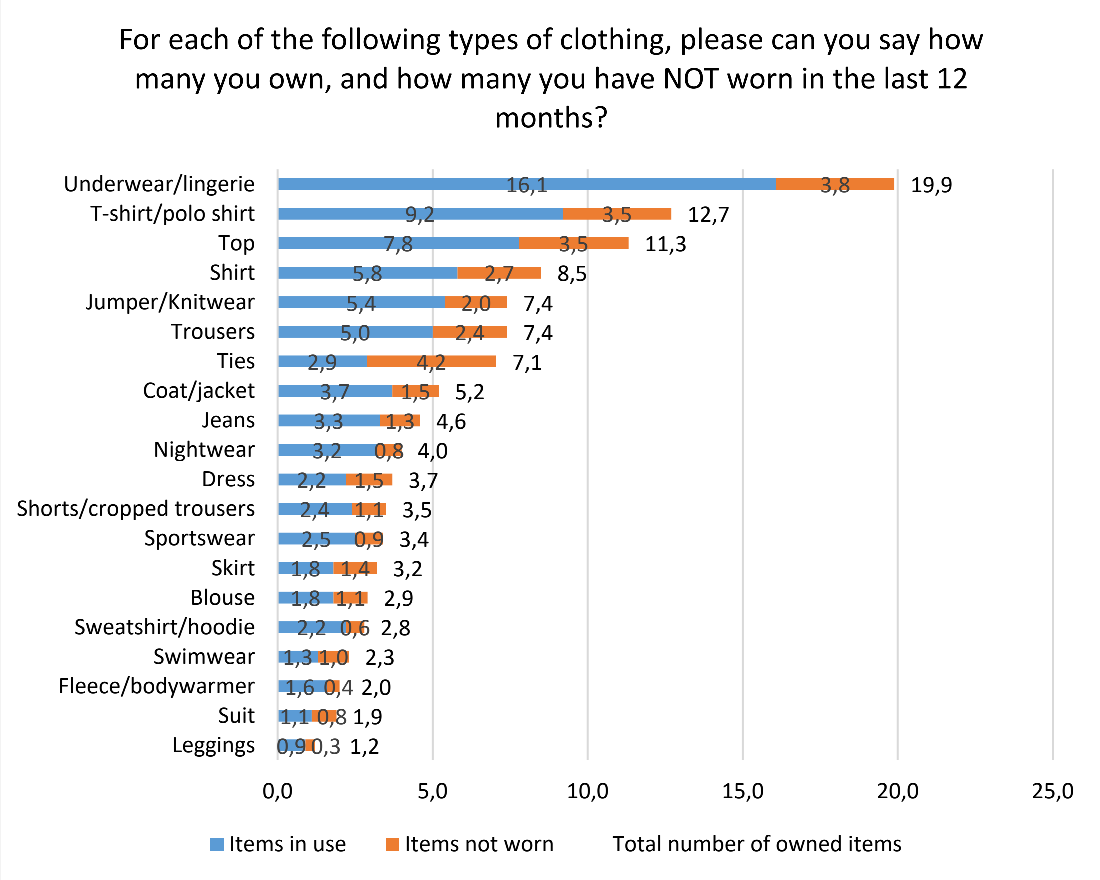

Figure 32 Clothing ownership and number of unworn items in the UK (Figure 16 from (Gracey and Moon, 2012)

A consumer survey in four countries asked questions about jeans and t-shirts. The results showed that the respondents estimated they possessed 18.6 ± 12.72 t-shirts and 6.00 ± 4.90 pairs of jeans (Gwozdz et al. 2017). Another Swedish survey showed similar results, as respondents estimated they had on average 6 pairs of jeans (Granello et al., 2015)

In Finland, crafts education students of the University of Helsinki have made a systematic yearly inventory of their clothing items during the past 20 years (Aalto 2014). The sample cannot be considered representative for the average population, but the results given in

Table 57 show how the number of clothes owned by this group has almost doubled since 1990, and that the total number is much higher than the estimates that are given in previously presented surveys. This was also observed in a study of a single wardrobe in Oslo, where the owner first estimated how many clothing items she had in different categories, and then calculated them. The difference between what she assumed and what she found was large. This was particularly true when she owned several items of a particular type of clothing. She believed she had 15 T-shirts but had 34, 13 of which she did not use. For small items the difference was even greater. She had 54 panties, not 23 and 187 pairs of socks, not 53, and 22 scarves, not 10. In total, she thought she had 227 garments but had over twice as many, 519. Of these, approximately 10% were passive (Klepp and Laitala, 2015). Her estimate of the number of clothes was also initially almost two times higher than the averages presented in the surveys in the UK and other countries (The Nielsen Company, 2012; Gracey and Moon, 2012; Langley et al., 2013). More comparisons where both of these methods are employed, could be used to correlate survey results for systematic errors, such as the underestimation of the number of clothing items when there are many. There should also be greater emphasis on actual counts rather than the estimated number of owned clothing.

Table 57 Clothing ownership of Finnish textile students (Translated Figure 1 from Aalto 2014)

Type of clothing	Year 1990	Year 2010-2012
Underwear	21	42
Nightwear, bathrobes, dressing gowns	5	9
Socks, stockings, leggings	25	57
Blouses, shirts, sweaters	29	71
Skirts	7	11
Dresses	5	16
Trousers	10	15
Outdoor clothing, sportswear	4	17
Jackets, coats	5	11
Accessories: belts, scarves	14	25
Total	**125**	**274**

3.3.2 Use frequency and inactive clothing

During the use period of clothing, the garments are in active use (worn) only part of the time. A Dutch study showed that adult respondents on average wore 4.4 clothing items and children 4.2 when they were interviewed indoors (Uitdenbogerd et al. 1998). The number of items was mainly affected by whether an undershirt was worn. The use frequency will vary greatly depending on type of garment and other factors such as how many garments the user has available. Studying this is difficult, as most consumers cannot recall how many times, days or hours they have worn a specific item, at least if it has been used more than once or twice. Therefore, surveys and interviews give limited information about this, and other methods such as diaries are more suitable for obtaining accurate data.

We have not found any studies that document the actual use frequency of garments. The topic was included in the Norwegian "Textile waste" project (Laitala 2014), where consumers were asked how often some specific item had been worn, and answers included for example "about weekly at work during the two years' ownership" (Laitala, 2014). Unfortunately, the consumers were not able to give accurate enough answers for most of the garments to enable analysis of the results in detail, except for the items that were used very little. This and another Norwegian study on clothing to be disposed of, showed that 20% of garments were either never used or used only a couple of times by the current owner (8-9% were never used by anyone) (Klepp, 2001, Laitala and Klepp, 2013).

A survey in the UK showed that respondents estimated that about 20.5% of their clothing items (excluding footwear and accessories) had not been worn in the last 12 months (Langley et al., 2013), which is close to the Norwegian estimates. Another study in the UK indicated even higher rate of inactive clothing, 30.4% (Gracey & Moon, 2012). This is close to values provided by a Dutch wardrobe study that showed that on average, 28% of the garments had not been worn during the past year (Maldini et al., 2017). The share of inactive garments varies between different garment types.

Table 58 shows that largest share of inactive garments could be found in ties, jumpsuits, hats, dresses, scarves and skirts, while the smallest share of inactive garments could be found in underwear, nightwear, coats, jackets, sweaters and cardigans (Gracey & Moon, 2013; Maldini et al., 2017). In Germany, where the average wardrobe size was larger, the share of inactive garments was also higher, 30% (Maldini et al., 2017).

Table 58 Share of inactive items in different garment and accessory categories in the Netherlands and in the UK (Maldini et al. 2017; Gracey & Moon, 2013).

Garment category	The Netherlands (Maldini et al., 2017)	UK (Gracey & Moon, 2013)
Coats and jackets	19 %	30 %
Shoes and boots (pairs)	24 %	-
Bags (only bags used as clothing accessories)	16 %	-
Scarves and shawls	36 %	-
Ties	-	59%
Hats	42 %	-
Gloves (pairs)	25 %	-
Suits	30 %	43 %
Trousers	26 %	32 %
Jeans	27 %	28 %
Shorts	29 %	32 %
Sweaters and cardigans	22 %	23 % (sweatshirt/hoodie) 27 % (jumper/knitwear)
Fleece/bodywarmer	-	21%
T-shirts/polo shirt	28 % (short sleeve) 32% (long-sleeve)	27%
Top	-	31%
Blouses and shirts	26 %	38% (blouse) 32% (shirt)
Dresses	36 %	42%
Jumpsuits	43 %	
Skirts	36 %	42%
Underwear/lingerie	-	19%
Leggings	-	21%
Swimwear	-	42%
Sportswear	(included in other categories)	28%
Nightwear	-	21%
Other	35 %	
Total	**28 %**	**30%**

Wardrobe ethnography interviews in seven countries showed that many respondents used the “high-care” items that require dry-cleaning more seldom than casual wear (The Nielsen Company, 2012a). This was especially mentioned for woollen garments in the USA and China.

Cooper et al. (2014) estimated use frequencies of five different garment examples as indicated previously. According to their assumptions that were validated by industry interviews, jeans have the highest wearing frequency of 75 wears per year, followed by socks (50 wears), knitwear (50 wears), t-shirts (25 wears) and finally shirts (16 wears). They indicated that each clothing item is worn 12 hours per wearing day, but this will also vary depending on how many times a day the user changes clothing. For example, sportswear is likely to be worn shorter periods per instance of wear, mainly during the activity. Many people also change to casual clothing after coming home from work.

A consumer survey conducted in four countries (USA, Germany, Sweden and Poland) asked questions about the use of jeans and t-shirts. The results showed that the respondents estimated they kept these items for about 3-4 years and wore them at least monthly, in total 36 to 48 times during their use period (Gwozdz et al. 2017). Another survey in Sweden reported a much longer use period, as 93% of respondents said they wore their jeans at least 100 times before disposing of them (Granello et al. 2015). Another survey concentrated on woollen socks and garments, and these results indicate wear frequency of 9.2 wears per month for socks, and 8.3 wears for the next-to-skin garment (Slocinski & Fisher, 2016).

3.4 Reuse

Clothing reuse is usually defined to occur after the clothing changes owner and the new owner starts using the item. These items are usually called second-hand or pre-owned clothes. Here, we review literature that discusses consumers' second-hand clothing acquisition behaviour, in order to see to what degree reuse is likely to replace new purchases, and if there are differences in reuse of clothing made of different fibres.

Quite a few studies have focused on second-hand clothing acquisition behaviour, and then especially on aspects such as which consumer types are likely to acquire clothing in this manner, and what their motivations are for this. The focus has mainly been on second-hand markets where used clothing is exchanged for money, instead of looking into the exchanges that occur in private spheres such as inheritance, gifting and hand-me-downs within families and circles of friends.

As opposed to the limited number of studies on informal clothing circulation, many studies have focused on the proportion of the population that have bought second-hand clothing. In Sweden, Ekström et al. (2012) reported that 23% had bought second-hand clothing during the past year. This survey targeted low-price shoppers where women constituted the majority of respondents. In the US, a survey among 282 adult women showed that 6% bought second-hand clothing often, 46% sometimes and 49% never (Stephens, 1985), while some later figures for college students are higher, as 80% of them had sometimes acquired second-hand clothing, and 20% did so on a regular basis (Hiller Connell, 2009).

Gwozdz et al. (2017) asked respondents in four countries (Germany, Poland, Sweden, and the U.S.) to estimate the clothing materials they typically acquire. The results showed the majority of acquired clothing is made of conventional new materials (61.1%), followed by organic new materials (17.8%), reused second-hand products (13.2%) and last, recycled products (7.8%). However, the share of organic materials is higher than what is available on the market, which makes this estimate likely to be too high. Nevertheless, it shows that respondents in these four countries estimate that substantial part of the clothing they acquire is either reused or recycled (21% in total).

One of the few studies that includes gifts is from the UK. According to Gracey and Moon, 51% of the British adult population had sometimes bought clothing from charity shops, 39% from online sites for used items, 28% had bought clothing from vintage shops, and 25% had received clothing from friends or acquaintances (Gracey and Moon, 2012).

In the UK, there are relatively good studies on the consumption of clothing, but private exchange of clothing has only been tentatively estimated. The studies assume this amounts to 100 000 tons per year, compared to 350 000 tons collected for recycling and reuse by charitable and commercial organizations (Morley et al., 2009).

However, for the purpose of this study, it is more important to know to which degree these acquisitions replace purchase of new items. Farrant et al. (2010) studied the rate at which reuse of clothing replaces purchase of new items, and conclude that it varies depending on where the reuse takes place. Based on a survey of second-hand clothing customers in Sweden, Denmark and Estonia, purchase of 100 second-hand garments would save 60 new garments if the reuse takes place in Sweden/Denmark, and 75 new garments if the reuse takes place in Estonia. In addition, based on secondary sources (Baden and Barber, 2005, Hansen, 2004), they assume that the replacement rate in Sub-Saharan Africa is high, about 85%.

Data from a Norwegian textile waste project show that many of the woollen items had a previous owner, thus confirming that consumers attach more value to wool and, therefore, prioritise reusing it instead of binning it (Figure 33).

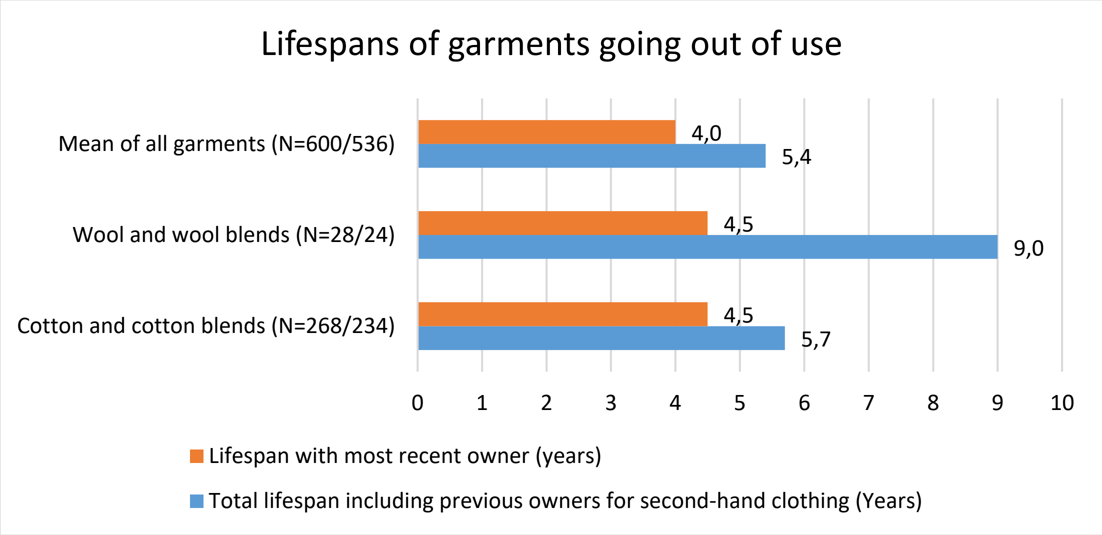

Figure 33 Length of clothing lifespans by fibre type for clothing collected in a Norwegian textile waste project

A wardrobe study in the Netherlands showed that 5.5% of the garments were pre-owned (Maldini et al., 2017). The share was higher in women's wardrobes (6%) than in men's wardrobes (4%). The figures were similar in Germany, where 10% of women's clothing and 4% of men's clothing was preowned. In both countries, young respondents (aged between 18 and 30) owned more second-hand items than elder respondents. The largest share of second-hand items were found in categories for "other", dresses, bags, hats, sweaters and cardigans, and the least among long-sleeve T-shirts, shoes and gloves. This wardrobe analysis excluded socks and underwear.

Table 59 Average percentage of second-hand garments and accessories in the Netherlands (Maldini et al. 2017).

Garment category	**Percentage of second-hand garments in each category**
Coats and jackets (including rain jackets and sport jackets)	5.6 %
Shoes and boots (pairs)	1.9 %
Bags (only bags used as clothing accessories)	8.7 %
Scarves and shawls	5.5 %
Hats	8.4 %
Gloves (pairs)	2.8 %
Suits	3.7 %
Trousers	4.4 %
Jeans	6.8 %
Shorts (including sportswear)	3.3 %
Sweaters and cardigans	7.2 %
Short-sleeve T-shirts	5.9 %
Long-sleeve T-shirts	1.5 %
Blouses and shirts	5.9 %
Dresses	8.8 %
Jumpsuits	4.1 %
Skirts	6.7 %
Other	11.1 %
Total	**5.5 %**

3.5 Fate at the end of use

This section includes studies that document the behaviour of consumers when they are about to stop using clothing, i.e. how they dispose of the garments.

A literature review of studies of clothing disposals over the past 30 years showed that most consumers prefer to deliver clothing for reuse rather than to bin them, but convenience is paramount (Laitala, 2014b). Common reasons for disposal of apparel were wear and tear, poor fit and fashion or boredom, in addition to lack of storage space. The studies that reported destination of clothing after use are included in Table 60.

Table 60 Review of consumer studies that included destination of clothing after use (based on Laitala 2014b)

Publication	Sample	Country	Clothing destinations
Stephens (1985)	Survey of 282 adult females at a shopping mall	USA	53.2% recycled more than half of their clothing and 29.1% recycled over three fourths of the wardrobe (meaning either remodelled, sold, donated or gave to friends or family).
Chun (1987)	Survey of 89 females aged 18-30 (college) Average age 19.8 years	USA	Garment most recently gone out of use: saved it 39.3%, charity 27.0%, friends 19.1%, sold on consignment 5.6%, threw it away 4.5%, sold at garage sale 2.2%, used as rags 1.1 %
Francis and Butler (1994)	Survey of 402 adult females	USA	Most commonly disposed to charity, followed by giving to friends, saving for the future, for rags, and selling at garage sales. Least often used methods were selling through consignment store and reusing/remaking.
Koch and Domina (1997)	Survey of 277 College students (82% female, 91% below the age of 24)	USA	Disposition methods were: passing to family/friends 82%, use as rags 76%, Goodwill/Salvation Army donation 64%, garage sales 42%, modified 38%, church donation 36%, returning to parents for recycling 35% and consignment 30%.
Daneshvary et al. (1998)	Survey of 817 adults, average age 48, 46% female	USA	81% had donated textiles during the past year. 62% supported local curbside textile recycling.
Domina and Koch (1999)	Survey of 396 adults. 88% female, median age 38	USA	Most commonly used disposal methods were rags 88%, donation to Salvation Army/Goodwill 87%, passing on to family/friends 81%, garage sale 44%, religious organizations 41%, modified 35%, and consignment 29%. (Binning was not studied as an option). Damaged textiles were most often used as rags. Less than 1% never recycled.
Walter (2008)	Survey of 194 College students age 18-54, average age 22. 59% female	USA	Students seldom throw away clothing in the trash, as they preferred giving them away, donating, or use them as rags.
Charbonneau (2008)	Survey of 26 women who acquire second-hand clothing and three focus groups	USA	65% of respondents said that they gave more than 3/4 of their family clothing to recycling, charities or friends. Women who consumed second-hand clothing mainly disposed to thrift stores (preferred non-profit organizations), gave to family/friends, repurposed, rejuvenated, recycled or sold. Dumpster disposing was the last option for clothing that could not be reused or repurposed.
Ha-Brookshire and Hodges (2009)	15 interviews of adults age 19-64, average 25, 93% female	USA	Friends and family were preferred receivers, but often not possible due to size or other issues. Then given to charity.
Stall-Meadows and Goudeau (2012)	Survey of 126 adults, 96% female (included students, county fair participants, and church's women's group)	USA	Participants preferred options for good condition clothing was donating, followed by giving to friends/family and selling it, both before and after the information session.
Lee et al. (2013)	71 written essays by undergraduates aged 18-24, 96% female	USA	Participants disposed of clothing usually twice a year. Donation and giving away were most common behaviours. Some also sold, repurposed, redesigned and exchanged clothing.

Publication	Sample	Country	Clothing destinations
			Some was thrown away primarily because it was damaged or worn out. Some garments with sentimental value were stored.
Ungerth and Carlsson (2011)	Survey of 1014 adults between 16 and 74	Sweden	If clothing was not worn out, it was most often donated (52%), given to family/friends (18%), binned (17%), or sold (9%). Worn out garments were most often binned (59%), used as rags (35%) or given to charity (5%). 70% had binned clothing during the past year.
Ekström et al. (2012)	Survey of 689 adult low-price shoppers, 76.5% females. In addition 29 interviews and 3 focus groups	Sweden	In all focus groups, worn out or damaged garments were mainly binned. Swapping participants very seldom binned clothing, and usually either donated them, gave to friends and family, and sometimes tried to repair or make something new from them. Clothes beyond repair were used as rags.
Koukouvinos (2012)	Survey of 201 young consumers age 18-35, 75% female	Greece	Within a time-frame of 2 years, 40% of participants had binned one or more t-shirts, and 70% some other garment. Most popular alternative disposal methods for t-shirts were giving away 29%, donating 25%, and using them as cleaning rags (22%).
Björnman and Kaloper (2012)	Focus groups of 17 young female students aged 20-26	Sweden	Most participants donated clothing, Some also gave to friends/family, and a few participated in clothes swapping events with friends, and a minority sold some garments. Clothing that was damaged was mostly binned.
Klepp (2001)	24 in-depth interviews with 40 year old females, about 329 clothes they disposed of	Norway	The women preferred to give the clothing for reuse to friends and relatives or various types of collections. Throwing away (usable) clothes is associated with guilt and moral qualms.
Gregson and Beale (2004)	Interviews with 20 women, aged 16-early 40's, who were either pregnant or recently had a baby	UK	Maternity wear circulates between wardrobes instead of accumulating like some other clothing items. Given most often to siblings and other relatives, friends, and acquaintances.
Hibbert et al. (2005)	Survey of 210 households	UK	Most common disposal channels for clothing were charity, followed by giving to friends/family and binning. Selling was less common.
Birtwistle and Moore (2007)	Focus groups with 71 young females (age 17-25)	UK	Most frequently disposed to charity (36%), followed by giving to family/ friends (24%), reuse at home (20%), and 7% for each of the following: recycling bins, selling, and throwing away.
Fisher et al. (2008)	9 focus groups with 99 participants	UK	Most participants donated their clothing. Few participants sold their clothing. Children's clothes were often passed on. Some items were kept as a memento.
Moraes et al. (2009)	3 interviews in the UK and 4 in Brazil of middle class mothers in their 30's and 40's	UK and Brazil	Both UK and Brazilian respondents said they either gave clothing to family and friends, or donated it. In the UK, some were also delivered to recycling bins. Respondents said they also repaired clothing.
Bianchi and Birtwistle (2010)	Survey of 504 adults in the UK and 239 in Australia, females above the age of 15.	UK and Australia	In both countries, most common disposal methods are donating (35/44%), giving to family/friends, re-use at home, recycling bins, kerbside rubbish bins and finally selling.
Sung and Kincade (2010)	Survey of 600 adults aged 20-49, average age 34, 50% female	Korea	Respondents were divided into three groups based on their disposition behaviour; resell, donate and non-recycle groups. Donation behaviour was most common
Saunders (2010)	10 interviews of poor consumers aged 25-56, 60% female in Johannesburg	South Africa	Clothing disposition behaviour differed from other items, as when they were considered beyond repair or of no use, participants wanted to destroy them completely through burning.
Gwozdz et al., (2017)	Survey with 4617 adult respondents, over 1000 / country	USA, Sweden, Germany and Poland	The respondents estimated they gave 70.7% of their clothing to reuse, down-cycled at home 15.2%, and binned the remaining share of 14.1%.

The global wardrobe audit conducted by the Nielsen Company (2012c) asked the respondents where they planned to dispose of each of the clothing items they owned when they no longer wanted it. The distribution of answers is given in Table 61, and indicates that about 42.5% of disposed clothing is destined for reuse (either donated or sold), 11.5% is recycled at home, and 31.5% is binned. It was about as common to donate to family/friends and recycle at home, and very uncommon to sell the used products. In addition, for many items respondents chose the 'other' alternative or did not know what they would do with many items (14.5%).

Table 61 Clothing disposal methods that respondents aimed to use in the global wardrobe audit (The Nielsen Company, 2012c)

Disposal method	Men	Women	Average
Donate to charity	24 %	31 %	27.5 %
Donate / give to family / friends	11 %	14 %	12.5 %
Bin	33 %	30 %	31.5 %
Recycle at home (e.g. cleaning cloth)	14 %	9 %	11.5 %
Sell (e.g. garage sale, eBay)	1 %	4 %	2.5 %
Other	6 %	5 %	5.5 %
Don't know	11 %	7 %	9 %

A higher proportion of wool garments were planned to be delivered for reuse (50%) than cotton (42%) or synthetics (44%) (Table 62). Synthetics were more likely to be binned (39%), while cotton products were more commonly recycled at home (i.e. used as rags). When comparing the reuse of cotton and wool, wool is 19% more likely to be delivered for reuse (through charities, family, friends or sold) than are cotton products.

Table 62 Which of the following would you use to dispose of this clothes item or accessory when no longer wanted? Answers were divided according to fibre content, and the average calculated for men and women. (The Nielsen Company, 2012c).

Fibre content	Donate to charity	Donate to family / friends	Bin	Recycle at home	Sell	Other	Don't know	Total for reuse
Cotton and blends	29 %	11 %	32 %	14 %	2 %	6 %	7 %	**42 %**
Wool and blends	27 %	20 %	31 %	9 %	4 %	3 %	7 %	**50 %**
Synthetics	28 %	13 %	39 %	8 %	3 %	5 %	6 %	**44 %**

There were quite large differences between the respondents from different countries (Figure 34). The Japanese did not donate any clothing to charities, and very little to friends/family. They were most likely to bin clothing after use. However, it was more common for Japanese women to sell clothing than for other respondents (8%).

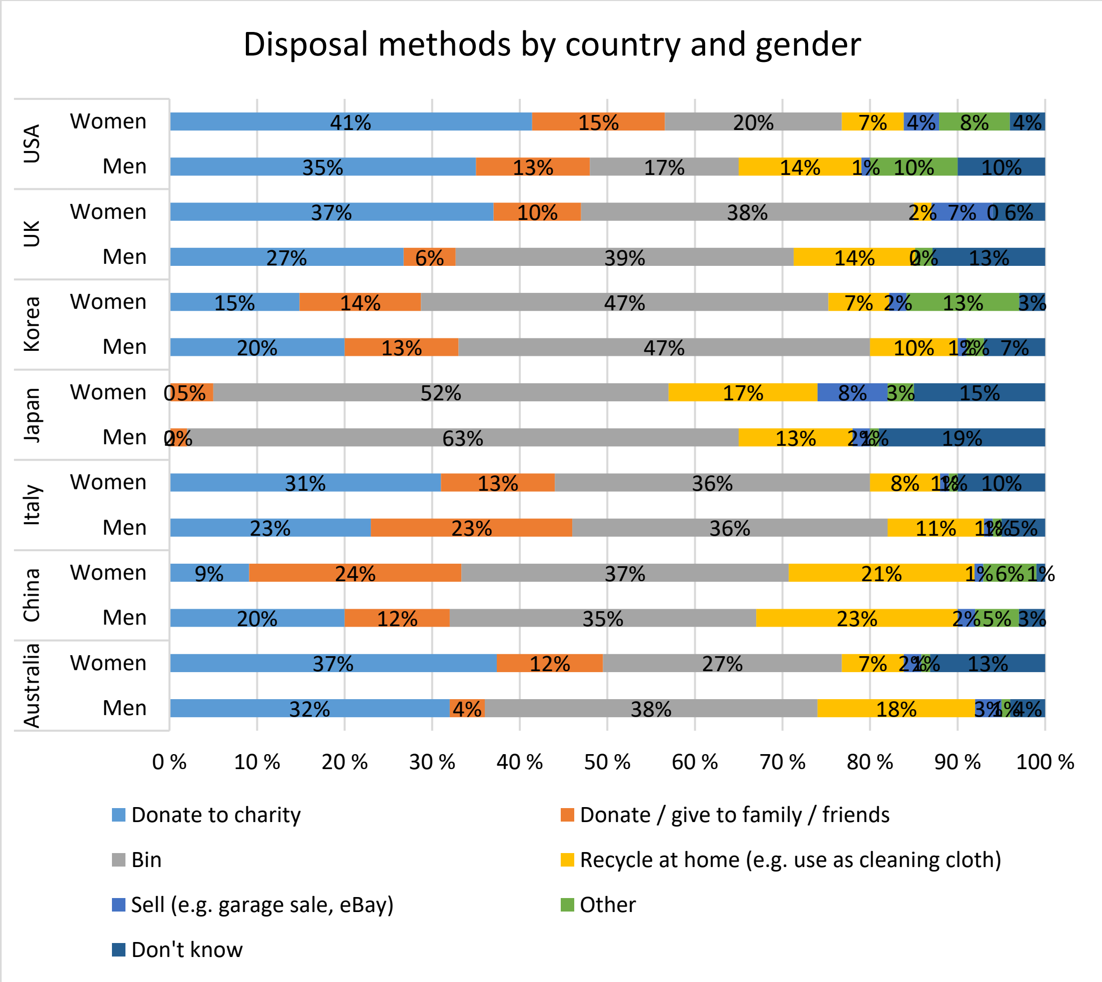

Figure 34 Fate of clothing items divided by country and gender from the Nielsen Company wardrobe study (2012c)

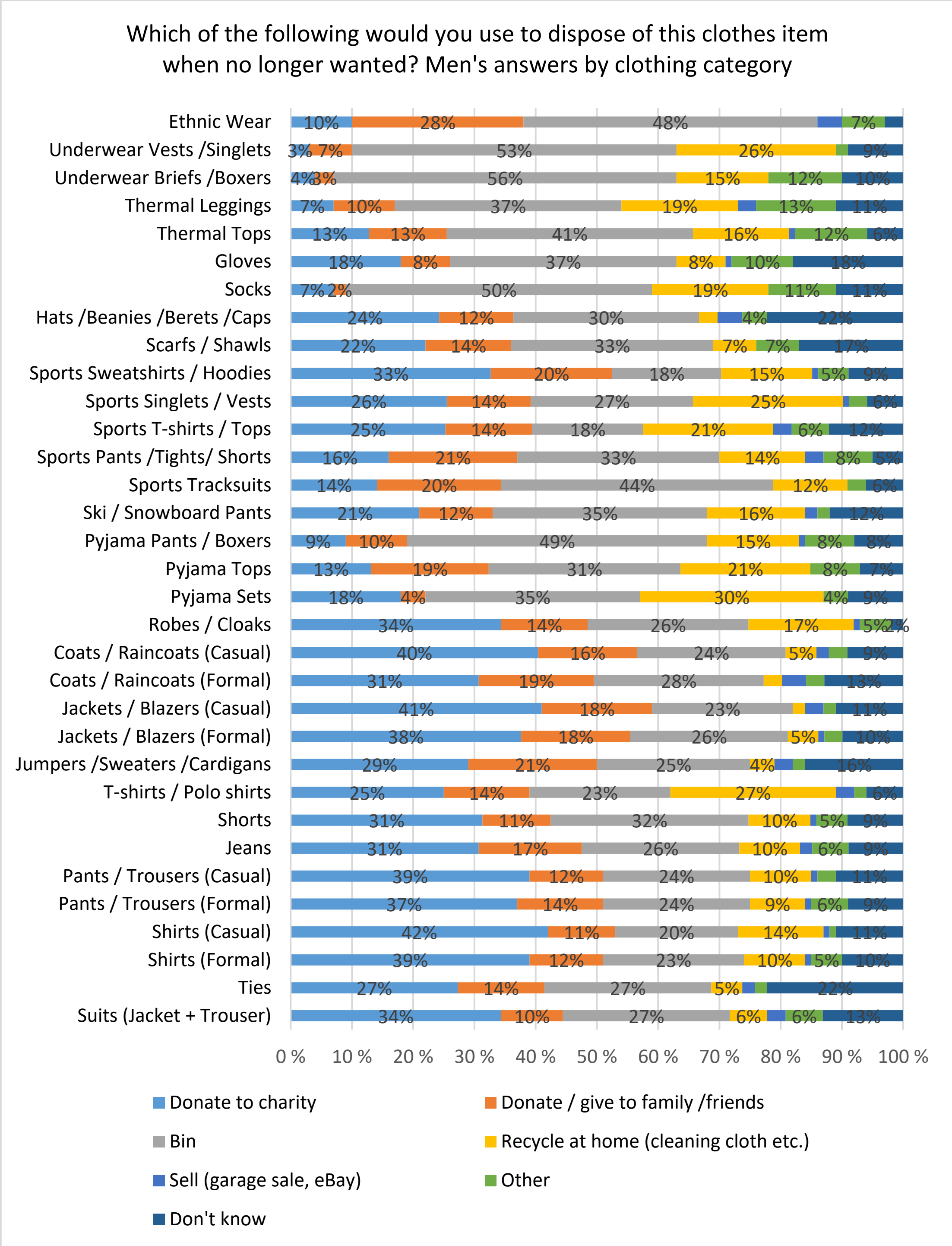

Figure 35 Disposal method nominated by men, specified by type of clothing item (The Nielsen Company, 2012c)

The respondents were more likely to deliver some specific garment types or materials for reuse than others. Donation to charities and family was highest for formal and casual clothes followed by sportswear and accessories. Underwear and socks were typically binned. It was most common to recycle cotton products and nightwear, socks, sportswear and underwear at home.

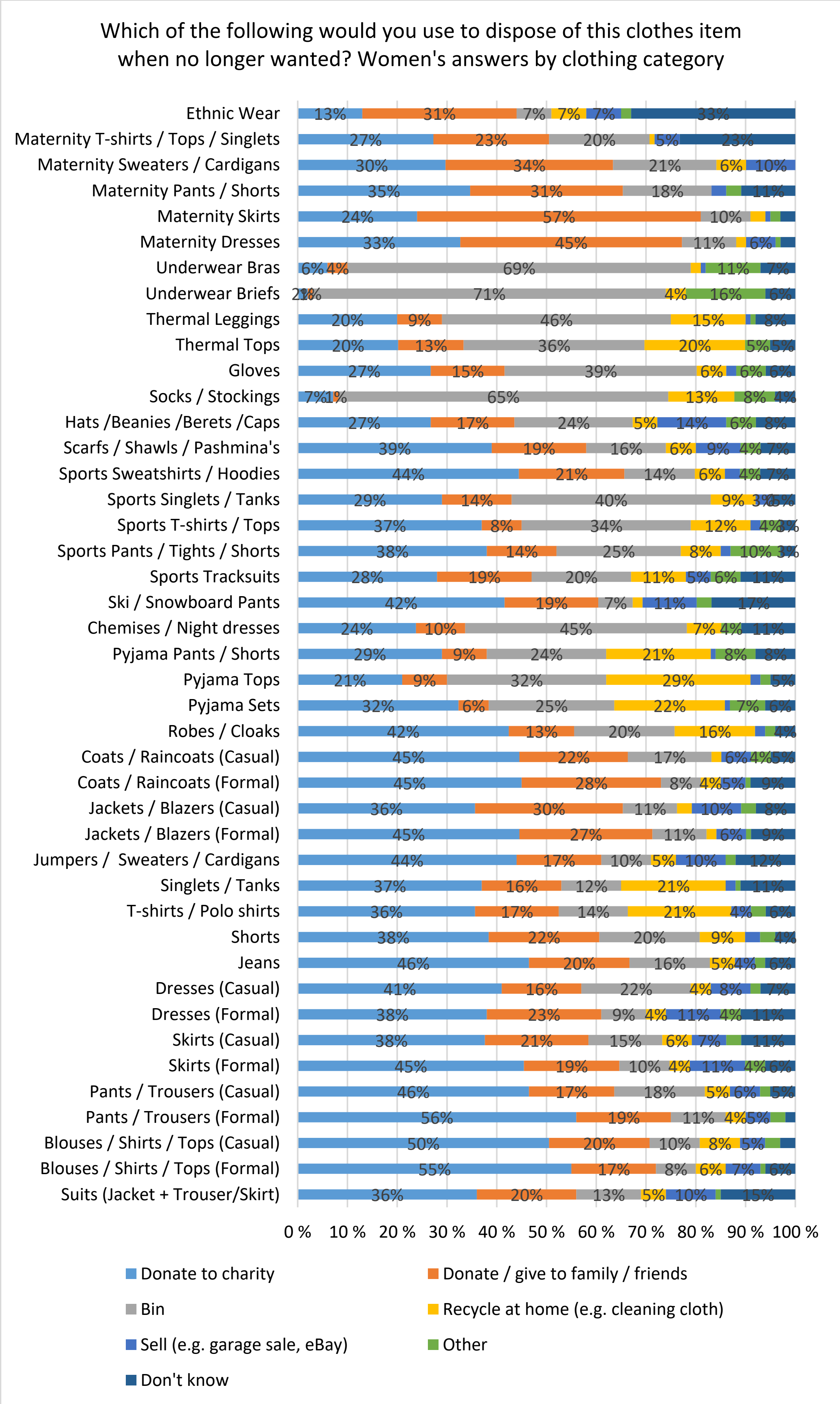

Figure 36 Disposal method nominated by women specified by type of clothing item (The Nielsen Company, 2012c)

This topic has also been studied by many other researchers. The study of disposed clothing in Norway showed how the informants were going to dispose of specific clothing items that actually went out of use (Figure 37). The results showed clearly how different garments are treated differently. Smaller items that often were considered as "consumables" such as socks, stockings and underpants were mainly binned, while the most common disposal channel for other clothing was donating to charity.

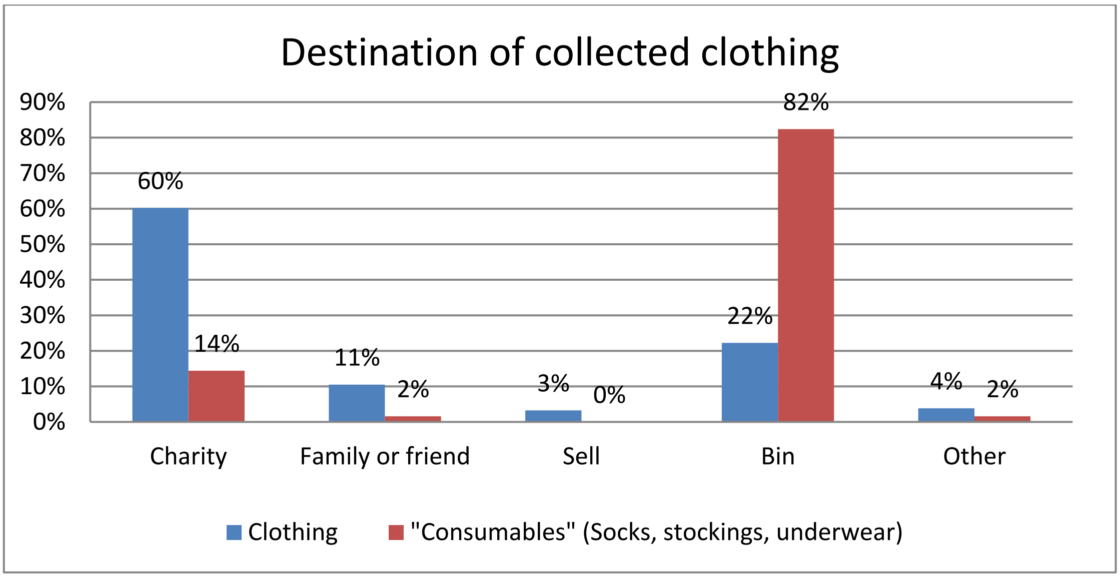

Figure 37 Intended destination of clothing items collected in the Norwegian Textile waste project (Laitala, 2014a)

The data on the materials was reanalysed in order to see if the fibre content was likely to affect the disposal method (Figure 38). Some differences between fibres can be seen, especially among the smaller items (socks, underwear etc.), where 40% of woollen items are intended for reuse, while reuse is planned for only 23% of synthetics and 27% of cotton items. Among larger garments, 68-81% were intended for reuse. Interestingly, even though a larger portion of woollen garments already had a previous owner, 79% were intended for reuse again. The same figure for cotton items was 71%. Wool stands out also in categories of clothing intended to be repurposed, at 5% for smaller items, and 4% of garments are planned to be kept as mementos, indicating higher emotional value.

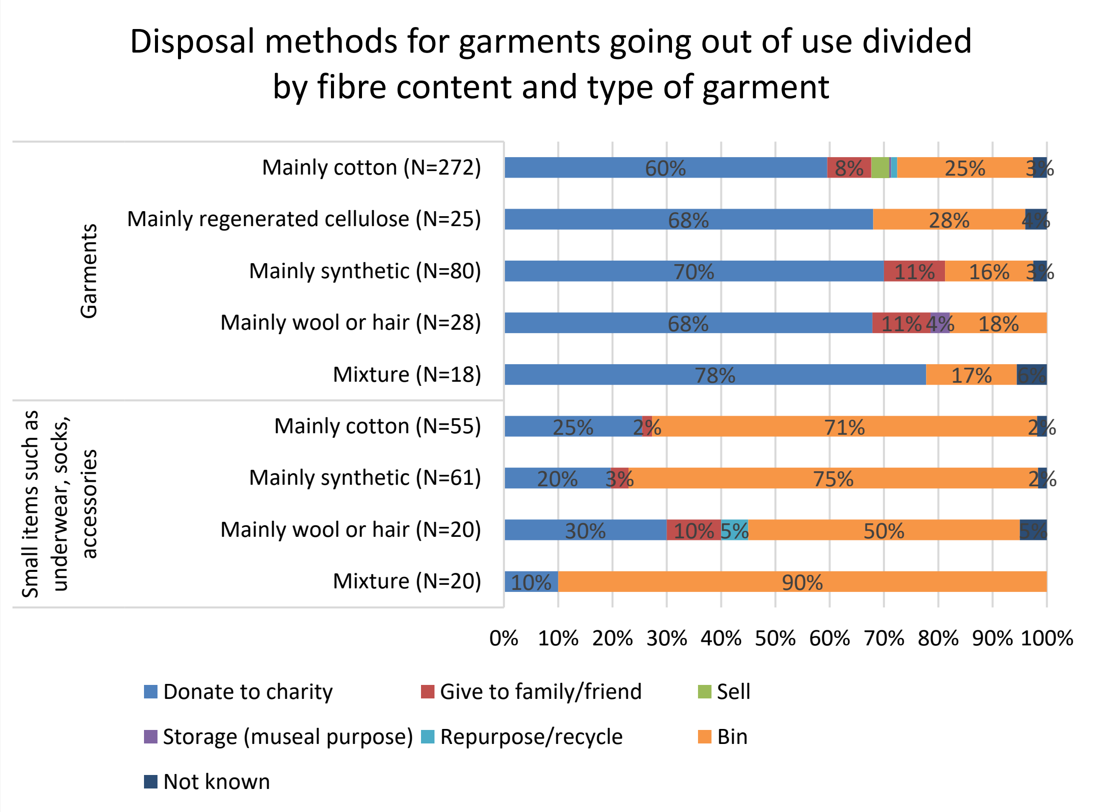

Figure 38 Disposal methods of clothing made of different materials (Norway, unpublished reanalysed material from the Textile waste project, SIFO)

In Finland, survey respondents indicated the share between usable and unusable clothing and household textiles going out of use (Figure 39). Only 13% respondents reported that all clothing they disposed of was unusable. A rough estimate based on a calculation of the share of usable clothing and share of respondents in each category indicates that 54% of all clothing going out of use is still usable, and 44% of all household textiles are usable. These figures seem lower than what other studies report, which may be based on the difference between self-reported behaviour and observations, as well as the selection of respondents that have an above average interest in the topic, and a positive response bias based on social desirability (i.e., over-reporting of "good" behaviour).

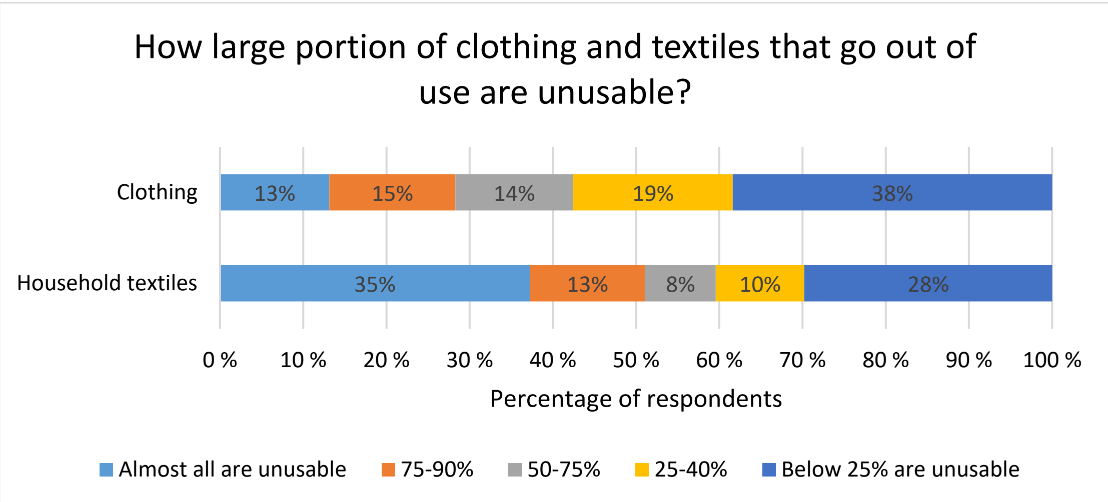

Figure 39 Share of clothing and textiles that is unusable when disposed of. (Translated figure 12 from (Aalto, 2014)

Figure 40 indicates where clothing that is still in usable condition is disposed of in Finland. The main disposal channel is charity. It is more common to give women's and children's clothing to family and friends than men's clothing, while men's clothing was more often material recycled (Aalto, 2014).

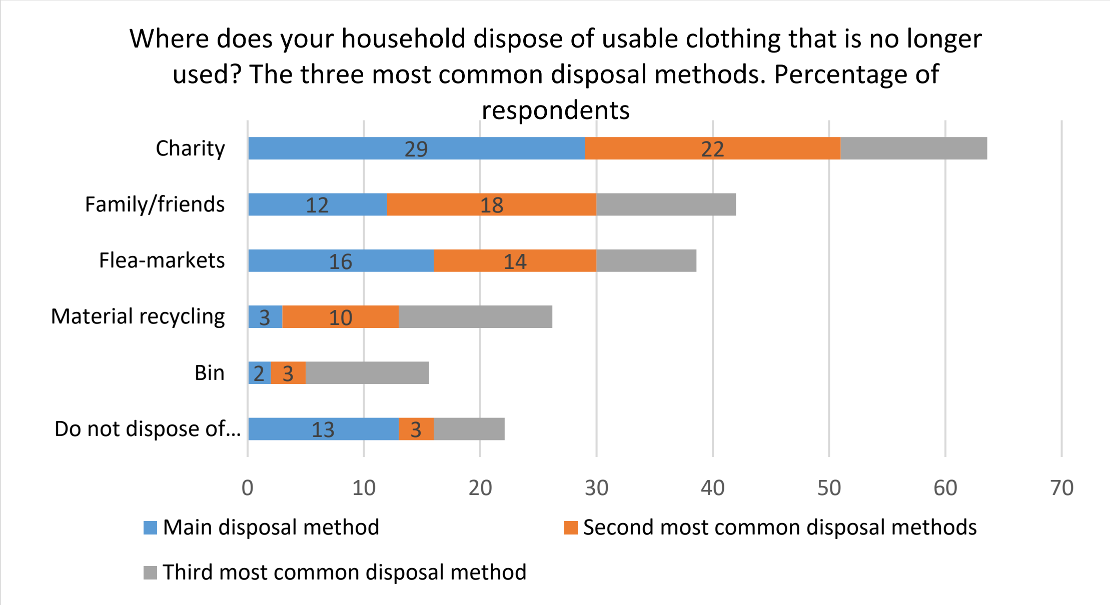

Figure 40 Most common disposal methods of usable clothing in Finland (Translated figure 13 from Aalto, 2014)

In the UK, it is estimated that around 62% of discarded clothing is collected for reuse and recycling through charities, friends, family or other channels such as online sales (Gracey and Moon, 2012). A review by Russell et al. (2015) on wool reuse and recycling shows that woollen garments are more likely to be delivered for reuse and recycling than materials made of other fibres, because wool's share of donated clothing is about 5% by weight in the UK (Ward et al., 2013) and USA (Chang et al., 1999), which is substantially higher than wool's share of the virgin fibre supply of about 1.5%. However, this is not taken into account in a majority of LCA studies for clothing fibres, which usually assume that garments are landfilled or incinerated directly after use (Russell et al., 2015).

A WRAP study estimated that about half of woollen jumpers that reach their end of life in the UK are destined for reuse, while the other half is either recycled, incinerated or sent to landfills (Fisher et al., 2011).

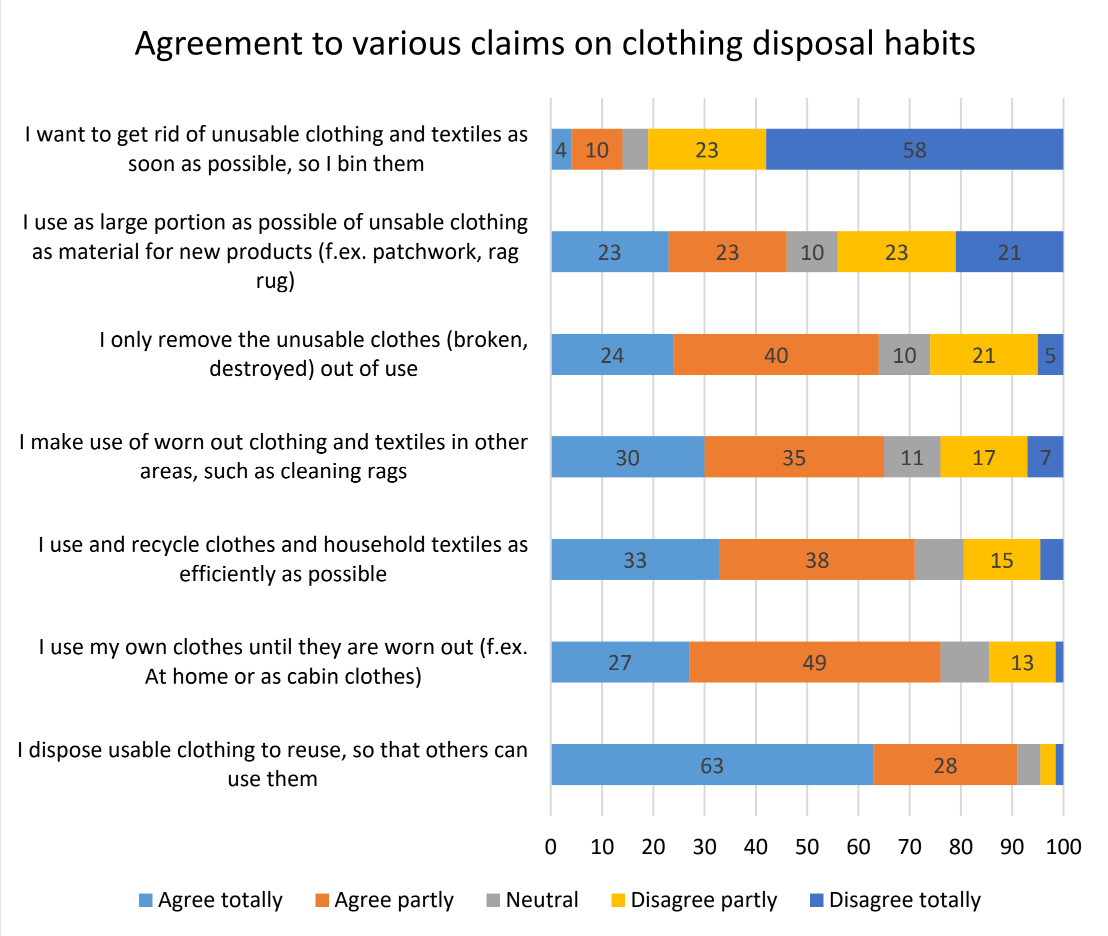

Figure 41 Clothing disposal habits in Finland (Translated parts of figure 4 from Aalto, 2014))

3.6 Recycling

There are several alternative commercial ways for recycling post-consumer textiles. The largest portion goes to down-cycling, mainly either as fabric for use as wipers and rags, or as shredded materials in non-woven applications such as insulation materials (Morley et al., 2006). Up-cycling and redesign to new clothing products constitutes only a small portion of recycling.

Woollen fibres can be mechanically recycled, and this is commonly done as wool is a valuable fibre for recycling industries. Here, the type of garment is crucial for whether the fibres are suitable for high grade recycling. The garments should preferably be made of 100% wool, and be of similar colours. During the process of pulling the fibres, their length should be preserved as long as possible to make the subsequent processing stages easier and product quality better. The fibres can be pulled out from knitwear easier than from woven fabrics (worsteds), which means that they can keep their fibre length to a greater degree (Russell et al., 2015). Fibres with sufficient length can be spun back to yarns, while the short fibres are more suited for non-woven processing.

Recycled wool is often used for insulation materials due to its heat insulation and low flammability properties. Some products such as mattress and furniture fillings require a minimum wool content to meet fire retardant (flammability) requirements.

In addition to commercial recycling routes, private reuse and recycling are also possible, such as when old textiles are used as rags or redesigned into new products.

In the UK, the share of textiles going directly to waste (landfill and incineration) has been estimated to be about 38%, while about 48% is delivered for reuse and 14.5% is recycled (Table 63).

Table 63 Fate of clothing waste in the UK (Table 5 from Gracey & Moon, 2012)

Fate of waste	Proportion to this route
Re-use (UK and abroad)	47.6%
Recycling (closed loop)	0.0%
Recycled (open loop)	14.5%
Incineration with energy recovery	7.2%
Landfill	30.7%

In the US, it is estimated that about 48% of the volume of the used textile market is exported for reuse, 29% is recycled to new products for shoddy (from knitted products) or mungo (from woven garments), 17% is used as wiping cloths, less than 7% goes to landfills or incineration, and 1-2% is considered to be “diamonds”, high value items that give high profits (Hawley, 2009). This category includes products made of luxury fibres such as cashmere or camel hair.

3.7 LCA studies on textiles

Several LCA studies on textiles and clothing have been conducted, and this chapter presents selected studies to show how the use phase has been modelled.

3.7.1 Modelling the Use Phase in textile LCA

Environmental impacts of the use phase of apparel and textiles are affected by several factors, including:

- Method of cleaning, e.g. a wet process (either manual or using an appliance), dry-cleaning, spot cleaning or airing;
- Characteristics and efficiency of each appliance used for washing, drying and ironing;
- Detergents and other chemicals used;
- Consumer behaviour and practice in laundry, period of use of the item, and fate at the end of use.

Diversity in behaviour

In LCA, the relative contribution of the use phase in the garment supply chains depends on several factors, including material and product type, and assumptions made about consumer practices in care and reuse, recycling and disposal. For example, Allwood et al. (2006) analysed the importance of consumer practices for wash temperature, drying method and ironing in comparative studies of a cotton T-shirt and a viscose blouse. Figure 44 shows the data for primary energy use over 25 washes when it is assumed that the cotton T-shirt is washed at 60°C, tumble dried and ironed while the viscose blouse was washed at 40°C, line dried and not ironed. Under this assumption, the total primary energy consumption of the cotton T-shirt during its lifetime was 109 MJ (mostly during consumer use) while the viscose blouse only required 51 MJ. However, Allwood et al. (2006) demonstrated that elimination of tumble-drying and ironing, together with lowering the wash temperature from 60°C to 40°C, could lead to around 50%

reduction in the global climate change impact of the product, predominantly through lower energy demand for care.

The results of Allwood et al. (2006) highlight the importance of realistic assumptions on use phase practices for different fibre types. A screening study undertaken as part of the European Union Product Environmental Footprint (PEF) category rules pilot for T-shirts also identified the use phase as one of the four most relevant life cycle stages. However this pilot testing assumed the same care treatment (a cotton scenario) across all T-shirt categories regardless of fibre type and more disaggregated information is needed for accurate estimates of the use phase in LCA.

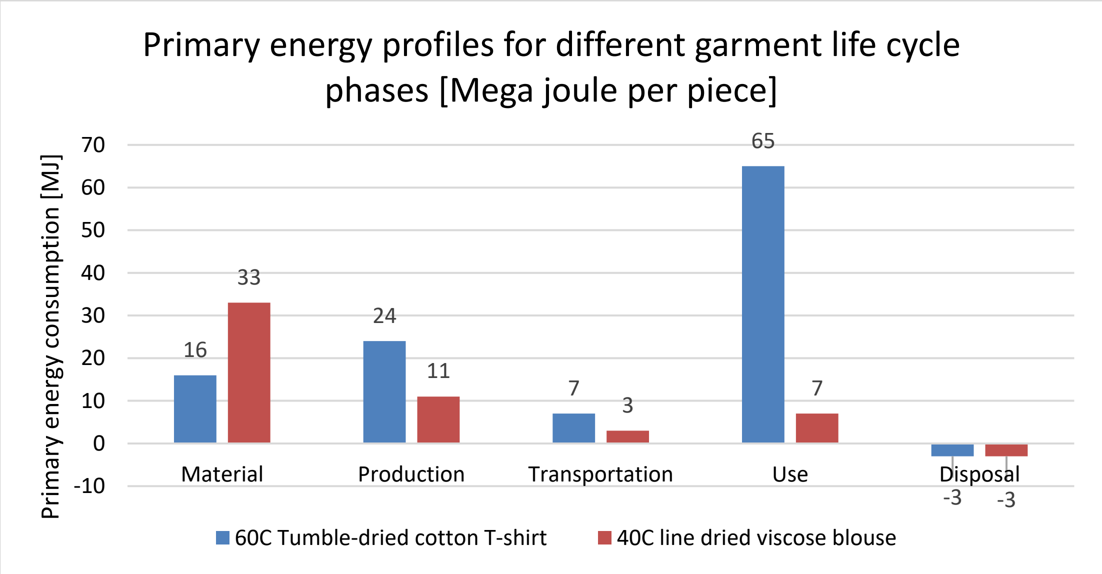

Figure 42 Primary energy consumption of the main life cycle stages in LCA of a cotton t-shirt and a viscose blouse over 25 washes when it is assumed that the cotton t-shirt is washed at 60C, tumble dried and ironed, while the viscose blouse is washed at 40C, line dried and not ironed (Allwood et al., 2006).

Choices made by individual consumers have the greatest influence on the environmental impacts in use phase and in re-use, recycling and end-of-life disposal stages. Factors that are decided by consumers such as washing frequency, wash temperature and drying methods, as well as how long a garment is in active use, are decided by the individual consumer. These behaviours are highly diverse and characteristically differ between countries and cultures. Recognizing the importance of use stage modelling in LCA and the lack of robust methodology to incorporate the diversity of consumer practices, some recent studies have sought to use social science concepts such as Design for Sustainable Behaviour (Daae and Boks, 2015) and Behavioural Science (Polizzi di Sorrentino et al., 2016) to inform more robust use phase modelling in LCA and ultimately to influence consumers towards more sustainable practices. However, these applications to textile LCAs are still in their infancy and largely untested.

Methods and data requirements

One of the most significant challenges arising from the uncertainty in use phase modelling relates to the use of LCA in comparative assertions of textiles. Assumptions relating to washing, drying, lifespan and end of use scenarios can dominate outcomes on relative performance of different garments and therefore have the potential to result in misleading information for industry, consumers and policy. Therefore, improving methods and data to give results that are more relevant and representative as a basis for better consumer choices, is critical. Background assumptions, as illustrated in the results of Allwood et al. 2006, and the uncertainty in data inputs, must be explicit in order to better understand differences in the results of studies, and enable reliable interpretation of the findings.

Methods

Examples of guidance for textile environmental impact assessments based on life cycle thinking include:

- BSI PAS 2395:2014 Specification of the assessment of greenhouse gas (GHG) emissions from the whole life cycle of textile products (BSI, 2014)
- Product Environmental Footprint (PEF) Category Rules (PEFCR) Pilot: T-shirts (Fourdrin et al., 2016).
- IWTO Guidelines for conducting a life cycle assessment of the environmental performance of wool textiles (IWTO, 2016).

Data needs

Each set of guidance defines the data requirements for the methodology provided for one or more impact categories. Data elements important for modelling impacts, particularly climate change water use, energy use, in the Use Phase as described in these documents or identified in our review of published LCA studies include (but are not restricted to):

- Effective lifetime
- Frequency of wash

Washing machine

- Washing temperature
- Energy consumption
- Water use
- Kg of laundry
- Type and quantity of detergent
- Washing cycle (Gentle wash reduces energy consumption)

Dryer

- Proportion of wash dried in a dryer
- Energy consumption
- Kg per load
- (Water consumption if condenser dryer with water cooling)

Iron or steam press

- Iron energy consumption per time
- Time of ironing per item
- Proportion ironed.

Because of the significance of the use phase in the full life cycle of apparel and textiles, primary data should be used as far as possible. However, dealing with the uncertainty that arises from the diversity of practices and variations in consumer practice, is a major challenge for the LCA practitioner. In practice, secondary data are used in many (or most) cases. This challenge makes it difficult to compare different products and account for change over time.

Interpreting results of textile LCA

Assessment of environmental impact categories for the different processes within the use phase can identify hotspots for further data collection and practice understanding as well as starting to identify mitigation opportunities. For example Beton et al. (2014) estimated the contribution of each of the four main consumer use processes to the range of major mid-point and end-point impact categories as shown in Figure 43. It shows the importance of ensuring all use phase activities, including use of detergents and other chemicals, are adequately accounted for in apparel LCA.

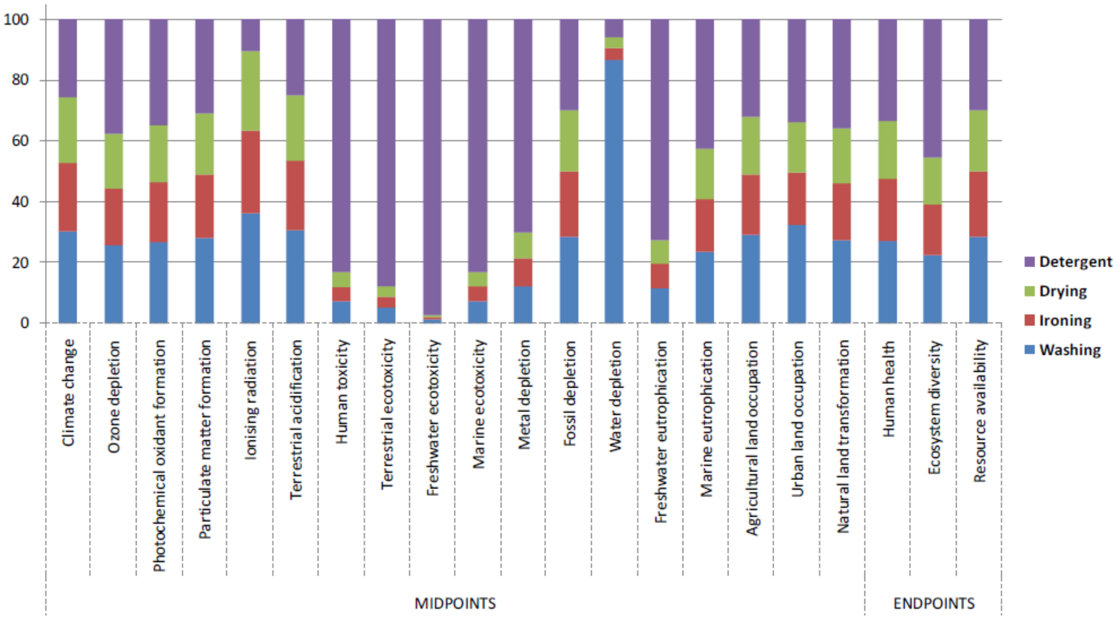

Figure 43 Impacts of the use phase of textile consumption in the EU-27, for the use phase, broken down by process (Figure 37 from Beton et al. 2014).

Examples of environmental analysis of garments

In this section, some relevant clothing LCA and other environmental assessment studies with fewer impact categories studies are presented and their assumptions for use phase are summarised in Table 65.

Laursen et al. (2007) have conducted a comprehensive LCA study for four different garments; a T-shirt, jogging suit, work jacket, and a blouse. In their study, they assume a baseline scenario and then potential alternative scenarios for production and use, followed by analyses of environmental impacts of the different scenarios. The scenarios related to use include variations in product quality (colour loss or staining, longer lifespan) and maintenance (different washing temperatures, methods and drying alternatives). The key figures for use of a work jacket that is professionally cleaned, were received from the laundry sector, but for the other products, no evidence was given for the assumptions that are made of the base case use scenario (i.e. how often the product is worn and laundered, and how the lifespan is estimated).

Collins and Aumônier (2002) calculated the energy footprints of polyester trousers and cotton briefs in a cradle-to-grave study in the UK. They used the lifetime of the studied products as functional unit. The lifespan estimate was based on advice given by the producing company, while no source for estimations related to laundering was given. Collins and Aumônier suggest that efforts to improve the environmental profile of clothing, with regards to energy, should be directed at consumer use.

Franklin Associates (1993) conducted an LCA of a polyester blouse including production and use phases. The study was based on different sources: government references, company specific, and industry provided. Similarly to many other studies, they indicate that consumer use data proved difficult to locate. The major assumptions affecting the results of this study involved the consumer use and maintenance of the product. Life span (number of wearings) and laundering practices had the single largest effect on the study results. For this study, new research was conducted in the areas of washing temperature, load size, and dryer time.

The aim of a paper by Bevilacqua et al. (2011) was to assess the carbon footprint measured in CO_2-equivalents of a merino wool sweater. The use of the sweater was based on company data and from ENEA (2003) guidelines. A medium life of 5 years with 15 washes per year was considered, 30°C washing temperature, 10 litres of water for each cycle, 130ml of chemicals (soap and conditioner). For the final life phase, the final disposal, from the literature data, it was established that 49% was disposed of, 49% was burned, and the last 2% was reused. For environmental improvement, they suggest cutting down the number of washings per year to less than the 15 times. The consumer could modify the washing temperature (assumed as 30°C in this research) changing considerably the climate change impact. While this paper presents a detailed study of the use phase, it is noted that, at the farm scale, the study accounted only for fossil carbon emissions and did not account for greenhouse gas emissions from sheep production including the major sources of enteric digestion and manure management.

Allwood et al. (2006, 2008) have prepared a full LCA including use, reuse, recycling. Hotspot analysis for UK clothing and textiles supply chains used a mass balance approach and economic analysis. The 2006 study and updates include a scenario analysis for future sustainability using an LCA approach and covers a range of manmade and natural fibres including conventional cotton, organic cotton and wool.

Russell (2009) reported an LCA study of three different woollen garments, a fine wool knitted garment, a medium-micron wool men's suit, and a slightly coarser wool knit outerwear garment. Similar to many other LCA studies, the figures used to estimate use and disposal phases were mainly based on assumptions but these were developed using extensive industry experience to be realistic. The knitted garments were assumed to be laundered in a gentle warm wash cycle and air-dried, while the suit was assumed to be dry-cleaned. For the knitted garments, a lifetime of 20 washes was assumed, while the suit was assumed to be dry-cleaned four times a year during 3 years (total lifetime of 12 dry-cleaning rounds). At the end-of-use, the study assumed that 40% of wool garments were recovered/recycled, 7% incinerated and 53% disposed of to landfill. The results showed that garment care accounted for most of the lifetime water use and much of the energy consumption.

A thesis by Strand (2015) described a general LCA model for Swedish textile consumption. The model was based on consumption statistics (import, export and Sweden's own production) and existing literature and databases. The functional unit was consumption of one kg textile. For estimating the lifespans, Strand used the same assumptions as a similar European study by Beton et al. (2014) where lifetime was simplified to being the number of washes. Ironing, softener and dry-cleaning were not taken into consideration since they were assumed not necessary in order to continue further use. Laundering was assumed to be done at 60°C with the cotton program, which is quite a lot higher than the average washing temperature reported in other studies (see section 3.1.5). Tumble drying of all textiles was assumed, which is a rather high estimate since only a little over half of the Swedish households own a clothes drier. No reuse was explicitly included, because it was implicitly in the total lifespan, and recycling was excluded, due to lack of data.

The European Commission's Joint Research Centre report Environmental Improvement Potential of textiles (IMPRO Textiles) identified the market share and consumption of textile products in EU-27. The study estimated the environmental impacts taking into account the overall value chain (life cycle) of these products and suggested improvement options (Beton et al., 2014). The study was based on existing literature and LCA databases, and included 18 midpoint indicators (e.g. climate change, ozone depletion, human toxicity) and 3 endpoints indicators (i.e. damages to human health, ecosystems and resource availability). It included different use and end-of-life scenarios. The data on use and end-of-life were derived from a series of European studies which focused mainly on user washing habits and the model presented an average scenario in the EU-27.

Roos et al. (2015) prepared an environmental assessment of five garments in Sweden. The environmental impact of "one average use" of each of these garments was assessed and then scaled up to represent Swedish national clothing consumption for one year.

Fourdrin et al. (2016) prepared a pilot study that aims to evaluate the environmental impacts of T-shirts sold in Europe based on Product Environmental Footprint (PEF). The functional unit of the T-shirt is defined as "to wear a T-shirt for a period of 1 year". The defined life span is one year including 52 washes where the T-shirt is worn and cleaned once a week. The reference flow is therefore systematically 1 T-shirt. The modelling of the laundering is based on the information given on the care label, and related energy and water use data is collected from research literature. The methodology specifies that the use phase scenario shall be based on the best-known average situation. In case of different user patterns, more than one scenario should be provided, such as potential technical lifespan and current average lifespan in consumer use.

Boulay et al. (2015) presented the results of a water impact study for one wash in an 'average' French laundry. They assessed 5 mid-point indicators and 9 end-point indicators for a full life cycle assessment of the wash from production of the detergent to end-of-life treatment of the waste water from the laundry. The calculation was of the water impact as a 'water footprint'. The authors included a sensitivity analysis for different methods, which was important as there is currently no broad consensus on one method for the water footprint. Figure 44 summarises the water footprint results.

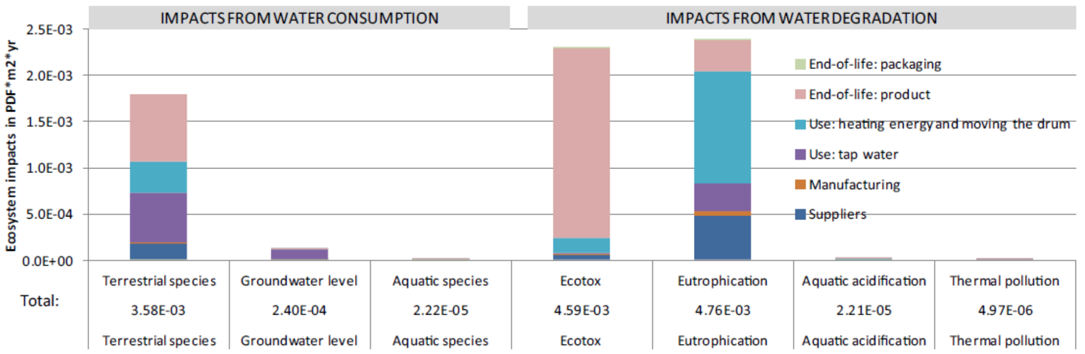

Figure 44 Water footprint profile results for laundering (Figure 7 from Boylay et al., 2015)

Thomas et al. (2012) summarised the carbon footprint associated with reuse and recycling of different garments, including by fibre type as carbon dioxide emissions per tonne of waste. These data provided some support for inclusion of recycling in LCA studies, however there is as of yet no global consensus on a method.

Table 64 Carbon footprint associated with reuse, recycling, incineration and landfill of different garments (Table 16 from Thomas et al., 2012)

Fate of Waste	Carbon Footprint [kg CO2e per tonne waste][1]	References
Reuse in UK (cotton)	-14,904	Informed by Farrant (2008), WRATE (2010)
Reuse in UK (wool)	-27,083	
Reuse in UK (silk)	-13,429	
Reuse in UK (flax/Linen)	-6,604	
Reuse in UK (viscose)	-16,447	
Reuse in UK (polyester)	-10,68	
Reuse in UK (acrylic)	-21,872	
Reuse in UK (polyamide)	-12,658	
Reuse in UK (polyurethane)	-9,674	
Reuse abroad (all fibres)	0	
Closed loop recycling (cotton)	-1,28	Informed by Oakdene Hollins (2009), WRATE (2010)
Closed loop recycling (wool)	-18,412	
Closed loop recycling (silk)	-1,529	
Closed loop recycling (flax/linen)	-3	
Closed loop recycling (viscose)	-1,607	
Closed loop recycling (polyester)	-4,522	
Closed loop recycling (acrylic)	-6,52	
Closed loop recycling (polyamide)	-6,964	
Closed loop recycling (polyurethane)	-2,488	
Open loop recycling (all fibres)	-2,259	Informed by ERM (2006), Oakdene Hollins (2009), WRATE (2010)
Incineration (synthetic fibres)	1006	WRATE (2010)
Incineration (natural fibres)	-433	
Landfill (all fibres)	222	

[1] A negative value indicates that the offset benefits of the reuse/recycling or incineration (energy recovery) outweight the GHG emissions from waste management activities.

The Carbon Footprint is estimated the net of GHG emissions from transportation, sorting, recycling, incinerator operation or decomposition and offsets generated by displacement of production of alternative equivalent items e.g. new clothing for purchase. A negative footprint indicates that the benefits of the displaced product or incineration exceeds the burdens associated with waste management. In the case of incineration, these data assume that all incineration of clothing waste in the UK is associated with energy recovery, which displaces conventional electricity generation, with natural fibres but not synthetics providing a net benefit. Note that these results relate to the proportion of clothes ultimately processed rather than the proportion of waste clothing collected for reuse/recycling, and relate to activities, energy mix etc. in the UK and cannot be extrapolated to other countries. It must also be noted that Wrate software is intended for modelling municipal solid waste systems, not for product LCA studies.

The functional unit of a number of textile LCA studies has been a specific garment. However, some have also attempted to make a mass balance analysis of national or international textile flows and connected environmental impacts. Most of these studies point to similar uncertainties, especially regarding the use phase and consumer behaviour. In these calculations, a specific way of laundering, use frequency, lifetime and disposal method is assumed, but often without giving references to studies that would document these aspects.

Table 65 LCA results tabulated

Study	Textile/apparel type	Fibre/material type	Environmental impact categories	Post use phase included	Data	Assumptions			Wash conditions
						Frequency of wear	Wash per year	Service life (years)	
Laursen et al. (2007) [28]	T-shirt	Cotton[29]	Primary energy Resource consumption Toxicological impacts Environmental impacts for energy Environmental impacts for waste	Incinerated with energy recovery (except for some reuse in developing countries) Note: Disposal of textiles to landfill is not permitted.	Data from partner organisations and Danish Textiles EDIP Database. Work jacket key figures for use phase from the laundry sector	50 days/yr (1/week)	50 i.e. after 1 wear	1	Temp: 60°C Dry: Tumble Iron: yes
	Jogging suit	Outer shell of woven nylon (polyamide) and lining of knitted cotton				24 days/yr (2/month; 0.5/week)	24 i.e. after 1 wear	1	Temp: 40°C Dry: Tumble Iron: no
	Work jacket	65 Polyester / 35 cotton				40 days/3 yrs	14 i.e. After 1 wear	3	Temp: 80°C (Industrial wash)
	Blouse	V70 iscose, 25 nylon (polyamide) and 5 elastane				25 days/yr (0.5/week)	25 i.e. after 1 wear	1	Temp: 40°C Dry: Line Iron: no
UK Collins and Aumônier (2002)	Trousers	Polyester	Energy use						
	Briefs	Cotton							
UK, Franklin Associates (1993)	Blouse	Polyester			government references, company specific, and industry provided	40 wears, 20 washes			Warm wash 92°F (33°C) Dry: tumble
Bevilacqua et al. (2011)	Sweater	Wool (merino)		Disposal: Y (49% land-fill, 49% burned, 2% reuse)	Company/national energy (ENEA)		15	5	Temp: 30C Water use: 10l/cycle Soap+conditioner): 130ml/cycle (per sweater?)

[28] Laursen et al. (2007) state (page 19) 'Only producers of floor coverings, rugs and blankets state an interest in wool. No producers of garments made of wool or blends thereof have showed an interest in participating in the project, and several important links in the production chain for wool for garments are missing in the Danish group of enterprises. However, a large part of the lifecycle of wool products is covered by the project "Livscyklus i salg, design og produktudvikling" (lifecycle in sales, design and product development – only available in Danish) carried out by the textiles enterprise Gabriel A/S in cooperation with COWI and Dansk Kvalitetsrådgivning. The project dealt with woollen furniture fabrics and it was based on the EDIP method. On the basis of this, wool products have not been included in this project.'

[29] Contributions from primary use phase processes accepted only as Wash: Tumble dry: Iron 25%:68%:7%

Study	Textile/apparel type	Fibre/material type	Environmental impact categories	Post use phase included	Data	Assumptions			Wash conditions
						Frequency of wear	Wash per year	Service life (years)	
Australia Russell (2009)	Knitted garment	Wool (fine)	Energy use Water use	Disposal: Y (53% land-fill, 7% burned, 40% re-use/ recycle)	Assumptions (expert opinion)			20 washes	Warm gentle wash Dry: air-dried
	Men's suit	Wool (med woven)					4	3	Dry-cleaned
	Knitted sweater	Wool (med/broad)						20 washes	Warm gentle wash Dry: air-dried
Sweden, Strand (2015)	All textiles	Average mix for Swedish textiles		Disposal: Assumed reuse included in lifespan; recycling not included – no data	Consumption statistics Lifetime from Beton et al (2014) as no. of washes			2	Temp: 60C (Cotton program) Dry: Tumble (Ironing, dry-cleaning softener use not counted)
EU-27 average Beton et al (2014). 10 top categories of clothing by volume given here. (Table 25) Note: Many assumptions seem unrealistic	Hosiery	(knitted or crocheted)	18 mid-pt indicators; 3 end-pt indicators	End-of-life scenarios	Literature & LCA databases + scenarios All assume all cleaning by machine wash or dry-cleaning	104 washes	52	2	Dry/wet wash: 0% Iron: no
	T- shirts, vests, singlets					52 washes	52	1	Dry/wet wash: 25% Iron: 100%
	Briefs, panties, underpants	(knitted or crocheted)				104 washes	52	2	Dry/wet wash: 25% Iron: no
	Gloves	(knitted or crocheted)				4 washes	2	2	Dry/wet wash: 0% Iron: 100%
	Shirts or blouses	(not knitted or crocheted)				25 washes	25	1	Dry/wet wash: 25% Iron: 100%
	Jerseys, jumpers, pullovers	(excluding cotton)				50 washes	16.7	3	Dry/wet wash: 25% Iron: 100%
	Shirts or blouses	(knitted or crocheted)				25 washes	25	1	Dry/wet wash: 25% Iron: 100%
	Jerseys, jumpers, pullovers	cotton				50 washes	16.7	3	Dry/wet wash: 25% Iron: 100%
	Interior textiles e.g. curtains and interior bed valances (m^2)	Woven				20 washes	2	10	Dry/wet wash: 45% Iron: 100%
	Brassieres					40 washes	20	2	Dry/wet wash: 0% Iron: 100%

Study	Textile/apparel type	Fibre/material type	Environmental impact categories	Post use phase included	Data	Assumptions			Wash conditions
						Frequency of wear	Wash per year	Service life (years)	
UK Thomas et al. (2012)	All UK clothing	All materials					9.9 washes per kilogram of clothing per year		Assumed that all clothing was washed and dried with the same frequency and temperature regardless of fibre type. This was acknowledged as disadvantaging wool but has been cited and adopted as a valid assumption in other studies.
Sweden Roos et al. (2015)	T-shirt	Cotton	Water use, non-renewable energy use, agricultural land occupation, contributions to climate change freshwater ecotoxicity, freshwater eutrophication, human toxicity photochemical oxidant formation, and acidification.	Incineration. Reuse only in alternative scenarios	Based on consumer surveys and statistics	22 wears, 11 washes			Washed at 40°C after 2 uses dried with heat:34% ironed:15%
	Jeans	98% cotton 2% elastane				200 wears, 20 washes			Washed at 40°C after 10 uses dried with heat: 29% ironed: 41%
	Dress	Polyester				10 wears, 3.3 washes			Washed at 40°C after 3 uses dried with heat: 19 % ironed: 18%
	Jacket	44% polyamide 48% polyester 18% cotton/ elastane mix				100 wears, 1 wash			Washed at 40°C once dried with heat:21% ironed: 5%
	Hospital uniform	50% cotton 50% polyester				75 wears			Industrial laundering after 1 use dried with heat:100% ironed:0%

Study	Textile/apparel type	Fibre/material type	Environmental impact categories	Post use phase included	Data	Assumptions			Wash conditions
						Frequency of wear	Wash per year	Service life (years)	
(Fourdrin et al., 2016) PEFCR T shirt (Pilot)	T-shirts	Various (12) fibres/materials	15 Impact categories 0f the PEF program but focus on 5	Full life cycle, including use and end-of-use		1 wear/ week i.e. wash after each wear (Same assumption for all fibres)	52 washes/yr	1	Temp:: 40C Energy: 0.638 kWh/wash Water: 11.11 L/ kg Laundry load: 4.5 kg Detergent: 8.3g (liquid)/kg 8.3g (powder)/kg Dry: 90% Air dried 10% tumble dried Dryer energy: 2.01 kWh/cycle (full load of 6 kg) Iron: Time- 1min 50% T-shirts ironed Iron energy: 1.6 kWh/hr
France Boulay et al. (2015)	One wash		Water impact (5 mid-pt & 9 end-pt indicators, including different methods)	Full life cycle of the wash (includes data/assumptions for detergent related to water ecosystem impacts)					Temp: 40 °C (av. French conditions) Detergent: 37 g of concentrated laundry liquid detergent

4 Discussion

This review of consumer studies on clothing use phase has shown the great variation in how garments are used, taken care of and disposed of. These aspects vary greatly depending on the user, garment, fibres, geographic and cultural differences, available technologies and several other parameters. Here, we suggest some generic use scenarios that could be used in LCA studies. We introduce average current practices for various geographic areas, when data has been available. This is followed by some product specific examples. One option is to divide the use between percentage of consumers that are likely to use garments in a specific way.

The laundering practices vary greatly around the world. The four main cleaning methods and their use areas are listed in Table 66.

Table 66 Main laundering methods and areas they are used

Cleaning method	Region	Types of garments
Horizontal axis front loading machines	Europe, about 23% of the washing machines in the USA, increasingly in Asia and Australia	Main laundry
Vertical axis top loading machines	Most of USA, Asia, Australia (decreasing)	Main laundry
Hand wash	Global, main method in rural areas of developing countries	Main laundry in developing countries, some delicates in Western countries (about 5-7% of laundry)
Dry-cleaning	Western countries, used more often in the USA than many other countries	Suits, coats, some delicates

The portion of horizontal axis drum machines (front loading) is increasing in USA, Asia and Australia, and they dominate domestic use in Europe. They have been demonstrated to use 38% less water and 58% less energy than the standard top-loading v-axis models (Tomlinson & Rizy, 1998).

Based on The Nielsen Company 2016 survey in 61 countries it is also possible to estimate the distribution between the various clothes cleaning methods (

Table 67). Category “someone else does washing for me” is recalculated to be more relevant for our study in a way that washing machines are the most likely used alternative in developed countries, and divided evenly between hand wash and machine wash in developing countries. The category “laundrette” is also allocated to washing machine, but most likely involves use of larger types of machines than the ones used in households.

Table 67 Distribution of laundering methods globally (estimation based on Nielsen Home care survey 2016)

	Washing machine	Laundrette	Hand wash
Asia-Pacific-developed markets (Australia, New Zealand, Hong Kong, South Korea, Japan etc.)	87 %	5 %	8 %
Asia-Pacific Developing markets (India, China, Philippines etc.)	56 %	5 %	39 %
Europe	92 %	3 %	5 %
Africa/Middle-East	53 %	28 %	18 %
Latin America	78 %	4 %	19 %
North America	88 %	8 %	4 %

Table 68 gives the current practices for washing an average laundry and, when available, for wool in the different regions of the world. For some areas, there is not sufficiently comprehensive data for extracting exact numbers and, in these cases, either an estimate is made, or if that's not possible, the statement of missing information is given.

Table 68 Current practices for average laundry and wool (generic, not product specific)

Parameter	Area	Average all clothes (mainly cotton and synthetics)	Wool
Cleaning method	Europe	92% H-axis washing machine 5% Hand wash 3% Laundrette	~70% machine wash ~20% Hand wash ~10% Dry-clean (suits)
	North America	20% H-axis washing machine 68% V-axis washing machine 4% Hand wash 8% Laundrette	Mainly dry-clean Some hand wash Machine wash (socks)
	Developed Asia-Pacific	87% V-axis washing machine 8% hand wash 5% Laundrette	Machine wash, delicate setting Hand wash
	Developing countries	56% V-axis Machine wash 39% hand wash 5% Laundrette	Hand wash dominates
Cleaning frequency	All	Product specific. Higher cleaning frequency in hot and moist countries.	About two times longer between washes than cotton
Average washing temperature	Europe	42.6°C	30.3°C
	North America	31.1°C	Seldom washed in machine, but if washed, at low temperature
	Asia-Pacific	Ambient	Ambient
Most used washing programs/cycles	Europe	Cotton cycle	Wool or delicates cycle
	North America and Australia	Warm cycle (daily /normal)	Seldom washed in machine, but if washed, gentle cycle
	Developing Asia Pacific	Economy/cotton cycle	Hand wash dominates
Average washing load in machine wash	Europe	3.3 kg	2.1 kg
	North America	3.1 kg	Seldom washed in machine
	Developed Asia-Pacific	2.6 kg (Japan)	
	Developing Asia Pacific	1.5 kg (China)	
Use of detergents (grams per kg laundry)	Europe and other developed countries	Compact and ultra-compact detergents used, average: 50% Powder 22.8 g/kg 50% Liquid 23.5 g/kg	Liquid wool detergent 26.5 ± 13.3 g/kg (global) (18.6 g/kg in Germany-compact type)

Parameter	Area	Average all clothes (mainly cotton and synthetics)	Wool
	Developing countries	Traditional detergents and soaps still used. 198 g per wash (hand washing in Kenya)	
Use of fabric softeners	Europe	Used at ~55% of washing cycles	No wool specific information available
	North America	Information missing, likely similar or higher than Europe	
	Developed Asia-Pacific	Information missing	
	Developing Asia Pacific	31% use them (China)	
Drying method	Europe	~88% hang dried ~12% tumble dried (large variations between countries depending on dryer ownership rate)	Mainly hang dried
	North America	~75% Tumble dried ~25% Hand dried	
	Developed Asia-Pacific	Mainly hang dried, but variations between countries	
	Developing Asia Pacific	Mainly hang dried	

Table 69 gives some garment specific examples for the use period, namely for a woollen sweater, cotton sweater, polyester fleece jacket, wool undershirt, cotton t-shirt, suit trousers and jeans.

Table 69 Product specific examples of use based on literature presented in chapter 3.

Product and weight[30]	Washing method	Laundry load[31] [kg]	Tempe-rature [°C]	Energy use per cycle[32] [Kwh/cycle]	Water use pr cycle [Liters/cy-cle][33]	Drying and ironing method[34]	Drying / ironing energy use per garment [kwh]	Number of days in use before clean-ing	Energy use per garment per one time use [kwh]	Water use per garment per one time use [liters]
Woollen sweater (450 g)	washing machine wool program	2.1	30	0.22	43	Line dried outside or un-heated room	0	10[35]	0.005	0.92
Cotton sweater (350 g)	Washing machine cotton program	3.4	40	0.68	55	Tumble dried after wash with spin drying at 1000 rpm, 0,7 kwh/kg	0.245	4	0.079	1.42
Fleece jacket, poly-ester (350 g)	Washing machine synthetics pro-gram[36]	3	40	0.46	46	Line dried outside or un-heated room	0	10[35]	0.005	0.54
Wool undershirt (200 g)	washing machine wool program	2.1	30	0.22	43	Line dried outside or un-heated room	0	3	0.007	1.37
Cotton t-shirt (200 g)	Washing machine cotton program	3.4	40	0.68	55	Tumble dried after wash with spin drying at 1000 rpm, 0.7 kwh/kg	0.14	1.5	0.120	2.16
Suit trousers (wool mix) (400 g)	Dry-cleaning (PERC)	-	-	58.6 kwh/100 kg textiles	0	Ironed after dry-cleaning (0,75 kwh/h, 0,072 hours=4,3 min	0.054	10[35]	0.029	NA

[30] Weights from Textile waste project garments (Laitala 2014).
[31] Laundry load from Table 16 based on Kruschwitz et al 2014.
[32] Laundry energy use from Table 34 based on Laitala & Vereide 2010 and Dry-cleaning energy from Table 44 based on Troynikov et al. 2016.
[33] Water use from

Table 48 based on Laitala & Vereide 2010.
[34] Tumble drying energy from Table 36 based on Presutto 2009 and Schmitz & Stamminger 2014. Ironing energy from

Table 45 based on Thomas et al. 2012.
[35] Many users are likely to wash even more seldom.
[36] Releases microfibres during wash.

Jeans, cotton (650 g)	Washing machine cotton program	3.4	40	0.68 kwh	55	Tumble dried after wash with spin drying at 1000 rpm, 0.7 kwh/kg	0.455	5.5	0.106	1.91

When comparing the current consumer practices in laundering of wool and cotton sweaters, and wool undershirts and cotton t-shirts, the results indicate that cotton products consume 17 times more energy and 1.5 times more water per use than similar products in wool.

Prolonging clothing lifespans has the potential to decrease the environmental impacts of clothing consumption. This aspect is not included in Table 69 that focuses on the maintenance aspect of use phase. We were able to identify average lifespans for some garment types that had been included in various studies (Table 55). End-of-life studies showed that most consumers are interested in delivering clothing for reuse and do so frequently, but second-hand clothing is only a minor portion of the clothing they acquire.

4.1 Sensitivity analysis

A simple sensitivity analysis was conducted by comparing the base case scenario of a woollen jumper presented earlier in Table 69 with alternative scenarios. The magnitude of the impact on the end result was calculated (Table 70). The alternative variables tested here include:

- Washing method (cotton program instead of wool program, top loading machine instead of front loading, or dry-cleaning)
- Laundry load (garment washed alone, in half loaded machine 1kg, slightly overloaded 3kg, or full machine 5 kg)
- Temperature (cold water or 40°C)
- Drying method (line tried in heated room or tumble dried)
- Ironing (ironed)
- Number of days in use between washes (1, 5, 20, 50 or 100)

As the aim of this report is to provide data on the use phase for LCA to be performed at a later stage, the sensitivity analysis is limited to simple measurements of energy and water consumption. Therefore, the focus is on scenarios that affect these properties. Use of detergents and softeners is therefore excluded from this calculation. Indirectly, the main contribution of energy and water use during detergents' use phase is already included due to the laundering process itself.

The results in Table 70 are given for one time of use, i.e. one wear. For calculating the total, the results can be multiplied by the number of wears, and for calculating the consumption per year, the total can be divided by the length of lifespan.

The results show that changes that have largest contribution to energy and water consumption are:

- Only using garment once between washes
- Selecting tumble drying instead of line drying
- Selecting dry-cleaning instead of machine wash

Table 70 Sensitivity analysis for woollen sweater (450 g). Base case compared with alternative scenarios. (Empty cells mean the content is the same as in the base case)

Scenario	Washing method	Laundry load [kg]	Temperature [°C]	Drying and ironing method	Number of days in use before cleaning	Energy use per cycle [kWh/cycle]	Water use pr cycle [liters]	Drying or ironing energy use per garment	Energy use per garment per one time use	Water use per garment per one time use	Change to base case Energy use	Change to base case water use
Base case	**washing machine wool program, Europe**	**2.1**	**30°C**	**Line dried outside. No ironing**	**10**	**0.22**	**43**	**0**	**0.005**	**0.92**	**0%**	**0%**
Change in cleaning method	**Washing in cotton program**					0.48	54		0.010	1.16	118 %	26 %
	Washing in top loading machine USA[37]					0.35	59		0.007	1.27	58 %	38 %
	Dry-cleaned with PERC	-	-	-		58.6 kwh/100 kg textiles	NA		0.026	NA	459 %	NA
Changes in washing load		**0.45[38]**				0.15	21.5		0.015	2.15	222 %	133 %
		1				0.21	31.8		0.009	1.43	97 %	55 %
		3							0.003	0.65	-30 %	-30 %
		5							0.002	0.39	-58 %	-58 %
Changes in washing temperature			**Cold**			0.1			0.002	0.92	-55 %	0 %
			40°			0.44			0.009	0.92	100 %	0 %
Changes in drying method				**Line dried in heated room 0.628 kwh/kg**				0.083	0.013	0.92	175 %	0 %

[37] As no energy and water consumption data for washing wool in a machine in the USA was available, we have used the statistical difference between the machine types for evaluating the effect. Tomlinzon & Rizy (1998) showed that front loading h-axis washers used 57.6% less energy and 38% less water than the standard top-loading v-axis models.

[38] Experiments have shown that when the machine is half filled, it uses 94% of the energy and 74% of the water compared with a full machine. Washing only one garment (about 0.5 kg) at a time uses 69% of the energy and 50% of water of a full machine (Laitala, Boks & Klepp, 2011).

Scenario	Washing method	Laundry load [kg]	Temperature [°C]	Drying and ironing method	Number of days in use before cleaning	Energy use per cycle [kWh/cycle]	Water use pr cycle [liters]	Drying or ironing energy use per garment	Energy use per garment per one time use	Water use per garment per one time use	Change to base case Energy use	Change to base case water use
				water, 29.2% moisture content, 131 g water								
				Tumble dried. (1000 rpm. cotton dry, 0.7 kwh/kg)				0.315	0.036	0.92	668 %	0 %
Change in ironing				**Ironed (0.75 kwh/h 0.043 hours)**				0.032	0.008	0.92	68 %	0 %
Change in number of days worn between cleaning					**1**				0.047	9.21	900 %	900 %
					5				0.009	1.84	100 %	100 %
					20				0.002	0.46	-50 %	-50 %
					50				0.001	0.18	-80 %	-80 %
					100				0.0005	0.09	-90 %	-90 %

4.2 Level of confidence and uncertainty

The review of previous studies on clothing use phase has shown that there are large variations between results of different studies. Survey methods are most commonly used to collect data, but they are limited by the survey design as well as the respondents' ability and willingness to answer the questions. Washing technologies and their uptake are also constantly changing, and therefore the average energy and water consumption in laundering also changes.

This review has given an overview of the available data and the existing variations in figures that are available. Uncertainty is reduced by using several sources for the same property.

4.3 Best practice scenarios for use of wool

This chapter discusses best practice scenarios for use of wool by giving an overview of potential best practices in use related to cleaning methods, cleaning and use frequency, clothing lifespans and the end of life. This perspective is important when working with environmental improvements.

4.3.1 Cleaning

Current practice for clothes cleaning is a result of a historic development where habits, washing technologies and new textile materials all play a role (Kaufmann, 1998, Klepp, 2007, Shove, 2003). Since the mid-1800s, a lot of work has concentrated on increasing levels of cleanliness and hygiene. This has increased the washing frequency considerably, which then has had consequences for the development of cleaning technologies. The health authorities, industry and research and information offices for home economics and domestic work have been important actors. Consideration of environmental sustainability has not been a part of this development until recently.

The use of cotton increased rapidly in the 1800s and was followed by an increase of synthetic fibres after 1960 (Figure 45).

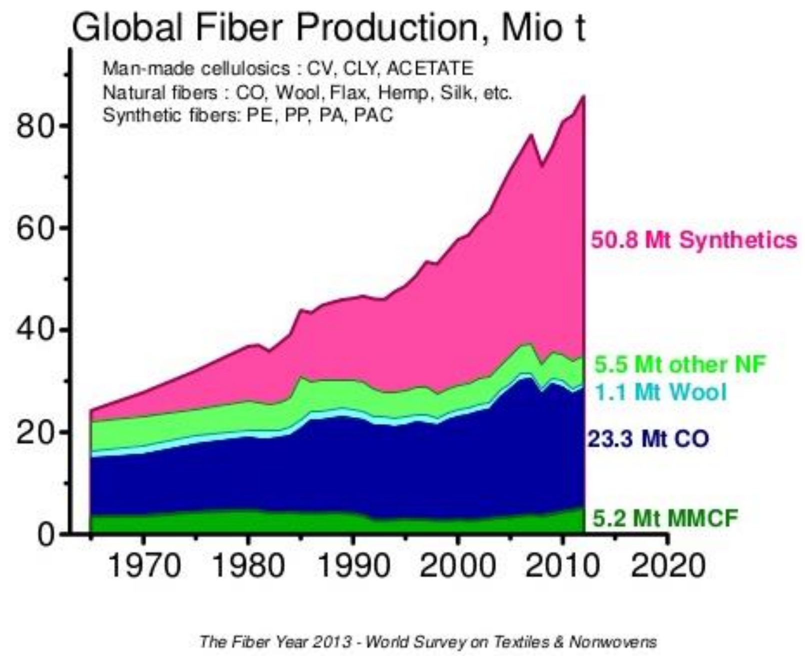

Figure 45 Global fibre production (Sixta, 2014, based on The Fiber Year Consulting, 2013) Abbreviations: CV=viscose, CLY=lyocell, PE=polyester, PP=polypropylene, PA=polyamide (nylon), PAC=acrylic, NF=natural fibres, MMCF= man-made cellulosic fibres

Cotton and synthetics dominate today's laundry, and this has consequences for the laundering methods used as well as the washing frequency.

- Due to cotton fibres' porous structure and hydrophilic nature they get easily dirty (unless dirt-repellent treated), and therefore require harsh washing, preferably with alkaline soap and high temperature (Blanke, 2001, Kjeldsberg et al., 2011).
- Synthetic fibres get dirty quickly and easily take up and develop odour after exposure to sweat (McQueen et al., 2014, McQueen et al., 2008).

Today's laundering methods adapted to suit these two fibre categories with frequent and harsh washing, have, therefore, become the current "standard" of how to do laundry. However, if we compare this to the standards for cleaning in 1850 or 1950, the washing frequency was completely different. Many clothes were not washed at all, and clothing that we today wash after each use, was washed once a year or once a week. Of course, it is clear that today we want and have the opportunity for an entirely different standard of hygiene, but this overview indicates how rapidly the changes in laundering have occurred.

Our studies of the use of wool have shown an interesting correlation between ownership of a lot of wool and low washing frequency (Klepp et al., 2016b). What is done often is perceived as easy and normal, while what is done rarely is perceived as "difficult". As a consequence, families that have a lot of wool find it easier to wash, but they also increase the number of days in use between washes. We also see that the differences between practices in the use of wool are greater than the differences in use practices for the more common fibres such as cotton. A standardised "washing package" has been developed for cotton and synthetics, including the use of washing machines and specific detergents. What is done more seldom, or that deviates from this standard, does not fit in the package, and is, therefore, subject to larger differences and discussion. In the Woolbed project, we observed that for similar products, such as thin wool sweaters, practices in use can vary from washing after each use to washing seasonally (Klepp et al., 2016b).

Most scientific research, as well as daily decisions on washing methods and frequencies, have been conducted based on ideal hygiene level and / or aesthetic reasons. The washing frequency has increased during the 1900s in order to limit the spread of infections as well as to inhibit body odours (Klepp et al., 2016a). In decisions on best practice, it is important to take into account these aspects, in addition to environmental considerations. These considerations are not static. We know that sensitivity to body odour has changed a lot in Western countries over the latest 100 years, and is changing. The population has become much more aware of body smell than before, and the experience of perfume and other odours are different both in time and in different regions. This change has been aided by advertisements for deodorants and other odour-inhibiting products (Klepp et al., 2016a).

Best practice can be studied in different ways.

1) Best practice currently in use. Such an approach will be based on knowledge of variations in practice. Best practice will be the best of what is already practiced by some consumers. It can be studied through various forms of diaries, recording and interviews, as demonstrated in this report. Best practice in use can be within a country, but it could also be perceived as the country or region that has less environmentally damaging practices than others. How large a group of consumers the best practice should be based on, must of course be discussed.
2) Analytical potential for best practice, i.e. what could be achieved in an ideal situation, regardless of whether it is currently practiced or not. This understanding is based more on knowledge of a materials' potential. It is possible that we do not currently have products that address the opportunities that exist in the best possible way. It is also possible we do not exploit the ones we have in an optimal way. This can also be studied experimentally, not by looking at actual use, but through experiments. Such experiments can for example involve letting a group of people use certain fabrics, and then see how long it is acceptable to use them between washes according to themselves and to others around them. This type of research has been conducted by companies as a way to draw attention to the possibility that their products represent. These products include running shoes (Three Over Seven, 2014), wool shirts (Ha, 2014, Wool&Prince, 2013) socks (Tobiasson, 2016), and a T-Shirt for running (Blaine, 2016, Oosthuizen, 2016). As far as we know, these results have only been used in marketing and not documented in a form that is suitable for scientific research. However, this does not imply that the results are worthless.

4.3.2 Clothing lifespans

When working with clothing lifespans, it is important to take into account both social and technical life, and how these two interact. The technical life will depend on how fast and in what way garments show signs of wear. However, the wear will also be subject to a social assessment. Worn jeans are assessed differently than worn dress pants. Technical wear thus also has a social aspect. Nevertheless, best practice within lifespan is in practice about exploiting clothes as long as they measure up technically, and is correlated to the social life.

Also best practices related to lifespans can be understood in two different ways.

1) Best practice currently in use. We believe this is close to a convergence between technical and social maximum lifespan. This has been considered before, and for example in the UK it is thought that the target lifetime of clothing could be one third longer than the current average practice (Cooper et al., 2014).

2) Analytical potential for best practice should most likely go into more detail on the conditions of this practice and if aspects such as maintenance and repair could be used, and how the materials could be improved (developments within services and products).

4.3.3 End of life

There are several alternative paths for clothing items that go out of use. For finding best practice for the end of life phase, one should follow the waste hierarchy that indicates an order of preference for action to reduce and manage waste from an environmental point of view. It starts with prevention, which reduces waste generation, followed by reuse, material recycling, energy recovery and finally disposal.

1) Best practice currently in use can be studied empirically to see what are the best practices from an environmental point of view today (follow the waste hierarchy).

2) Analytical potential for best practice will be a maximum long lifespan in use as garments, either by one or several users, followed by material recycling. Here, the available infrastructure and technologies set limits, for example, for what is potentially possible and what is found in the different regions.

4.3.4 Best practice scenarios in previous studies

Some previous studies have estimated the impacts of changing consumption towards selected best practice scenarios. Allwood et al. (2015) analysed the impacts of change in consumer behaviour by modelling scenarios of (1) extending the lifetime and (2) better practice in cleaning. Scenario 1 suggested that through extending the lifetime of a viscose blouse so that demand for new items dropped by 20%, environmental impacts across a range of categories would be 15% lower. Scenario 2 took a cotton T shirt as the example product, and showed that if cleaning was done in a similar way as the viscose blouse, the better practice through lower washing temperature (40°C rather than 60°C) lowered environmental impacts by about 10%. Additionally, combination with air drying instead of tumble drying and not ironing, climate change impact fell by 50% (Figure 46).

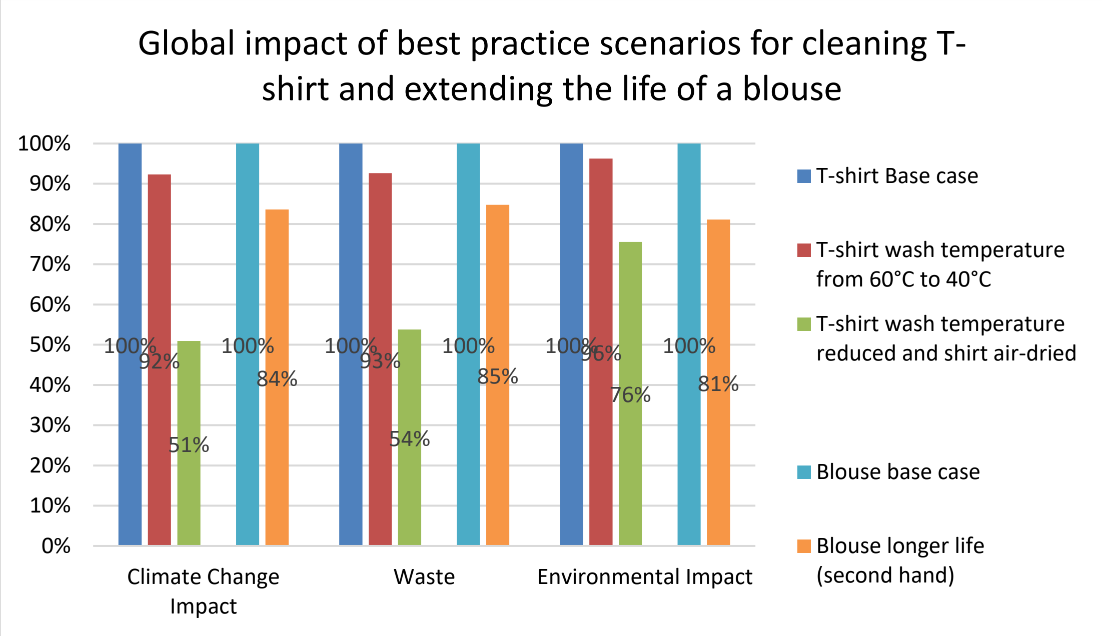

Figure 46 Reduction in global environmental impacts for changing to best practice scenarios in cleaning a t-shirt and extending the life of a blouse (Allwood et al., 2015)

Laursen et al. (20017) used scenario analysis to evaluate the influence of changes in Danish textile supply chains on environmental impacts. They ran six different textile case studies. The following examples relate to the use phase for a cotton T-shirt:

- Replacing tumble drying of a cotton T-shirt with line drying reduces overall consumption of primary energy by almost 50%, with consumption of resources being reduced by as much as 60% for coal. Because of lower consumption of electricity, most of the impact potentials in the environmental impacts related to energy are reduced by 40-50%. There are only slight changes in the toxicological environmental impacts (about 1%).
- Eliminating ironing reduced the total consumption of primary energy by 2-6% depending on the assumption for ironing percentage in the reference case and in almost all impact categories corresponding to the energy consumption in ironing. The toxicological environmental impacts are unchanged compared with the reference scenario.
- Halving the wash frequency, i.e. after two wears instead of every wear, reduced consumption of primary energy by 40 per cent with a 30-40% reduction in environmental impacts related to energy and a slight reduction in toxicological environmental impacts. The impact on consumption of fossil fuel was largest for coal at 50% less.
- For an optimised use phase with half the number of washes, no tumbler drying, 10 per cent ironing and double the lifetime, reduction in consumption of primary energy of about 75% occurred with similar reductions in consumption of resources and environmental impacts related to energy. The reduction is primarily due to no tumble drying and fewer washes in the use phase. Because materials, production, transport and disposal of a T-shirt are spread over 2 years instead of 1 year, the contributions are reduced by 50% and similarly half of the toxicological environmental impacts relative to the base case. This is primarily related to pesticide use in cultivation of cotton.

4.4 Geographic variations

There are large geographical differences in clothing use which will make a significant contribution to LCAs. The materials used, types of garments and technologies vary, which can be observed especially in laundering practices where the most common cleaning methods vary from hand washing to machine wash with different types of machines, cleaning programs and temperatures that all affect the environmental impact of the use phase. In addition, different climate conditions, such as temperature and humidity, set varying requirements for clothing. In the disposal phase, the infrastructure and how well various reuse and recycling alternatives are established, play a significant role.

In the use of woollen clothing, the main differences are related to the amount of woollen garments in use, their types, which situations they are used in, and how they are taken care of (The Nielsen company, 2012).

4.5 Differences in use between wool and other fibres

Where information has been available, the results have shown that wool is used in a different way than other textiles, especially those of cotton. Wool is washed differently with about ten degrees lower washing temperature than the average laundry in Europe. Wool is also more likely to be either dry-cleaned or washed by hand than other textiles. Moreover, when dried, it is less likely to be tumble-dried. When comparing the number of days between the washes of different types of clothes, we found that respondents were likely to use their woollen products about twice as long between washes as similar products in other materials. We also found results that showed that woollen products had longer average lifespans and were more likely to be reused or recycled.

4.6 Data and knowledge gaps in the use phase

Despite the extensive amount of literature on clothing use phase, several gaps in data still exist. Very little is known about the frequency of use, that is, how many times garments are used during the period they are owned by a user (active service life).

Some studies have examined the number of items people own, but based on the differences between surveys and actual wardrobe audits, we note that the figures found by surveys are lower than independently verified wardrobe audits in most cases. For example, the Dutch wardrobe studies showed that respondents had on average 22.7 items (21%) more than they thought they had (excluding socks and underwear that could have made the estimations even more difficult) (Maldini et al., 2017).

When it comes to clothing reuse, more is known about the disposal phase and where people give their clothing than how large a portion of clothing is actually reused. For example, a major part of used clothing from Western countries is exported, and not much is known about how large a portion of these items ends up in use and how many items are recycled or end up in waste instead. One thing to consider is that all of them will at some point become unusable and end up in waste (either directly or after recycling). The waste treatment technologies vary greatly between countries. Developed countries are using more and more cleaner alternatives such as waste to energy incineration in modern facilities with strict regulations to emission levels, while in developing countries, landfilling is still common. The carbon footprint of waste to energy incineration facilities has been shown to be lower than the footprint based on biogas retrieval from landfilling (Jeswani et al., 2012). In addition, airborne as well as solid waste emissions from incineration are controlled (Porteous, 2001, Sabbas et al., 2003).

Therefore, it would be preferable from the environmental point of view, if a larger portion of clothing was used until its end by the first owner and, if going to reuse, it would be better if the used clothing was reused in developed countries.

Most of the studies found for this review were conducted in Europe, and therefore there is a need for more data for the other areas, especially Africa and South America, but also Australia and several Asian countries, as well as Russia.

4.7 Priorities for future studies

For improving the LCA calculation on the use phase, the following areas should be given highest priority:

4.7.1 Empirical studies

Use frequency: Obtaining information on the number of times and/or hours that each garment is used during its lifespan (service life) in order to calculate the environmental impacts for functional units related to wear, instead of per garment or kg textiles

Geography: Most of the laundering research was conducted by European researchers. Data from other regions was not as readily available and detailed study is needed for representative regional information.

Fibers: To continue to study the impact of clothing material during use, including fibre blends.

4.7.2 Methodological studies

Cross discipline studies: More studies that combine surveys and practice based methods are needed in order to determine the ratio between the results and to correlate differences in survey results. Practice based methods observe actual behaviour as opposed to methods where informants only tell what they do.

Clothing function: Development of a method for measuring effective lifetime, where the unit is adapted to the clothes' function.

Best practice: To study how best practice scenarios are used in other contexts and material groups, thus finding a good method for quantifying the use phase for clothes in LCA.

Clothing categories: Systematization of clothing categories, so that it becomes easier to compare between studies. Currently the divisions are based partly on garment types and partly on fibre content and this makes comparisons difficult. Categories should be made larger, but at the same time more precise, for example durables and consumables in different fibres.

4.7.3 LCA methodology development

Impact categories in LCA: Determining which impact categories should be prioritised for assessing the environmental impact during the use phase of clothing. The categories most commonly reported included climate change (carbon footprint), water consumption or water footprint, and energy use

Eutrophication and toxicology: In addition to these commonly used impacts, eutrophication and toxicology impacts are likely to be important.

Microfibres: Growing concern regarding the possible impacts of microfibres from synthetic clothing means that research is needed to understand microfibre shedding from clothing during wear and laundering, and the possible impacts in the environment and on human health.

4.8 Recommendations for inclusion in LCA

Despite major gaps in knowledge, it is possible to include the use phase in LCA based on the existing studies, and our conclusion is that it should be done. This is based on these factors:

- Use is an important parameter in relation to environmental impacts, especially water and energy consumption.
- Consumer behaviour is individual and varies a lot, but the practices also vary systematically so that it is possible to study and compare them at an aggregated level.
- It is possible to document differences based on fibre type in terms of use and end-of-life
- It is possible to find regional differences which have a large impact on the use and end-of-life
- The emerging priority to develop indicators to quantify and monitor microfibre loss and impacts of synthetic textiles during use phase
- This knowledge should be taken up in LCA studies, however also be related to the best practice scenarios and thus into work on environmental improvements.

When including use phase, the functional unit should be considered carefully. It is likely that per day or year of use is better than per garment. The main aim of producing the garment, wearing of it, occurs during the use phase, and the importance of this should be acknowledged in LCAs as well as other environmental assessments such as fibre ranking tools. When comparing analysis of other products, for example paint, the functional unit for a paint system may be defined as the unit surface protected for 10 years, not per litre of paint.

5 Conclusions

The literature review has shown that there is a lot of information about the use phase of textiles. The amount of information varies geographically and for various aspects related to use. There is less information appropriate for comparisons between fibres than for generic clothing; nevertheless, we believe that based on the literature it is possible to answer the questions we asked at the beginning:

1. *Which parameters of the use phase should be addressed in order to be able to properly include this phase in LCA studies?*

We have shown that there are several parameters to address when including the use phase in LCA studies.

- Method of cleaning, e.g. wet process either manual or using an appliance, dry-cleaning, spot cleaning or airing;
- Characteristics and efficiency of each appliance used for washing, drying and ironing that determine the water and energy consumption.
- Type and quantity of detergents and other chemicals used;
- Consumer behaviour and practice in laundry (decision to launder after use, filling grade of the washing machine, selection of washing cycle, temperature, etc.)
- Period of use of the item, (length of effective lifespan)
- Fate at the end of use.
- Material properties of textiles, such as durability, ease of cleaning, and design aspects that may affect the social lifespans.
- Properties of textiles and cleaning methods that determine the potential for microfibre shedding.

2. *Is there enough information available about the use and re-use phases, that makes it possible to ground LCA studies on research-based information on use?*

There is quite a lot of research based information available concerning both use and reuse, and we believe it is enough to ground LCA studies on these results. However, we have also shown that there are several methodological, conceptual and empirical knowledge gaps in existing literature. For example, one methodological knowledge gap concerns use of surveys and their relationship to results obtained by using practice-based methods that for example observe the actual behavior. One conceptual gap was found in large differences of categorizing of clothes and ambiguity around important terms such as clothing lifespans and effective use period.

3. *Does the information indicate that it would be possible and appropriate to use fibre content as one of the parameters for environmental impact in use?*

The review showed that clothing made of different materials are used and reused differently, and therefore fibre content is a relevant category to be taken into account. It is particularly relevant in assessment of potential for microfibre pollution since natural fibres are biodegradable and do not contribute to accumulation of plastics in the environment. However, some knowledge gaps remain, such as potential differences in use between various man-made fibres that are either cellulose or oil based, as well as use of blend materials.

4. *Does the information indicate that regional differences are relevant for the use phase of LCA?*

This review has shown that there are large differences between regions. It is possible to divide into regions with large differences in clothing use, although practices vary even within these areas. Some examples are the differences in energy consumption related to the laundering and drying, where the United States stands out clearly due to higher rate of top loading machines and use of clothes dryers, differences in the post-use phase where particularly areas where textile waste is landfilled, has a major impact. Also clothing quantities, usage, use of dry-cleaning, fabric softeners and washing methods vary widely geographically.

5. *Where are the largest and most significant knowledge gaps?*

As discussed in section 4.6, several knowledge gaps exist despite the extensive amount of literature on the clothing use phase. The ones that cause largest problems for LCA studies are the lack of empirical data on clothing use frequency and effective lifetimes (service life), reuse of clothing (the ratio of clothing that is reused and whether the reuse differs from the first use), data from less studied geographic areas such as Africa, South America and some Asian countries, methodological knowledge gaps related to lack of suitable methods for studying effective service lifetimes, surveys and practice based methods, and factors, including fibre type, garment age and washer type, that determine the degree of shedding of fibres during washing.

6. *How can a literature review of the use phase help:*
    a) *to improve LCA on textiles?*

- Use phase has a great importance for the total environmental impact and should therefore be incorporated into analyses that attempt to cover the entire clothing life cycle.
- The use phase is important for several environmental impact categories such as climate change, ozone depletion, water consumption, eutrophication, human and ecotoxicity, that are also relevant for the other life cycle phases. However, the use phase also includes environmental impacts that are not covered by the current environmental impact categories used in most LCA studies: release of microfibres in laundering.
- LCA studies should be knowledge-based and not based on guesses, especially when such knowledge is actually available.
- Incorporating the use phase properly in LCA studies will therefore make them more knowledge-based and potentially also contribute to a change of focus towards environmental impacts specifically related to these stages in the product's lifecycle.

    b) *to improve practices related to use in order to reduce environmental impacts??*

The overview and comparisons of the different fibres and regions globally makes it possible to show where there is the greatest potential for improvements. By working towards use of functional units and best practices, it will be possible to align the environmental improvements towards the areas where they make the largest impact. Improvements in textile LCAs will make the various fibre ranking and benchmarking tools that are based on them better suited to promote sustainable development.

We believe that this can be done by incorporating existing knowledge, while at the same time working with filling the key knowledge gaps, and thus contributing to more robust terms, data and parameters in the future.

This study has been conducted with the starting point of finding out whether wool comes out differently in comparisons of environmental impacts between fibres during use. A goal has been to see if the incorporation of the use phase in comparisons between fibres could affect the ranking in tools such as Made-By[39] and Higg Index[40]. The basis for this was the assumption that wool is used, washed and disposed of in ways that have a smaller impact on the environment. We have shown that this is true; wool has longer life and greater tendency to be reused and lower cleaning frequency, although the higher dry-cleaning rate reduces some of the positive impacts. Including the use phase in fibre ranking benchmark tools will thus benefit the ranking of wool.

However, we have also shown that there are large variations in whether the potential benefit of reduced environmental load is fully exploited. Thus, focusing on best practices will result in a bigger difference between the fibres than focusing on current practice.

We have seen a sharp and rapid growth in the use of textile fibres in developed countries during the past decades. This growth has been mainly in synthetics, especially polyester, and to some degree in cotton, while the use of wool and some other fibres such as silk and linen has not changed. The rapid growth of polyester and cotton has also influenced the patterns of use, laundering and cleaning technologies. We believe it is important that LCA and other sustainability tools do not favor the fastest growing segments, but also use the aspects that point toward quality, longevity and a good fit for the intended use area.

[39] http://www.made-by.org/consultancy/tools/environmental/
[40] http://apparelcoalition.org/higg-materials-sustainability-index-msi/

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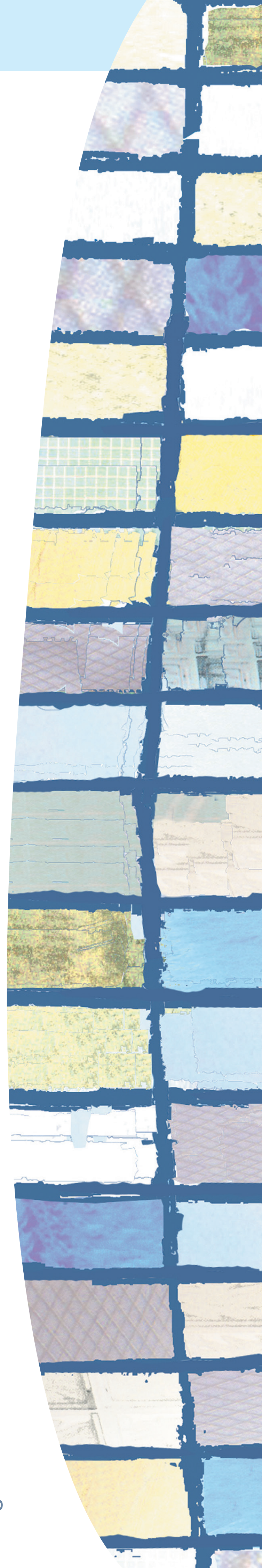
Consumption Research Norway SIFO at Oslo and Akershus University College of Applied Sciences (HiOA) has a special responsibility to contribute to the knowledge base for consumer policy in Norway and will develop new knowledge about consumption, consumer policy and consumer position and role in society.

Key research topics are:

- consumers in the market and consumer choice
- household resource allocations
- consumer economy - debt development and poverty
- technological development and consumers' every day life
- digital daily life and coping
- environmental effects of different types of consumption
- food and eating habits
- textiles - value chains - consequences for everyday life and environment
- consumption significance for social inclusion
- consumer policy



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