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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane

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Abstract
Purpose The purpose of this paper is to provide an improved (up-to-date) insight into the environmental burden of textiles made of the base materials cotton, polyester (PET), nylon, acryl, and elastane. The research question is: Which base material and which life cycle stage (cradle-to-gate as well as cradle-to-grave) have the biggest impact on the environment?
Methods Life cycle inventory (LCI) data are collected from the literature, life cycle assessment (LCA) databases, and emission registration database of the Dutch government, as well as communications with both manufacturing companies of production equipment and textile companies. The output of the calculations is presented in four single indicators: Eco-costs 2012 (a prevention-based indicator), CO_2 equivalent (carbon footprint), cumulative energy demand (CED), and ReCiPe (a damage-based indicator).
Results and discussion From an analysis of the data, it becomes clear that the environmental burden is not only a function of the base materials (cotton, PET, nylon, acryl, and elastane) but also of the thickness of the yarn (for this research, the range of 50–500 dtex is examined). The authors propose that the environmental burden of spinning, weaving, and knitting is a function of 1/yarn size. The cradle-to-grave analysis from raw material extraction to discarded textile demonstrates that textiles made out of acryl and PET have the least impact on the environment, followed by elastane, nylon, and cotton. The use phase has less relative impact than it is suggested in the classical literature.
Conclusions The impact of spinning and weaving is relatively high (for yarn thicknesses of less than 100 dtex), and from the environmental point of view, knitting is better than weaving. LCA on textiles can only be accurate when the yarn thickness is specified. In case the functional unit also indicates the fabric per square meter, the density must be known. LCA results of textile products over the whole value chain are case dependent, especially when dyeing and finishing processes and the use phase and end-of-life are included in the analysis. Further LCI data studies on textiles and garments are urgently needed to lower the uncertainties in contemporary LCA of textile materials and products.

Keywords Carbon dioxide (CO_2) · Clothing · Eco-costs · Fibers · Spinning · Textile · Use phase · Weaving

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1 Introduction

In recent years, life cycle assessment (LCA) has been increasingly adopted by textile and apparel companies. Many actors in the textile and clothing chain such as fiber manufacturers (e.g., Lenzing, Advansa, Dupont), producers of flooring material (e.g., InterfaceFlor, Desso, Heugaveld), fashion brands (united in the Sustainable Apparel Coalition), and even umbrella organizations (European Commission and the Dutch branch organization Modint) use LCA to assess the environmental impacts of textile-related products. In addition, educational textile and fashion institutes (e.g., the Amsterdam Fashion Institute) have moved towards life cycle thinking, picking up the signals from companies and other organizations.

In many cases, LCA studies and the development of LCA tools on textile products are carried out by consultancy companies or independent research institutes which interpret

LCA and the International Standard Organization (ISO) specifications in their own way. Results are presented in reports or online and reach the public via marketing departments or via the media. Despite of this growth in LCA work, not many (recent) LCA studies on textile products can be found in scientific literature. Consequently, there are gaps in the scientific framework for the interpretation of the previously mentioned market efforts. There is not enough literature available and there are no (open source) life cycle inventory (LCI) databases to build further scientific research upon. Nondisclosure of databases and company-related information might be due to the fact that confidentiality plays an important role. This article aims to open up the scientific discussion on LCA in textiles.

1.1 Existing LCA studies on textiles

A literature survey and some investigations among experts in the field of LCA studies on textiles showed that most of the publicly available LCA data and process data are outdated, not transparent (especially regarding system boundaries), and sometimes clearly out of range (outliers). It was quickly concluded that original data reflecting today's situation is urgently needed.

A summary of the results of the literature survey is given in the succeeding paragraphs and sections. Collins and Aumônier (2002) compiled the LCI data upon references dating from 1978 to 1999. Another research executed by Kalliala and Talvenmaa (1999) reports, for example, spinning energy which is derived from a study out of 1997. In-depth investigation on weaving led to the research of Koç and Çinçik (2010), but an analysis of the references revealed that only 5 out of 16 references were in English, which makes it very difficult to verify the results. In the recent thesis of Shen (2011), nonrenewable energy use for the production processes of different fabrics is given, based upon a report from 1997 (Laursen et al. 1997). Another recently published LCA study of Walser et al. (2011) uses inventory data for polyester (PET) textile production, partly built upon information dating from 1997 as well. The authors also noticed that the data in the Ecoinvent database (Ecoinvent 2010) on cotton and bast fibers do not specify the yarn size, which has an important influence on energy use. This aspect is further discussed in Section 3.

In general, it appeared to be very difficult to check the underlying datasets because researchers built up their own dataset by combining information from different and sometimes very old or confidential sources.

Tobler-Rohr (2011) gives an excellent overview of textile production but does not provide enough LCI data to base further LCA calculations on.

Steinberger et al. (2009) present a comprehensive LCA study on clothing which is focused on the use phase of textiles (i.e., washing clothes by the user); however, this lacks accurate data on the production phase.

1.2 Data collection

Most of the previously mentioned sources were considered to be not very valuable for our LCA on textiles conducted in 2011–2012 because, in the preceding period, companies may have made significant improvements on energy consumption, mainly driven by high energy costs. Firm underpinning numerical data for this change was not transparent, but percentages of 2 to 3 per year are quoted. A report of the united German textile machinery manufacturers (VDMA 2009) claims energy efficiency improvements of 15 % over the last 10 years. This figure was also quoted during a communication with Mr. Bernard Defraye of CIRFS, the European Man-Made Fibres Association.

An important observation is that the majority of the researchers do not take into account important technical specifications (e.g., the thickness of the yarn) which have a major impact on processing energy, as will be shown in Section 3.

The approach chosen in this study was, therefore, to collect all available data from the public domain (scientific literature and company information), from (LCA) databases, from the emission registration database of the Dutch government, and by contacting companies and experts.

We contacted (among others) the following companies/associations:

- Oerlikon Barmag,
- CIRFS, the European Man-Made Fibres Association,
- International Textile Manufacturers Federation (ITMF),
- Kuempers.

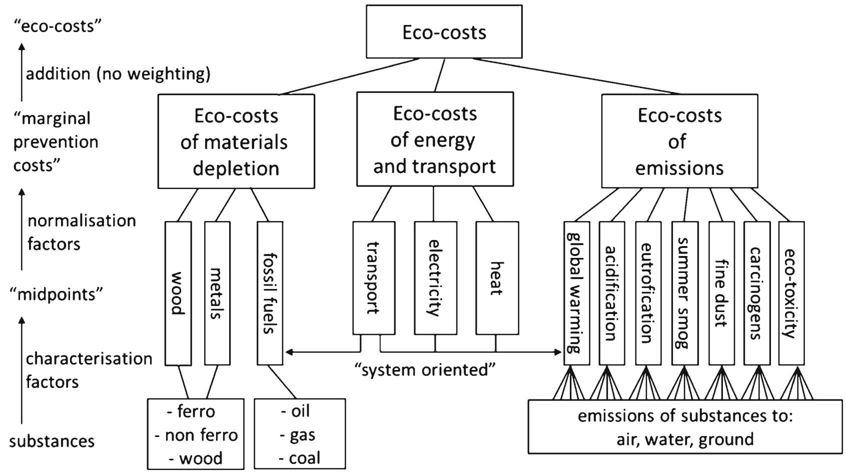
2 Goal and scope

2.1 Goal

The goal of the study is to develop an improved (up-to-date) insight into the environmental burden of the life cycle of textiles, for various types of materials (cotton, PET, nylon, acryl, and elastane), and as a function of the thickness of the yarn in the range of 50–500 dtex (decitex=the mass in grams per 10,000 m). The main focus is on the production of textiles (cradle-to-gate); some data on the use phase (washing by the user) and the end-of-life phase are also provided.

Since the goal of the study is to provide designers with environmental information, the output of the calculations is not presented in the form of a set of midpoints, but in the form of single indicators. A single indicator in LCI analysis is one single score to express the result of the cumulative inventory list in one indicator, either at the midpoint or endpoint level.

Fig. 1 Calculation structure of the Eco-costs 2012



To provide the reader with information on the effect of the choice of a single indicator, data on four single indicators are given:

- Eco-costs 2012 (a prevention-based indicator),
- CO_2 equivalent (a single indicator at midpoint level),
- Cumulative energy demand (CED),
- ReCiPe (a damage-based indicator).

Eco-costs is a measure to express the amount of environmental burden of a product on the basis of prevention of that burden and has also been introduced in this journal before (Vogtländer and Bijma 2000, 2001). They are the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth. The eco-costs system has been updated in 2007 and in 2012. The characterization ("midpoint") tables which are applied in the Eco-costs 2012 system are (see Fig. 1 and Vogtländer 2013):

- IPPC 2007, 100 years, for greenhouse gasses;
- USETOX, for carcinogens and ecotoxicity;
- ReCiPe, for acidification, eutrophication, and summer smog (photochemical oxidant formation);
- IMPACT 2002+, for fine dust.

Eco-costs is part of the bigger model of the eco-costs value ratio (EVR) and the method of eco-efficient value creation (Wever and Vogtlander 2012; Mestre and Vogtlander 2013).

The advantage of the single-issue indicators (CO_2 equivalent and CED) is that they are simple to understand. The disadvantage, however, is that toxicity and materials depletion is not taken into account. That is the reason why data on eco-costs and ReCiPe are given as well: they both incorporate human toxicity, ecotoxicity, materials depletion, and land use.

ReCiPe is a damage-based indicator. It is the successor of the famous Eco-indicator 99, introduced in this journal (Goedkoop et al. 1998). We present the data for the Europe H/A weighting set for human toxicity, ecotoxicity, and materials depletion (H/A refers to the default ReCiPe endpoint method, H=hierarchist and A=average weighting set).

2.2 Scope, system boundaries, and declared unit

The scope of this study is cradle-to-grave. It includes the cradle-to-gate processes of the production chain from raw material extraction to manufactured greige[1] fabric for cotton, PET, nylon, acryl, and elastane, as well as the gate-to-grave processes for textile products made out of these materials.

The LCAs for greige textile manufacturing phases are full analyses. For dyeing and finishing processes, ranges and an example of LCA based on best practices are given. A cutoff criterion of 1 % is applied to decide on the exclusion of (sub)processes, inputs, and outputs, in compliance with ISO 14044 Section 4.2.3.3. For the use phase and the end-of-life phase, ranges are given based on specific cases. The scope excludes the following phases related to the textile product: manufacturing (sewing and assembling), distribution, marketing, and sales of the textile.

The choice of the declared unit (functional unit) is "1 kg of (greige) textile." This paper shows that a unit in kilograms is a logical choice from the point of view of production, since the eco-burden of the base materials, spinning, and weaving of all materials is a function of kilograms and yarn size (decitex). However, from the point of view of textile applications (cloth, carpets, etc.), it seems logical to have a declared unit in 1 m^2, so Section 8 provides some information per square meter.

Table 1 summarizes the scope of this study and simultaneously explains the outline of this article. The full cradle-to-gate analyses on the production of materials in phase A and phase 1 are based on Ecoinvent LCIs (Ecoinvent 2007a, b). These LCIs include transport and the required production infrastructure (the so-called third-order LCIs).

[1] The term "greige" is industry jargon for "untreated woven or knitted fabric" and refers to the fabric before the final phases of dyeing and finishing. In this context, "greige" is defined as "unbleached and undyed or untreated."

To determine whether the impact of the emissions from the following production process steps stays below the 1 % cutoff criterion, the emission registration database of the Dutch government (http://www.emissieregistratie.nl/erpubliek/bumper.nl.aspx, accessed on 20 January 2013) is used. This database shows that emissions from the production sites of process phases B to D and 2 to 5 are less than 1 % of the emissions from the production of electricity and heat, so these emissions are below the 1 % cutoff criterion and are not taken into account.

The results of the analyses of the previously mentioned processes for greige fabric are included in Sections 4.1 and 4.2.

The Dutch emission database shows that emissions from production facilities for dyeing and finishing are above the 1 % cutoff criterion, so these emissions coming from phases E, F, 6, and 7 are included in the analyses. Note that the emissions of these process phases are highly dependent on the fact whether or not modern best practices of green production are used and on the specific colors and finishing processes. Only data on best practices in the Netherlands have been analyzed, since data from production facilities in other areas (for instance, India and China where the situation is without doubt expected to be much worse) are not available. Results of the analyses of the gate-to-gate processes E, F, 6, and 7 are included in Section 5.2.

The use phase (G and 8) and the end-of-life phase (H and 9) are strongly case dependent. For these phases, a few scenarios are provided in Section 6 to show the reader how important these phases are compared to the production phases.

In conclusion, Section 7 gives an overview of the breakdown of the environmental burden over the complete textile life cycle. Transportation in the first step of material production (polymers and cotton) is included; however, we disregarded transportation in the subsequent production chain for the following reasons:

- The extent of transportation services is very case specific and it, therefore, does not seem possible to develop generic estimates; moreover, a fair part of the environmental impacts caused by transportation cancels out across the options studied (the principle of "streamlined LCA"; Todd and Curran 1999).
- The pollution caused by the transportation of fabric is generally small compared to the pollution of other processes in the production chain, in particular material production. (Shipping textile products from China causes the following extra scores per kilogram: eco-costs, €0.078; carbon footprint, 0.16 kg CO_2 equivalent; CED, 2.6 MJ; ReCiPe, 0.02 Pt).

For electricity from the grid, the data of the UCTE (average electricity production in the European Union [EU]) has been applied. The reason for this choice is that the situation is quite dependent on the specific area. For instance, there are areas in China with old power plants which are extremely polluting, but more and more areas with modern power plants with pollution standards similar to the standards in Europe arise (Ecoinvent 2007c).

Table 1 Scope of research and outline of article

Process/life cycle phase Cotton	Synthetics (polyester, nylon, acryl, and elastane)	Specifications of analysis	Discussed in	Results in	
(A) Fiber production (cultivation and cotton treatment)	1. Polymer production (covering all process steps from the extraction of resources)	LCA based on Ecoinvent data	Section 3.2	Section 4.1 for processes (A) to (D) for greige cotton textile	Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 for processes (A) to (D) and 1 to 5
(B) Spinning to yarn	2. Spinning of filament	LCA as function of yarn thickness	Section 3.3		
	3. Texturing		Section 3.4	Section 4.2 for processes 1 to 5 for greige cotton textile	
(C) Weaving or knitting	4. Weaving or knitting		Sections 3.5 and 3.6		
(D) Pretreatment	5. Heat setting of fabric including washing	LCA based on energy	Section 3.7		
(E) Dyeing of fabric	6. Dyeing of fabric	Ranges and example of LCA based on best practice given	Section 5.1	Section 5.2	Processes (E) to (H) and 6 to 9 are case dependent
(F) Final finishing including drying	7. Final finishing including drying		Section 5.1	Section 5.2	
(G) Use phase	8. Use phase	Data given	Section 6.1	Section 6.1	
(H) End-of-life	9. End-of-life	Data given	Section 6.2	Section 6.2	

An overview over the complete life cycle is discussed in Section 7 and depicted in Figs. 13 and 14

Table 2 Cotton fiber production and spinning: data from literature and private communication

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fiber manufacturing														
Cotton fiber production	Fiber													
IFTH2 (n.a.)	1 kg	Intensive production (6 countries)	Cotton fiber			0.41		0.00	0.50	8.21				7,103.00
IFTH2 (n.a.)	1 kg	Biological production (6 countries)	Cotton fiber			0.41		0.00	0.50	8.21				7,103.00
Laursen et al. (2007) EDIPTEX	1 kg	Cotton cultivation and harvesting				0.91		6.33	0.58	8.21	4.13			2,000.00
Laursen et al. (2007) EDIPTEX	1 kg	Fiber production of cotton yarn according to figure 1.3	Cotton fiber including cultivation and harvest			13.89								
Yarn manufacturing														
Spinning	Yarn													
ITMF (2008)	1 kg	Rieter ring spinning (including winding)	CO combed ring, yarn 1 1/8 in., 30 Ne	180	200	3.34								
ITMF (2008)	1 kg	Rieter rotor spinning	CO carded, rotor yarn=open end 1 1/16 in., 20 Ne	265	300	1.42								
ITMF (2010)	1 kg	Rieter ring spinning (including winding)	CO combed ring, yarn 1 1/8 in., 30 Ne	180	200	*3.42*								
ITMF (2010)	1 kg	Rieter rotor spinning	CO carded, rotor yarn= open end 1 1/16 in., 20 Ne	265	300	*1.46*								
Kaplan and Koç (2010)	1 kg	Staple fiber to yarn+data are for world average	CO combed ring yarn			3.84								
Kaplan and Koç (2010)	1 kg	Staple fiber to yarn+data are for world average	CO open end yarn			2.54								
Kaplan and Koç (2010) Tarakcioglu[a], 1984 lowest limit	1 kg	Thermal energy (steam?) is needed for fixation				2.70	1.10							
Kaplan and Koç (2010) Tarakcioglu, 1984 highest limit	1 kg	Thermal energy (steam?) is needed for fixation				4.00	4.70							
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed weaving yarn	180	200	*3.32*								
Kaplan and Koç (2010)	1 kg	Only SEC+reported	CO combed weaving yarn	180	200	*3.64*								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed weaving yarn	108	120	*6.81*								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed knitting yarn	180	200	*3.06*								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed knitting yarn	108	120	*5.52*								
Confidential source no. 7	1 kg	Rotor spinning of CO				1.85			1.68		1.56			

Table 2 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Dahllöf (2004) Laursen, 1997 lowest limit	1 kg	Total energy demand for cotton spinning factory—6.33 MJ—assumed only electricity				1.76								
Dahllöf (2004) Laursen, 1997 lowest limit	1 kg	Total energy demand for cotton spinning factory—18.31 MJ—assumed only electricity				5.10								
Kaplan and Koç (2010)	1 kg	Ring spinning according to their calculations	CO combed weaving yarn	330	330	1.88								
Kim et al. (1983)	1 kg	Spinning energy usage per unit production (kWh/kg)>no specific material; reported data 1972				5.40								
Kim et al. (1983)	1 kg	Spinning energy usage per unit production (kWh/kg)>no specific material; reported data 1980				4.86								
Collins and Aumônier (2002)	kg product	Spinning including preparation=29.36 kWh/kg	For pair of cotton briefs (72 g) and pair of polyester trousers (=400 g)											
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	Yarn manufacturing	For shirt 65 PET/35 CO staple fibers			7.46								
Palamutcu (2010)	1 kg	Carded yarn spinning plant—average actual and estimated				3.30								
Laursen et al. (2007) EDIPTEX	1 kg	Combed ring yarn according to formula	65/35 PET/CO	117	130	*4.10*								2.20
Laursen et al. (2007) EDIPTEX	1 kg	Combed ring yarn according to formula	100 CO	117	130	*4.15*								2.20
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Yarn production, cotton fibers/kg/GLO+electricity, low voltage, at grid/CN U				5.10								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Yarn production, cotton fibers/kg/GLO+electricity, low voltage, at grid/US U				3.40								
Demir and Behery (1997)	1 kg	Ring spun	67 CO/33 PET		167	4.41								
Laursen et al. (2007) EDIPTEX	1 kg	Spinning of cotton yarn according to Fig. 1.3				11.61								2,000.00
Laursen et al. (2007) EDIPTEX	1 kg	Figure 3.3 blending, carding, combing, and spinning of CO and PES staple fibers (0.877 kg)				5.07								
Processor, 2011 phase 1	1 kg	Carding+sliving+spinning+winding	40 PET/60 CO+PES staple fibers	180	200	*7.00*								

Table 2 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Processor, 2011 phase 1	1 kg	Carding+sliving+spinning+winding	40 PET/60 CO+PES staple fibers	90	100	*12.00*								
Processor, 2011 phase 2	1 kg	Doubling+twining	40 PET/60 CO+PES staple fibers	180	200	1.60								
Processor, 2011 phase 2	1 kg	Doubling+twining	40 PET/60 CO+PES staple fibers	90	100	3.20								
IFTH1 (n.a.)	1 kg	Ring spinning	CO combed			2.88								
IFTH2 (n.a.)	1 kg					2.32					4.76			

IFTH1 (n.a.) refers to an unpublished report named: Extrait de "l'Analyse de Cycle de vie pyjama Bébé" par l'IFTH. Institut Francais du textile et de l'habillement. IFTH2 (n.a.) refers to an unpublished report named: Extrait de "aide à la prise en compte de l'environnement dans la conception d'articles textiles" par l'IFTH. Institut Francais du textile et de l'habillement

n.a. not available

[a] The notation "Kaplan and Koç (2010) Tarakcioglu, 1984" means that Kaplan and Koç (2010) are referring in their publication to another reference (in this case, they refer to a publication of Tarakcioglu out of 1984)

All auxiliaries in phases A and 1 are included, since the Ecoinvent data have been applied here. Auxiliaries for the manufacturing of textile (according to IPPC 2003, among others, dyestuffs, dye carriers, lubricants, detergents, and complexing agents) are not included, since the impact on the calculations is less than the cutoff criterion of 1 % (e.g., the input of dyestuffs based on a high liquor ratio according to the IPPC 2003 "fair practice" causes the following extra scores per kilogram: eco-costs, €0.015; carbon footprint, 0.08 kg CO_2 equivalent; CED, 2.7 MJ; ReCiPe, 0.011 Pt).

3 LCI data—cradle-to-gate for greige textile

3.1 Base materials

The LCI data for cotton fiber and polymer pellets are from Ecoinvent v2.2:

- Cotton, "cotton fibers, ginned, at farm/CN" (CN=China);
- Acryl, "acetonitrile, at plant/RER" (RER=Region Europe);
- Nylon, 50 % "nylon 6, at plant/RER" and 50 % "nylon 66, at plant/RER";
- PET, "polyethylene terephthalate, granulate, amorphous, at plant/RER S";
- Elastane (Spandex, Lycra), "polyurethane, flexible foam, at plant/RER."

3.2 The textile manufacturing process steps in general

All data for the manufacturing process steps of yarn and fabric are obtained by publicly available sources or directly from industry references, as well as information from confidential sources. This data is presented in Tables 2, 3, 4, 5, and 6. From these tables, we selected the LCI data in Section 3 for our calculations in Sections 4 and 5.

Most of the chosen datasets for the calculations come from sources of European origin (except for data on the production of cotton fiber and the data derived from the ITMF 2010).

Important selection criteria for the chosen data were the reliability and traceability of the underlying reference. We rejected LCA data from studies of which the references for the data used for the calculations are not traceable at all or are explained in an unclear manner.

Important references we selected are:

- Report of the ITMF (2010). ITMF is an international association for the world's textile industries based in Zürich, Switzerland. ITMF's (2010) International Production Cost Comparison, which is based on data coming from individual companies, consultants, and textile trade associations, provides—among other cost components—overviews of power costs per kilogram of product and of the cost of

Table 3 Cotton weaving: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
Warping and sizing	Yarn													
Palamutcu (2010)	1 kg	SEC is relatively low compared to steam and heat	Warp yarn			0.01								
Weaving	Fabric													
ITMF (2010)	1 kg	Mean of 96 Sultex air-jet weaving machines B190 N2 EP11, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric of 27.6/27.6 threads/cm, Ne 30 in warp and weft, gray width 168 cm, gray weight 190 g/m	180	200	*4.38*								
ITMF (2010)	1 kg	Mean of 72 Sultex air-jet weaving machines B190 N2 EP11, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric of 24.0/24.0 threads/cm, Ne 20 in warp and weft, gray width 168 cm, gray weight 248 g/m	265	300	*2.97*								
Confidential source no. 7	1 kg	Weaving with sizing in Sweden+ average of three mills producing CO, Trevira, and wool/PA				2.65			1.66		1.53			
Confidential source no. 7, lowest value	1 kg					1.82			1.66		1.53			
Confidential source no. 7, highest value	1 kg					4.19			1.66		1.53			
Dahllöf (2004), Laursen	1 kg	Total energy demand ranges between 10 and 30 MJ—no breakdown reported												
Kalliala and Talvenmaa (1999)	1 kg	Includes singeing and sizing energy (electricity) consumption—5.4 MJ—no breakdown reported												
Kim et al. (1983)	1 kg	Weaving energy usage per unit production (kWh/kg)>no specific material; 1972 reported data				4.76								
Kim et al. (1983)	1 kg	Weaving energy usage per unit production (kWh/kg)>no specific material; 1980 reported data				3.86								
Kim et al. (1983), Van Winkle, 1978	Per shirt	Energy requirements to produce the shirting material for 1 shirt in kWh of fossil fuel equivalents (1 shirt requires 2,368 m/m^2 of fabric and the CO shirt weighs 308 g; CO/PET 270 g and PET 240 g)	Cloth manufacture 100 % CO									18.50		

Table 3 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 50/50 PET/CO									20.20		
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 65/35 PET/CO									20.20		
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 100 % PET									7.30		
Koç and Çinçik (2010)	1 kg	Warping+sizing+drawing+air-jet weaving—SEC+9.85 kJ/kg for thermal energy (NWE=NWA=30 Ne=180 Td=20 tex)		180	200	*5.06*								
Koç and Çinçik (2010), Tarakcioglu, 1984 lowest value	1 kg	Electrical energy consumption for 1 kg of woven fabric+8.3–17 kJ/kg for thermal energy=negligible (+sort not specified)				2.10								
Koç and Çinçik (2010), Tarakcioglu, 1984 lowest value	1 kg	Electrical energy consumption for 1 kg of woven fabric+8.3–17 kJ/kg for thermal energy=negligible (+sort not specified)				5.60								
Koç and Çinçik (2010), Visvanathan, 2000	1 kg	2.2–25 kJ/kg for thermal energy= negligible (+sort not specified)				5.75								
Bahr Dahr Textile Share Company (2010)	1 kg	Weaving requires electricity+ compressed air+steam				9.44	4.50				9.07			
Collins and Aumônier (2002)	kg product	Weaving including beaming+winding for fabric for a pair of polyester trousers (=400 g) takes 12,60 kWh/kg product				12.60								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	Closed-off high-speed air-jet loom	One shirt (65 % PET/35 % CO) weighs 227 g			1.35								
Palamutcu (2010)	1 kg	SEC				1.80								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Weaving, cotton/GLO U, electricity, low voltage, at grid/CN U				7.08								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Weaving, cotton/GLO U, electricity, low voltage, production RER				3.03								
Kuempers, 2011, personal communication	1 kg		60 % CO+40 % PES			10.63								
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 3.3, 6.8 MJ per 1 working jacket of 770 g (fabric 877 g)	Weaving of fabric of 65 % CO+35 % PES			2.15								
Processor, 2011 phase 3	1 kg	6.5 kWh/10,000 picks; 37 picks/cm; 160 cm width	40 PET/60 CO+PES staple fibers	180	200	*9.39*								

Table 3 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Processor, 2011 phase 3	1 kg	6.5 kWh/10,000 picks; 48 picks/cm; 160 cm width	40 PET/60 CO+PES staple fibers	90	100	*19.50*								

SEC specific energy consumption, *EP11* a machine name, *Ne* number English (a unit for yarn thickness, 1 Ne=1/591 tex)

electric power per country. Using this information, it is possible to calculate back the power use.

– An anonymous company (named “Processor, 2011 phase X” in Tables 2, 3, and 4), which is a producer of (among other textile fabrics) shirt material and has production plants in Belgium and France.
– The company Oerlikon Barmag (referred to as “Barmag, 2011” in Table 5), which is a mechanical engineering company offering innovative spinning lines and texturing machines for man-made fibers.
– The EDIPTEX study by Laursen et al. (2007), which was set up in close cooperation with more than 15 Danish textile enterprises which contributed with comments on product models and processes or were directly involved in the collection of data and contributed with data on, e.g., chemicals being used, energy consumption, and waste. A lot of (recent) LCA studies, e.g., the Mission Linen report (Cartwright et al. 2011), refer to data contained in this report.

All collected data (and not only the chosen ones) for the gate-to-gate production processes are included in Tables 2, 3, 4, 5, and 6 to inform the reader about all results from the data-collecting activities. The chosen data are justified in the following sections (3.3 to 3.7 and 5.2) and rendered in italics in the Tables 2, 3, 4, 5, and 6.

Note that the textile industry is using several systems to express the thickness of yarn which must not be confused. Two important units are “tex” (mostly expressed in dtex=decitex=0.1 tex) and “denier.” While 1 dtex is equal to 1 g/10 km, 1 den is equal to 1 g/9 km. If a specification of yarn thickness is known, values in both units are presented in the tables.

3.3 Spinning of cotton and polymer filament

For the spinning process of cotton, only electrical power is important for the LCA calculation (the maintenance of the machine can be neglected, as well as the making of it). The results from the data collection are summarized in Table 2.

It was concluded from the physical characteristics of the spinning process that a thinner yarn (lower decitex) is related to a higher energy demand per kilogram, which can be seen in Table 2. Data, without specification of the yarn size, is, therefore, useless (approximately 50 % of the data in Table 2). Data from Ecoinvent is also useless for the same reason.

Figure 2 shows the data of Table 2 with a specified yarn size and which meet the following the criteria:

1. Is most recent.
2. Is for the specific energy consumption (SEC) spinning process of 100 % cotton.
3. The yarn thickness is within scope.

From Fig. 2, it can be concluded that the energy consumption per kilogram yarn is inversely proportional to the yarn thickness in decitex.

Table 4 Cotton knitting, pretreatment, dyeing, and wet processing: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
Knitting	Fabric													
ITMF (2008)	1 kg	Mean of 17 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO ring yarn to a fabric, single jersey Ne 30, unfinished width (open) 192 cm, unfinished weight 230 g/m	180	200	*0.19*					0.19			
ITMF (2008)	1 kg	Mean of 13 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO rotor (open end) yarn to a fabric Lapique Ne 20, unfinished width (open) 224 cm, unfinished weight 358 g/m	265	300	*0.16*					0.19			
ITMF (2010)	1 kg	Mean of 17 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO ring yarn to a fabric, single jersey Ne 30, unfinished width (open) 192 cm, unfinished weight 230 g/m	180	200	*0.19*					0.19			
ITMF (2010)	1 kg	Mean of 13 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO rotor (open end) yarn to a fabric Lapique Ne 20, unfinished width (open) 224 cm, unfinished weight 358 g/m	265	300	*0.16*					0.19			
Kim et al. (1983)	1 kg	Knitting energy usage per unit production (kWh/kg)>no specific material; reported data 1972				1.75					0.19			
Kim et al. (1983)	1 kg	Knitting energy usage per unit production (kWh/kg)>no specific material; reported data 1980				1.29					0.19			
Collins and Aumônier (2002)	kg product	Knitting including winding for fabric for 1 pair of cotton briefs (72 g) takes 8.08 kWh/kg product				8.08					0.19			
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 1.3, 2.3 MJ per 1 shirt of 250 g>275 g CO fabric needed				2.32					0.19			
IFTH2 (n.a.)	1 kg	Knitting machine	CO for a thin sweater			0.85					0.19			
IFTH2 (n.a.)	1 kg	Rib trimming holding' knitting	CO for a thin sweater			1.17					0.19			
IFTH2 (n.a.)	1 kg	Flat knitting with large panels	CO for a thin sweater			1.16					0.19			
IFTH2 (n.a.)	1 kg	Flat knitting with normal panels	CO for a thin sweater			1.17					0.19			
IFTH2 (n.a.)	1 kg	Fully fashioned flat knitting	CO for a thin sweater			4.59					0.19			
IFTH2 (n.a.)	1 kg	Seamless flat knitting	CO for a thin sweater			5.42					0.19			
IFTH2 (n.a.)	1 kg	Fully fashioned flat knitting	CO for a thick sweater			2.29					0.19			
Pretreatment	Fabric													

Table 4 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 1.3, 2.4 MJ per 1 shirt of 250 g (fabric 275 g)	Pretreatment of fabric of 100 % CO			2.42								
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 3.3, 5.2 MJ per 1 jacket of 770 g (fabric 877 g)	Pretreatment of fabric of 65 % CO+35 % PES			1.65								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g	Scouring in alkaline solution+bleaching			1.20								
Processor, 2011 phase 4	1 kg	Bleaching	40 PET/60 CO+PES staple fibers	180	200	0.40	14.4							
Processor, 2011 phase 4	1 kg	Bleaching average	40 PET/60 CO+PES staple fibers			*0.50*	*16*							
Processor, 2011 phase 4	1 kg	Bleaching	40 PET/60 CO+PES staple fibers	90	100	0.63		18						
Dyeing	Fabric													
LCA pyjama bebe IFTH	1 kg	Reactive dye for CO; PES not dyed; softening treatment during the last rinsing wash; LR=1/8	80 % CO/20 % PET, 290–300 g/m^2			1.15		31.30						104.00
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 1.3, 3,3 MJ per 1 shirt of 250 g (fabric 273 g)	Reactive dye on 100 % CO			3.36								
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 3.3, 9 MJ per 1 jacket of 770 g (fabric 877 g)	Dyeing of 65 % CO+35 % PES in automatic jigger			2.85								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g				1.84								
Processor, 2011 phase 5	1 kg	Dyeing	40 PET/60 CO+PES staple fibers	180	200	1.00		28.80						
Processor, 2011 phase 5	1 kg	Dyeing	40 PET/60 CO+PES staple fibers	90	100	1.25		33.75						
IPPC (2003), lowest value Table 4.28, LOW	1 kg	Airflow jet operating at LR 1:4.5 (CO) and 1:2–3 (PES)	Dyeing CO or PES			0.36	3.78							80.00
IPPC (2003), lowest value Table 4.28, HIGH	1 kg	Airflow jet operating at LR 1:4.5 (CO) and 1:2–3 (PES)	Dyeing CO or PES			0.42	5.04							80.00
Wet processing	Fabric													
Confidential source no. 7	1 kg	Wet treatment				2.73			0.38		69.90			
Confidential source no. 7	1 kg	One time washing				1.06								
Confidential source no. 8	1 kg	Subtotal scouring, dyeing, washing, softening, centrifugation	Viscose			1.14	18.32	0.00	0.00	0.00	0.00	0.00	0.00	
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 1.3, 3.1 MJ per 1 shirt of 250 g (270 g fabric)	Drying final fixing+set m^2 weight+softening 100 % CO			3.19								

Table 4 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 3.3, 4.8 MJ per 1 jacket of 770 g (fabric 868 g)	Softening; drying; final fixing 65 %CO+35 % PES			1.54								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g				0.88								
Processor, 2011 phase 6	1 kg	Finishing	40 PET/60 CO+PES staple fibers	180	200	0.60		28.8						
Processor, 2011 phase 6	1 kg	Finishing	40 PET/60 CO+PES staple fibers	90	100	0.75		33.75						
IFTH2 (n.a.)	1 kg	Total	CO yarn			2.10		14.26						27.00

IFTH2 (n.a.) refers to an unpublished report named: Extrait de "aide à la prise en compte de l'environnement dans la conception d'articles textiles" par l'IFTH. Institut Francais du textile et de l'habillement

n.a. not available, *LR* liquor ratio

Figure 2 shows that data from Kaplan and Koç (2010) and Demir and Behery (1997) (along the lower striped line) show a considerable lower energy demand (approximately 40 %) than data from the anonymous Belgium/French factory "Processor, 2011 phase 1" (along the upper continuous line). The EDIPTEX scores of ITMF (2010) and Laursen et al. (2007) were even lower than Kaplan and Koç (2010).

For the calculations in Section 4, it was decided to take the average of the two lines in Fig. 2. For extruding and spinning of polymer filament, less data are available, and it seems to be scattered, see Table 5 (under "Spinning filament"). The energy required for filament extrusion is governing the process. PET, nylon, and elastane have the same extrusion energy (CES 2012) of 6.2 MJ/kg or 1.7 kWh/kg. Note that extruding is not a function of decitex, but a function of the extrusion energy of the polymer.

3.4 Texturing of synthetic yarns

Texturing is a processing step that is applied to synthetic filaments in order to produce yarns that are more flexible, are softer, have a more natural feel, and have improved yarn recovery power. This is achieved in many ways, such as thermal and mechanical deformation of the individual filaments and their spatial arrangement in the yarn bundle.

For texturing, various technologies are being used which differ substantially in energy use. During the actual process, the feeding material (named "partially oriented yarn" [POY]) is processed into either drawn textured yarn (abbreviation is "DTY") or air textured yarn (abbreviation is "ATY"). The old ATY machine with heated "godets" (spouts), collective drives, and water jet texturing (water and electric) was more expensive per kilogram yarn, compared to the current DTY technology (personal communication with a regional sales director from Barmag, 2011).

The energy use value for texturing (on high-end modern equipment), comes from the ITMF (2010) data and refers to a new Oerlikon Barmag machine (named "10 Barmag eFK, 240 positions") which is based on the process of false twist texturing with manual doffing system. During the texturing process, the filament yarn is simultaneously drawn, heated, and twisted. In our calculation, we take 1 kWh/kg for texturing, being the average of the ITMF and Barmag data on texturing in Table 5, since the energy required in these machines is mainly heat to bring the material to the necessary temperature: that is, primarily a function of kilograms. Cotton yarn does not require texturing due to the natural twist of cotton.

3.5 Weaving

The energy of weaving is obviously a function of decitex; however, most of the literature does not report any information

Table 5 Manufacturing of synthetic yarn: data from literature and private communications

Process step/source	Quantity	Specification of process and/ or extra remarks	Specification of product (PET=polyester)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fiber+yarn manufacturing														
Pellets/flakes production	Pellets													
Cumulative energy demand, confidential study 2008	1 kg	Gate to gate				0.20		0.53	0.02	0.01	0.00			
PET production. calculation 2011, personal communication Defraye	1 kg	Nonrenewable energy use is 68.6 MJ and 2.00 kg CO_2	Bottle grade			See specs								
PET production. calculation 2005, personal communication Defraye	1 kg	Nonrenewable energy use is 80.5 MJ and 3.30 kg CO_2	Amorphous PET			See specs								
Spinning staple fibers	Fiber													
Confidential source no. 1	1 kg	Recycled PET pellets to staple fiber (or POY?)				0.89						0.48		
Confidential source no. 2	1 kg	Recycled PET flakes to staple fiber				0.52		2.21	0.02					
Confidential source no. 3	1 kg	Recycled PET pellets to staple fiber				0.31							10.57	
Confidential source no. 4	1 kg	PET flakes to staple fiber				0.69	4.75							
Defraye, 2011, personal communication	1 kg	Nonrenewable energy use is 9.4–10.5 MJ, unclear whether staple fiber, filament or mix				See specs								
IFTH1 (n.a.)	1 kg	PTA (purified terephthalic acid) and MEG (ethylene glycol) to staple fibers				4.22		0.00		53.76			14.79	
Laursen et al. (2007) EDIPTEX	1 kg	Ring yarn according to formula	100 % synthetic	117	130	3.70								2,200.00
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, fiber/yarn? manufacturing of 70 %VI, 25 % PA, 5 % EL				50.62								
Spinning filament	Yarn													
Barmag, 2011	1 kg	PTA and MEG to filament ("direct spinning line")	POY	168	187	0.30								
Barmag, 2011	1 kg	PET pellets to filament ("extruder spinning line")	POY	168	187	0.50								
Barmag, 2011 PET extruder spinning	1 kg	PET pellets to filament ("extruder spinning line")	FDY	75	83	1.00								
Barmag, 2011	1 kg	PTA and MEG to filament ("direct spinning line")	FDY	75	83	0.80								
Brown et al. (1985)	1 kg	PET pellets to filament ("extruder spinning line")				0.64	5.00							
Confidential source no. 3	1 kg	PET pellets to filament ("extruder spinning line")	POY			1.19						0.48		
Defraye, 2011, personal communication	1 kg	Nonrenewable energy use 9.4 MJ, unclear whether staple fiber, filament or mix; estimated en. eff. improvement taken into account				See specs								

Table 5 (continued)

Process step/source	Quantity	Specification of process and/ or extra remarks	Specification of product (PET=polyester)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Confidential source no. 5	1 kg	PET pellets to filament ("extruder spinning line")	POY	452	500	1.50	2.20							
Confidential source no. 5	1 kg	PET pellets to filament ("extruder spinning line")	FDY	452	500	1.70	2.20							
Texturing	Yarn													
ITMF (2010)	1 kg	POY to DTY, mean for 10 machines eFK with manual doffing system	POY of 125 den drawn and false twisted into a 75 den yarn of 72 filaments	75	83	1.21								
ITMF (2010) and Barmag, 2011	1 kg	Average of texturing values from ITMF and Barmag				*1.00*								
Barmag, 2011	1 kg	Filament to textured filament DTY (75/1.6>47 den)	Textured filament	47	52	0.7–0.9								
Barmag, 2011	1 kg	Filament to textured filament DTY (150/1.6>94 den)	Textured filament	94	104	0.5–0.6								
Confidential source no. 7	1 kg	Filament to textured filament, includes "general electricity for dyeing"	Fabric for sofa			3.75								
Confidential source no. 3	1 kg	POY to DTY	DTY			2.18								
Demir and Behery (1997)	1 kg	POY to ATY	POY	150	167	3.10								
Demir and Behery (1997)	1 kg	POY to ATY	Twofold 167 dtex POY yarn	300	334	1.80								
Confidential source no. 5	1 kg	POY to false twisted filament (including or excluding thermofixing?)	FTF			1.66								
Confidential source no. 5	1 kg	POY to air textured filament (including or excluding thermofixing?)	Air textured filament (ATY?)			3.33								
Confidential source no. 5	1 kg	POY to DTY?	DTY? (very uncertain)			2.22								

IFTH1 (n.a.) refers to an unpublished report named: Extrait de "l'Analyse de Cycle de vie pyjama Bébé" par l'IFTH. Institut Francais du textile et de l'habillement

POY partially oriented yarn, *FDY* fully drawn yarn, *DTY* drawn textured yarn, *ATY* air textured yarn, *FTF* false twisted filament, *n.a.* not available

Table 6 Fabric manufacturing from synthetic yarn: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=PES=polyester; CO=cotton; PA=polyamide; VI=viscose; EL=elastan)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
ITMF (2010)	1 kg	Mean of 60 Sultex rapier weaving machines S190 N4 SP12/20, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric, 38.0/31.0 threads/cm—gray width 177 cm—gray weight 106 g/m	75	83	10.88								
Confidential source no. 7	1 kg		PES fabric for sofa			2.65			1.66		1.53			
Laursen et al. (2007) EDIPTEX	1 kg	Figure 2.3	PA for jogging suit			6.73								
Knitting	Fabric													
ITMF (2010)	1 kg	Mean of 8 Mayer&Cie OV 3.2 QC circular knitting machines, 30-in. diameter, 28 gg, with side creel	Fabric interlock—unfinished width (open) 190 cm—unfinished weight 209 g/m	75	83	0.35					0.19			
IFTH1 (n.a.)	1 kg	Yarn to knitted fabric, circular knitting	80 % CO/20 % PET, 290–300 g/m^2			1.22					0.19			
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, circular knitting of 70 % VI, 25 % PA, 5 % EL (0.222 kg)				5.01					0.19			
Washing of fabric	Fabric													
Confidential source no. 7	1 kg	Unclear whether including drying; without NREU for surfactants	Fabric for sofa			0.82								
Drying of fabric	Fabric													
Confidential source no. 6	1 kg		What type of fabric? PES?			0.16		5.15						
Pretreatment	Fabric													
Laursen et al. (2007) EDIPTEX	1 kg	Tot. calc. for woven PA (0.402 kg) and knitted CO (0.583 kg) for jogging suit; CO is dominant					7.1							
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, pretreatment of synth. knitted 70 % VI, 25 % PA, 5 % EL (0.222 kg)				2.19	*7.9*							
Dyeing	Fabric													
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 2.3, acid dye	Nylon/PA			2.56								
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, dyeing of 70 % VI (reactive), 25 % PA (acid), 5 % EL (acid) (0.222 kg)				5.63								
Thermofixing (heat setting)	Fabric													
Confidential source no. 7	1 kg		Fabric for sofa								7.95			

Table 6 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=PES=polyester; CO=cotton; PA=polyamide; VI=viscose; EL=elastan)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Finishing	Fabric													
Laursen et al. (2007) EDIPTEX	1 kg	Tot. calc. for woven PA (0.402 kg) and knitted CO (0.583 kg) for jogging suit; CO is dominant				1.97								
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, finishing, drying, final fixing+set m^2 weight of 70 % VI, 25 % PA, 5 % EL (0.222 kg)				2.50								

IFTH1 (n.a.) refers to an unpublished report named: Extrait de "l'Analyse de Cycle de vie pyjama Bébé" par l'IFTH. Institut Francais du textile et de l'habillement

on yarn size (see Table 3). Figure 3 shows the required electricity as a function of 1/tex for cotton. For weaving, there is rather a big uncertainty: the anonymous factory ("Processor, 2011 phase 3) reports a doubling in energy consumption, compared to machine manufacturing data.

It is not expected that data on weaving polymers will deviate much from the data on weaving cotton. The ITMF (2010) reference (under "Weaving") in Table 6 fits the lower line of Fig. 3, which is 11 kWh/kg for 83 dtex (=0.12×1/tex). For the calculations in Section 4, it was decided to take the average of the two lines in Fig. 3.

3.6 Knitting

The energy required for knitting is considerably lower (approximately a factor of 20) than for weaving (compare, e.g., the values of ITMF 2010 in Tables 3 and 4). Knitting is, therefore, a better solution in terms of environmental burden. Elaborating on the data analysis for weaving, it is assumed that the energy consumption for knitting is proportional to 1/dtex as well, as illustrated by the line in Fig. 4.

3.7 Pretreatment of cotton fabric and thermofixing of polymers

Pretreatment of cotton comprises several wet operation steps (singeing, desizing, scouring, mercerizing, and bleaching) in order to prepare the fabric for dyeing. The decision to apply one or the other depends on the required grade of the end product. Scouring and bleaching are typically required for men's shirts since they are mostly of a lighter color. Scouring (also known as boiling-off or kier boiling) is aimed at the extraction of impurities present on the raw fiber or picked up at a later stage (IPPC 2003). Bleaching removes all natural color. Both processes are included in the values for the pretreatment of cotton shown in Table 4. The data come from Laursen et al. (2007), Cartwright et al. (2011), and the Belgian processor of shirt material ("Processor, 2011 phase 4" in the table).

For the calculation in Section 4, the average (0.5 kWh electricity and 16 MJ steam) of the data of "Processor, 2011 phase 4" in Table 4 has been applied. Typical pretreatment operations before coloring of synthetic fabrics are washing and thermofixing (heat setting). Heat setting of fabric increases the density of the fabric, avoids crimp later on (production and use), and enables dye fixation. This heat setting process on fabric must not be confused with the thermofixation of the fiber during texturing (which is normally processed at a lower temperature).

The IPPC (2003) report mentions heat setting temperatures ranging from 150 to 205 °C at different mills. In the calculations of Section 4, we apply 7.9 MJ heat/kg, according to the EDIPTEX score of Laursen et al. (2007), second line under "Pretreatment" in Table 6.

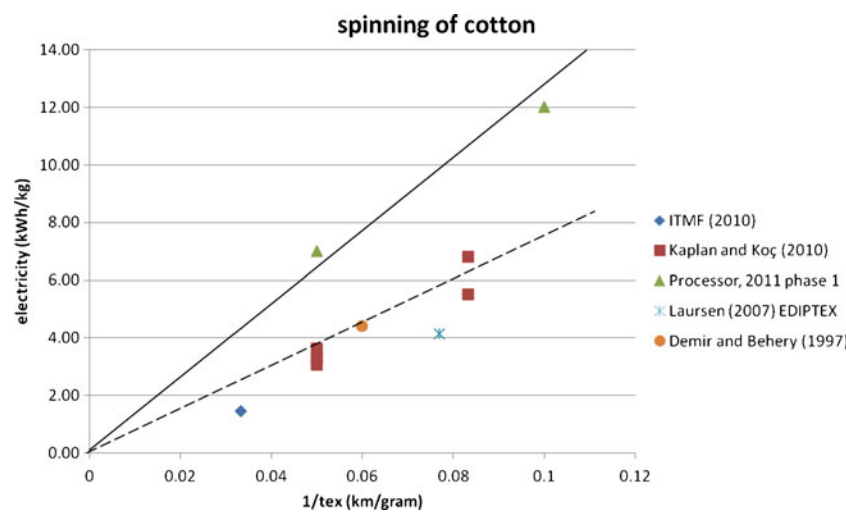


Fig. 2 Spinning of cotton: electricity demand as a function of 1/dtex

4 Results cradle-to-gate for greige textile

4.1 Cotton greige textile cradle-to-gate of the factory

Calculations have been made for cradle-to-gate (of the fabric dyeing factory) for 70, 100, 150, 200, and 300 dtex (1 dtex=0.84 den) woven material, for the process steps defined in Section 2.2, excluding dyeing and final finishing (see Figs. 5, 6, 7, and 8).

Figure 5 shows the eco-costs (in Euros per kilogram textile) for the fiber manufacturing, spinning, weaving, and pretreatment of cotton textiles. Figures 6 and 7, respectively, present the CO_2 equivalent values (in kilograms per kilogram) and the CED (in megajoules per kilogram) scores for the same processes. Finally, Fig. 8 shows the ReCiPe scores (in points) for greige cotton fabric. All indicators show that the thinner the yarn, the higher the environmental pollution per kilogram. The underlying datasets for the calculations leading to these figures are presented in Table 7. The Idemat database which is mentioned in Table 7 is based on Ecoinvent data and is open access for Ecoinvent license holders. Midpoint and endpoint calculations are open access (Idemat 2012).

A remarkable conclusion for yarn sizes less than 150 dtex is that the spinning and weaving energy seem to play a major role in the eco-burden of the woven material, rather than the production of cotton fiber. Another conclusion is that, in the eco-costs and the ReCiPe indicator, cotton production plays a relatively more important role than in the CED and CO_2 indicators, being a result of the fact that ecotoxicity and human toxicity are included in the first and the last indicators, see Section 2.1.

4.2 Synthetic greige textile cradle-to-gate of the factory

Calculations have been made for cradle-to-gate (of the fabric dyeing factory) for acryl, nylon, PET, and elastane (70 dtex=58 den) woven material, for the process steps defined in Section 2.2, excluding dyeing and finishing (see Figs. 9, 10, 11, and 12). The underlying datasets for the calculations leading to these figures are presented in Table 7.

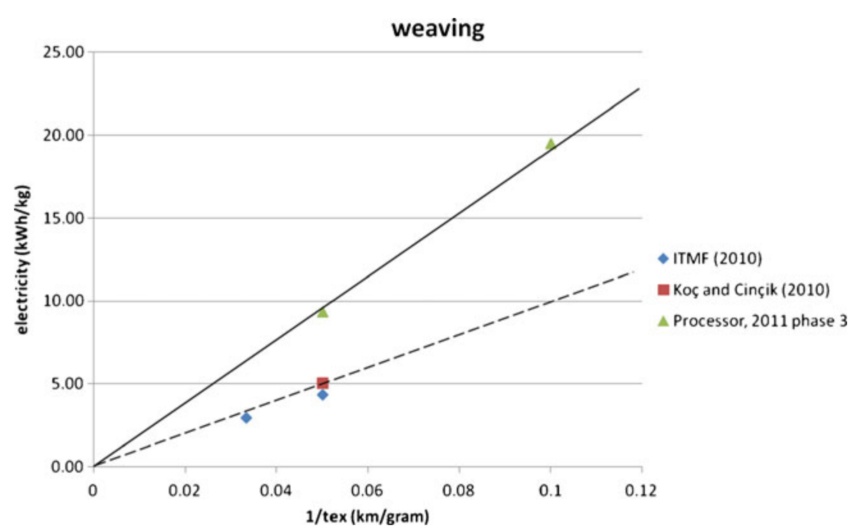


Fig. 3 Weaving of cotton and polymer fibers: electricity demand as a function of 1/dtex

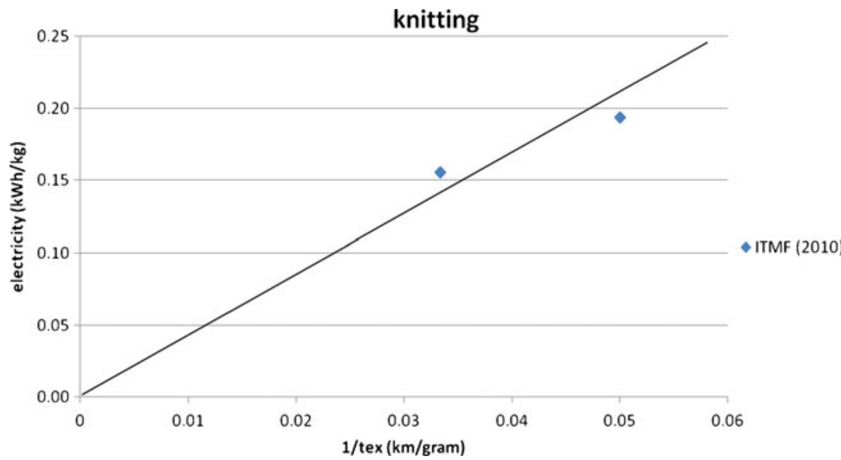


Fig. 4 Knitting: electricity demand as a function of 1/dtex

Figure 9 shows the eco-costs (in Euros per kilogram textile) for polymer pellet production, extruder spinning, texturing, weaving, and heat setting of synthetic textiles. Figures 10 and 11, respectively, present the CO_2 equivalent values (in kilograms per kilogram) and the CED (in megajoules per kilogram) scores for the same processes. Finally, Fig. 12 shows the ReCiPe scores (in points) for greige synthetic fabric. All figures show that, for woven fabric of 70 dtex yarn, acryl and PET textile have the best environmental scores and nylon textile is the most polluting.

5 Dyeing and finishing of fabric

5.1 LCI data—gate-to-gate for dyeing and finishing

The data for dyeing are highly case dependent:

1. Consumption and emission levels for dyeing are strongly related to the type of fiber, the makeup, the dyestuff, the dyeing technique, and the machinery employed (IPPC 2003).
2. Processing and formulas for dyeing are related to the quality requirements.
3. Process parameters are reaction type, availability of chemicals, time, temperature, and pH (Tobler-Rohr 2011).

All previously mentioned variables lead to an enormously wide range of processes and consequently also of energy use. There are some general rules regarding the type of dyestuff used per type of fiber (Tobler-Rohr 2011): PET is dyed with disperse dyestuffs (if acid and alkaline are used for PET, this results in a lower grade). Cotton is dyed with reactive dyestuffs (and vat, direct, or sulfur dyestuffs are also applied). Nylon can be dyed with disperse, metal complex, and acid dyestuffs. The usage of dye carriers for dyeing PET has been the subject of research and discussion for a long time. Yeh and Smith (1983) reported about the toxicity and volatility of this group of chemicals when used for dyeing processes. Several other references, e.g., the BATBREF report (IPPC 2003) and Yang and Li (1999) point out the dangers of dye carriers as well. No data could be found on how widespread these chemicals are applied today, but dye carriers are still used in many dyeing houses around the world. The IPPC (2003) report mentions that one of the best available technologies

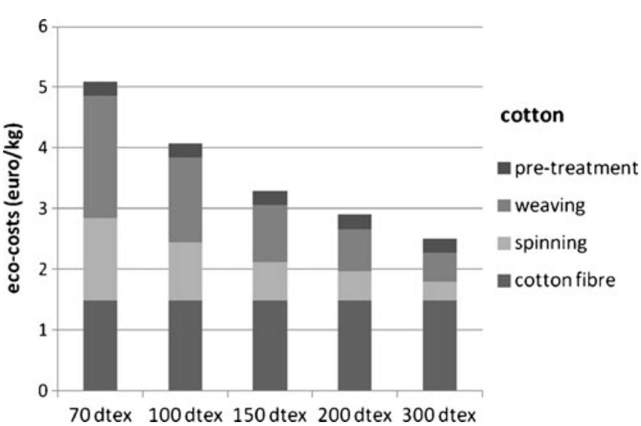


Fig. 5 The eco-costs of cotton textiles

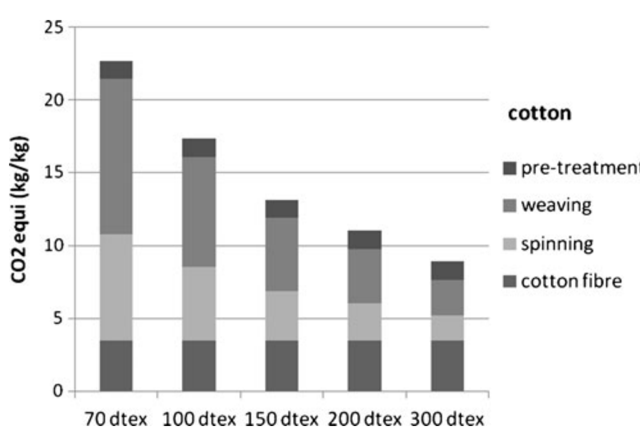


Fig. 6 The carbon footprint of cotton textiles

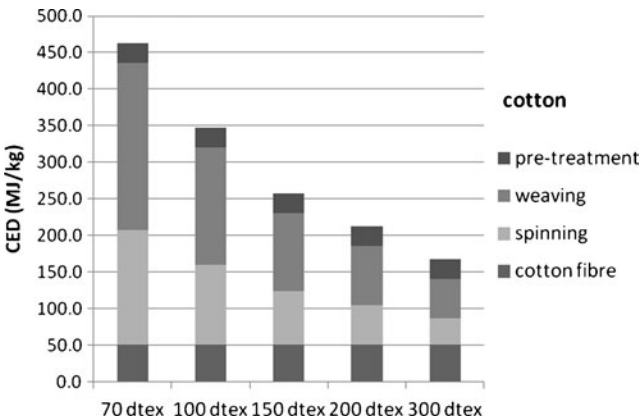


Fig. 7 The CED of cotton textiles

for dyeing of PET and cotton is the airflow jet machine and reports electricity input values for dyeing PET and cotton, with the range for the liquor ratio depending on the type of material (1:2–1:3 for PET and 1:4.5 for cotton).

After dyeing, a range of process steps are executed, depending on the desired fabric properties. Final finishing processes can, for example, consist of special treatments with flame retardants, softeners, easy care finishing, etc. Every extra step is likely to require the usage of chemicals and auxiliaries. Different bath temperatures, liquor ratios, and/or extra washing cycles are required. A thermofixation step could be part of final finishing as well.

References on final finishing processes report datasets which consist of very different process steps (if specified at all), and in addition, large ranges are found for comparable process steps. The toxic emissions of dyeing and final finishing have been analyzed for a best practice production facility in the Netherlands, based on the Dutch emission database. This production facility is Global Organic Textile Standard-certified and Oeko-tex-certified (an independent testing and certification system for textile raw materials, intermediate, and end products at all stages of production), the effluents are processed in water treatment plants, and emissions to air are minimized. Results are shown in Section 5.2. Although many West European facilities reach similar high standards, the reader must keep in mind that such standards are not common in other textile-producing countries outside of Europe, like, for example, India and China.

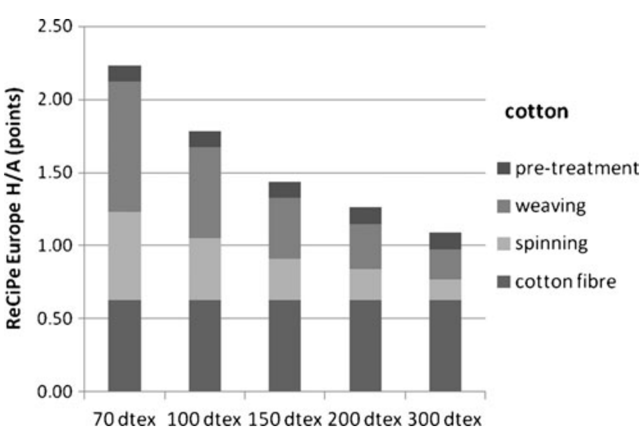


Fig. 8 The ReCiPe score ("Europe H/A") of cotton textiles

5.2 Results gate-to-gate for dyed and finished fabric

This section gives value ranges for the final processing steps (dyeing and finishing) for woven or knitted material, gate-to-gate. The first gate refers to the exit of the greige fabric from the material processing factory and the second gate refers to the entry of the textile to the product manufacturing factory.

The ranges of the single indicators were calculated based on the data in Tables 4 (for cotton) and 6 (for synthetics). Since the dyeing and final finishing processes often take place at one production site, the separate values per process step in Tables 4, 5, and 6 are added up and presented in the succeeding paragraphs. The lowest total score is found for Cartwright et al. (2011), and the highest total score is found for Processor, 2011 phases 5 and 6. The EDIPTEX scores of Laursen et al. (2007) are found in between. For the other data sources, we miss either data on dyeing or on finishing.

The value ranges of the single indicators for the energy required for dyeing and finishing of 1 kg cotton textile are:

- Eco-costs, €0.26–0.95;
- CO_2 equivalent, 1.39–6.08 kg CO_2 equivalent;
- CED, 30–108 MJ;
- ReCiPe, 0.12–0.54 Pt.

Note that some values are for dyeing of cotton blends (mixtures with other materials, e.g., PET), but cotton is always dominant. Fiber blends need to be dyed sequentially, for instance, separately for cotton dyeing and then PET dyeing. Therefore, values of dyeing of blends are larger than values of dyeing of pure cotton (and can reach twice the value).

The ranges of the single indicators for the energy required for dyeing and finishing of 1 kg synthetic textile are:

- Eco-costs, €0.43–0.77;
- CO_2 equivalent, 2.31–4.14 kg CO_2 equivalent;
- CED, 50–89 MJ;
- ReCiPe, 0.20–0.35 Pt.

The single indicators of the toxic emissions of the production facilities must be added. These toxic emissions are publicly available at the Dutch emission database for production facilities in the Netherlands. The toxic emissions of the best practice manufacturer mentioned in Section 5.1 are given in Table 8. This table shows the emission of a chemical substance (in kilograms per year), the eco-costs of that substance (in Euros per kilogram), the eco-costs of the emission (in

Table 7 LCA data used in Figs. 5, 6, 7, 8, 9, 10, 11, and 12

Ecoinvent LCI name or Idemat 2012 LCI name	Eco-costs	CO_2	CED	ReCiPe
Acetonitrile, at plant/RER	0.753	3.040	86.7	0.362
Cotton fibers, ginned, at farm/CN	1.481	3.474	50.4	0.628
Polyurethane, flexible foam, at plant/RER	1.324	4.836	103.1	0.517
Nylon: nylon 6, at plant/RER 50 %+nylon 66, at plant/RER 50 %	2.069	8.638	129.7	0.780
Polyethylene terephthalate, granulate, amorphous, at plant/RER	1.057	2.698	78.4	0.346
Dyeing, excluding pigments and carriers (Section 3.6)	0.422	2.245	48.2	0.199
Heat setting and washing synthetic fabrics (Section 3.5)	0.171	0.908	19.5	0.081
Knitting 83 dtex (electricity 0.51 kWh/kg, see Fig. 3)	0.048	0.257	5.5	0.021
Knitting 200 dtex (electricity 0.21 kWh/kg, see Fig. 3)	0.020	0.106	2.3	0.009
Knitting 300 dtex (electricity 0.14 kWh/kg, see Fig. 3)	0.013	0.071	1.5	0.006
Pretreatment of cotton (Section 3.5)	0.237	1.261	27.1	0.105
Spinning cotton 45 dtex (electricity 22.4 kWh/kg, see Fig. 1)	2.127	11.322	243.2	0.942
Spinning cotton 70 dtex (electricity 14.4 kWh/kg, see Fig. 1)	1.368	7.281	156.4	0.605
Spinning cotton 150 dtex (electricity 6.73 kWh/kg, see Fig. 1)	0.638	3.396	72.9	0.282
Spinning cotton 300 dtex (electricity 3.37 kWh/kg, see Fig. 1)	0.319	1.700	36.5	0.141
Spinning extruder polymer filaments (80–500 dtex) (Section 3.2)	0.168	0.896	19.2	0.074
Spinning viscose fibers (80–500 dtex) (Section 3.2)	0.042	0.223	4.8	0.019
Texturing polymer fibers (Section 3.3)	0.095	0.505	10.8	0.042
Weaving 45 dtex (electricity 32.9 kWh/kg, see Fig. 2)	3.118	16.595	356.4	1.380
Weaving 70 dtex (electricity 21.1 kWh/kg, see Fig. 2)	2.004	10.667	229.1	0.887
Weaving 150 dtex (electricity 9.87 kWh/kg, see Fig. 2)	0.936	4.980	106.9	0.414
Weaving 300 dtex (electricity 4.93 kWh/kg, see Fig. 2)	0.467	2.488	53.4	0.207

Euros per year), and the eco-costs of 1 kg of fabric (in Euros per kilogram). The total eco-cost of the toxic emissions of this best practice manufacturer is round €0.029/kg.

The best practice of Table 8 is not unique in the Netherlands: there are more manufacturers who reach similar green production standards. The situation in other countries like India and China is not known, however, since the environmental law is less stringent (or even absent) and the emissions are, therefore, not measured. The level of pollution can easily be a factor of 10 higher in these countries.

6 The use phase and end-of-life

6.1 Use phase

The main environmental impacts in the use phase are caused by the washing, drying, and ironing of the garments. Several studies and reports (e.g., Collins and Aumônier 2002; Steinberger et al. 2009; BSR 2009), which include the use phase in the assessment, identify this phase as the most important in terms of energy use and carbon dioxide emissions. When interpreting the results, it

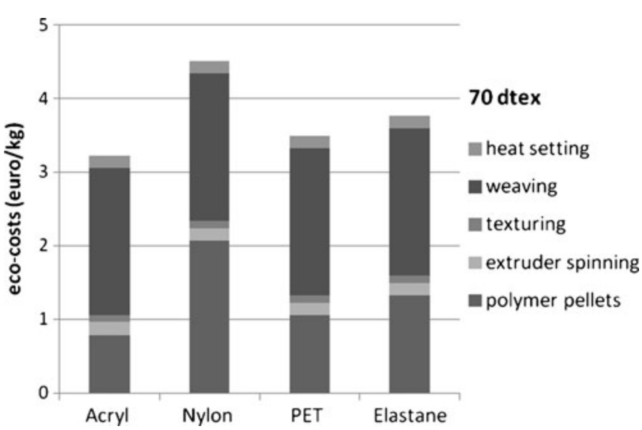


Fig. 9 The eco-costs of synthetic textiles, 70 dtex

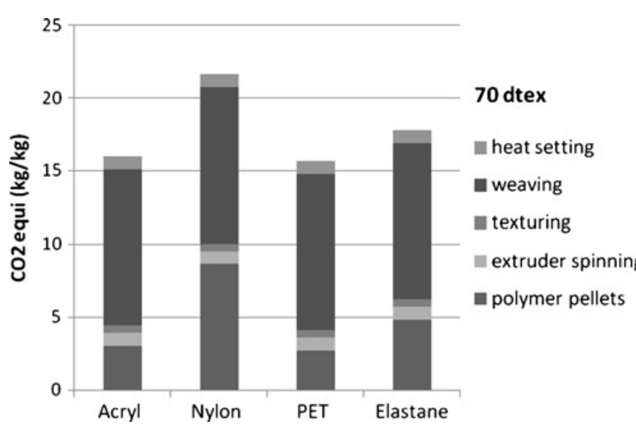


Fig. 10 The carbon footprint of synthetic textiles, 70 dtex

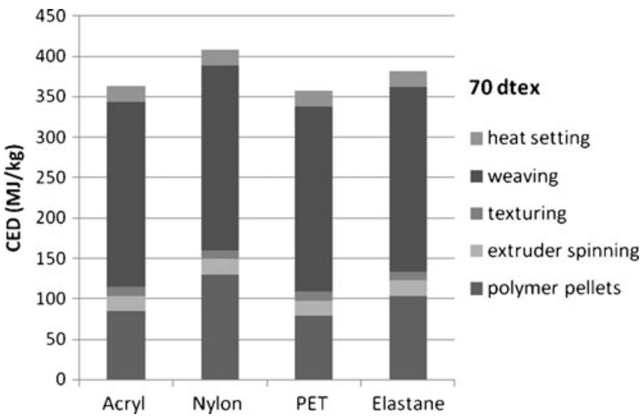


Fig. 11 The CED of synthetic textiles, 70 dtex

should, however, be considered that the outcome may vary substantially depending on the concrete circumstances. It is extremely difficult to determine the way the consumer wears and takes care of different clothing products. No literature data or empirical studies on wearing and laundry behavior of garments could be found. Literature data on the use phase are presented in Table 9.

It appears that user behavior has changed considerably in the last decennium:

- Ever more users tend to wash at lower temperature, i.e., 40 °C, rather than an average temperature of 60 °C as assumed in older studies.
- Most users in the EU buy "label A" washing machines and dryers.

According to Steinberger et al. (2009)), the reduction of washing temperature from 60 to 40 °C saves approximately 40 % electricity. According to the European energy consumption

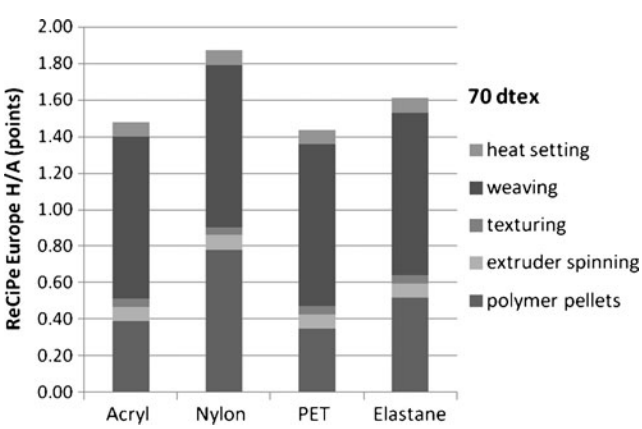


Fig. 12 The ReCiPe score ("Europe H/A") of synthetic textiles, 70 dtex

labeling scheme (EU Directive 92/75/EC), the energy consumption of an "energy label A" washing machine is (less than) 0.19 kWh for 6 kg laundry at 60 °C, so 0.11 kWh/6 kg laundry at 40 °C.

The single indicators for 50 times washing, 1 kg laundry, 40 °C, 0.917 kWh (3.3 MJ) electric energy, low voltage are:

- Eco-costs, €0.096;
- CO_2 equivalent, 0.52 kg CO_2 equivalent;
- CED, 11.2 MJ;
- ReCiPe, 0.043 Pt.

The energy consumption of dryers is considerably more than washing machines. An "energy label A" drying machine has an electricity consumption of (less than) 0.55 kWh/6 kg, which is 4.6 kWh (16.5 MJ)/kg for 50 drying cycles.

The single indicators for 50 times drying, 1 kg laundry, 16.5 MJ electric energy, low voltage are:

- Eco-costs, €0.48;
- CO_2 equivalent, 2.6 kg CO_2 equivalent;
- CED, 56 MJ;
- ReCiPe, 0.21 Pt.

6.2 The end-of-life

At their end-of-life phase, garments in Western Europe are either burned in a municipal waste incinerator or collected via the recycling bin. In the Netherlands (year 2000), 67 % ends up in a municipal waste incinerator and 33 % ends up in a recycle bin (in the Netherlands, there is virtually no textile in landfills). Of the recycled material, 20 % is wearable and exported to developing countries and 13 % is not wearable. This 13 % is downcycled in several low-value materials (Verhulst 2010). A new development is the mechanical or chemical recovery of the fibers from the fabric material, from which new high-quality textile can be woven. Accurate data for these upcycling processes of the materials under study are not yet available.

Cotton has a credit when it is incinerated with heat recovery, since the carbon is bio-based. The credit is based on "system expansion" in LCA and the fact that biogenic CO_2 emissions are not counted in LCA. It is related to the avoidance of fossil fuels and depends on the efficiency of the system. For a modern municipal waste incinerator, with an electric production efficiency of 25 %, the credit is estimated at eco-costs, −€0.11/kg; carbon footprint, −0.60 kg CO_2 equivalent/kg; CED, −15 MJ; ReCiPe, −0.051 Pt/kg. Note that these scores are negative since it is a credit (related to the delivery of electricity). Note also that such a rather high credit does not exist for fossil-based polymers, since the eco-burden of the emitted fossil CO_2 is of the same magnitude as the credit of the delivered electricity. Data

Table 8 Emissions of a best practice production plant for dyeing and finishing in the Netherlands, 150,000 kg/year

	Emissions (kg/year)	Eco-costs emissions (€/kg)	Eco-costs emissions (€/year)	Eco-costs textile (€/kg)
Substance				
Benzene	4.31	2.11	9.10	0.0001
Ethene	43.08	9.70	417.87	0.0028
Particulates, <10 μm	3.20	15.88	50.83	0.0003
Particulates, <2.5 μm	3.20	29.65	94.88	0.0006
Fluoranthene	0.01	0.93	0.01	0.0000
Carbon monoxide, fossil	95.80	0.26	25.07	0.0002
Methane	258.50	3.38	872.44	0.0058
Non-methane VOC*	172.30	5.74	989.00	0.0066
Nitrogen oxides	400.60	4.62	1,850.77	0.0123
Toluene	8.62	6.20	53.41	0.0004
Sulfur oxides	4.83	8.25	39.85	0.0003
Total eco-costs			4,403.22	0.0294

**VOC* volatile organic compounds

for combustion with heat recovery of cotton and polymers can be found in Idemat (2012).

7 Overview over the textile life cycle

Figures 13 and 14 give a final overview of the breakdown of the environmental burden over the textile life cycle. These diagrams show the total eco-costs for a woven textile product made out of cotton, PET, nylon, acryl, or elastane with yarn thicknesses of 70 dtex (Fig. 13) and 300 dtex (Fig. 14).

Figure 13 makes clear that the environmental performance of woven cotton textile products (70 dtex) is the worst, followed by (in order of magnitude) nylon, elastane, and PET. Acryl textile products represent the least eco-costs, and it can be concluded from this analysis that acryl textiles have the best environmental profile for the given specifications.

Note that the environmental burden is reduced at a higher yarn size due to the decrease in energy use for the spinning and weaving processes of thicker yarns (as described in Sections 3.3 and 3.5 and likewise in Section 3.6 for knitting). For example, as shown in Fig. 14, the total eco-cost for yarn of 300 dtex reduces by 24 % (for nylon) to 38 % (for cotton). As a consequence, cotton and nylon change places (a nylon textile product made out of 300 dtex yarn has higher eco-costs than one made out of cotton) and the ranking of the other materials stays the same (acryl is best, followed by PET and elastane).

In contrast with the outcomes of several other studies (e.g., BSR 2009; Collins and Aumônier 2002; Cotton 2011), Figs. 13 and 14 do not indicate the use phase as a primary "hot spot" for environmental burden. For thicker yarns, the share of the use phase in the total eco-costs will increase for obvious reasons, but will not become too important (for acryl textile of 70 dtex, the use phase represents 11 % of the total eco-costs and, for 300 dtex, this becomes 16 %). This analysis rejects the classical conclusion which identifies washing and drying during the use phase as the most significant life cycle stage for textile products and shifts the emphasis on the manufacturing processes.

8 Discussion and conclusions

8.1 Discussion

While the textile and fashion industry seem to concentrate their environmental decisions on the choice of the base material, this paper points out that much can be improved by selecting the right fabric specifications. Note that the right choice should always take into account the intended design and quality in terms of haptics ("touch"), insulation properties (warmth), and durability of the product.

The best choice from an environmental point of view is to use a knitted fabric (compare Figs. 3 and 4). Based on Figs. 2, 3, and 4, it could be easily concluded that it is better to use a thicker yarn, but this conclusion provokes the discussion whether to analyze the pollution of textiles per kilogram fabric or per square meter of fabric. Table 10 gives an overview. A heavier textile is more polluting per square meter, but has different physical properties than a lighter material. An example is the technical life span of woven textile, which is proportional to the thickness of the fiber (Manich et al. 2001). In applications where the textile is used

Table 9 Share of environmental impacts across the value chain

	Product studied	Use phase	Share of total primary energy use					
			Manufacturing	Washing	Drying	Ironing	Other	Total
Steinberger et al. (2009)	Cotton T-shirt	50 washes	27 %	26 %	47 %	0 %	0 %	100 %
Collins and Aumônier (2002)[1)]	Polyester trousers (0.4 kg)	92 washes	20 %	32.5 %	17 %	12 %	18.5 %	100 %
Collins and Aumônier (2002)[1)]	Men's cotton briefs (0.216 kg)	104 washes	16 %	40 %	38.5 %	0 %	5.5 %	100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg)[2)]	Average[3)]	16 % (approx. 190 MJ/kg)	84 % (approx. 1,000 MJ/kg)				100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg)[2)]	Best[3)]	49 % (approx. 190 MJ/kg)	51 % (approx. 200 MJ/kg)				100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg)[2)]	Worst[3)]	7 % (approx. 190 MJ/kg)	93 % (approx. 2,500 MJ/kg)				100 %
Smith and Barker (1995)	Polyester blouse (0.054 kg)	40 washes/94 °F+drying	18 % (approx. 305 MJ)[4a)]	55 %	27 %	0 %	0 %	100 %
Smith and Barker (1995)	Polyester blouse (0.054 kg)	40 washes/cold no drying	98 % (approx. 305 MJ)[4b)]	2 %	0 %	0 %	0 %	100 %
BSR (2009)[5)]	All clothing types	Aggregated	61 %	13 %	9 %	17 %		100 %
BSR (2009)[6)]	n.a.	Warm wash	n.a.	30 %	52 %	18 %		100 %
BSR (2009)[6)]	n.a.	Cold wash	n.a.	6 %	70 %	24 %		100 %
BSR (2009)[7)]	Denim jeans	104 washes	43 %	57 %				100 %

GHG greenhouse gas, *n.a.* not available

[1)] Prepared by Environmental Resources Management (2002) for Marks & Spencer

[2)] Very similar results for a pair of woven cotton trousers

[3)] Average, 54 % cold wash/46 % heated wash; load size, medium; washer efficiency, 70 % conventional/30 % Energy Star; water heater type, 50 % elec./50 % nat. gas. Drying, 84 % dryer/16 % air dry; dryer efficiency, 70 % conventional/30 % Energy Star. Best, 100 % cold wash; load size, extra large; washer efficiency, 100 % Energy Star; water heater type, 100 % nat. gas; drying, 100 % air dry; dryer efficiency, n/a. Worst, 100 % heated wash; load size, small; washer efficiency, 100 % conventional; water heater type, 100 % elec.; drying, 100 % electric dryer; dryer efficiency, 100 % conventional

[4a)] According to Fig. 2, the total energy requirements=1,607.4 million Btu=1,607×0.00154 MJ=1,694 MJ. This means 100 % is 1,694 MJ and subsequently 18 % represents 305 MJ

[4b)] Baseline washing temperature is 94 °F>when washing cold and no drying according to Fig. 11 the total energy for one laundry (=1.08 kg fabric) is 4,000 Btu~5.7 MJ~2 % of 305 MJ

[5)] Chart 3: use phase care options: comparative GHG emissions per event; several sources

[6)] Chart 1: aggregate clothing life cycle GHG emissions

[7)] Chart 6: source: Levi's Strauss

until it is worn out, the functional unit should include the aspect of the maximum life span and should be per square meters per year. The best choice then is to take a heavier textile because a thick fabric lasts longer.

From a life cycle perspective, much more research is required on the use phase, especially with regard to consumer behavior. For shirts, the assumption of 50 washes (as given in the literature) seems to be reasonable. However, trousers seem to be washed less often, say 15 to 20 washes, but no data are available. For party dresses, one to three washes seem to be a reasonable choice. The consumer behavior with regard to the use of drying machines also needs further research, since it seems that not all washes are dried in a machine.

The data presented in this report is subject to large uncertainties. This is partly a consequence of purely conducting the analysis on the basis of openly available data and voluntary

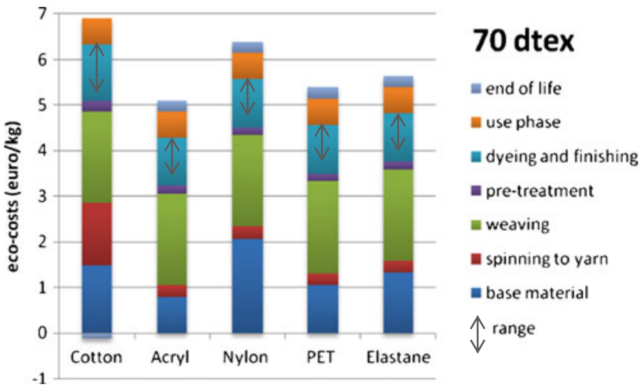


Fig. 13 The eco-costs over the life cycle for a woven textile product, 70 dtex

contributions of companies. A further reason for the large uncertainties is the nature of (parts of) the textile sector which is characterized by very diverse products and practices. Dyeing and final finishing processes are strongly case dependent, as well as the scenarios on the use phase and end-of-life. On top of this, there is a lack of data on wearing and laundry behaviors of consumers. The authors expect that the results presented in this article will hopefully be subject to further discussion, where the size of the yarn will be taken into account.

8.2 Conclusions

From the data tables, it can be concluded that the energy consumption per kilogram yarn is inversely proportional to the yarn size in decitex (i.e., the energy consumption per kilogram is proportional to the length). The energy of weaving and knitting is obviously a function of decitex as well, but most of the references do not specify the yarn count when they present energy data for these processes. LCA research on textiles can only be accurate when yarn thickness (e.g., in decitex or denier)

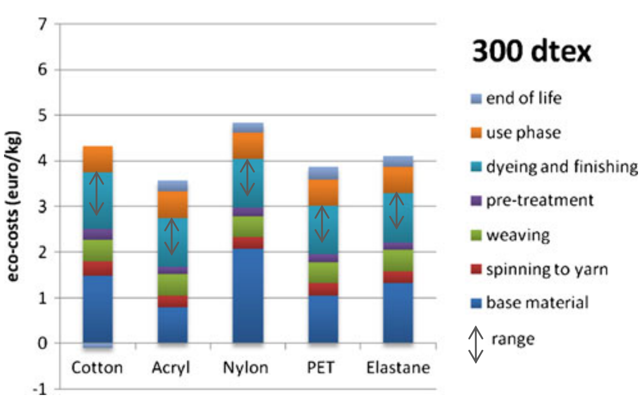


Fig. 14 The eco-costs over the life cycle for a woven textile product, 300 dtex

Table 10 Eco-costs of woven greige synthetic textile as a function of yarn thickness

Yarn thickness (dtex)	Eco-costs (€/kg)	Density (kg/m^2)	Eco-costs (€/m^2)
70	4.508	84	0.379
150	3.439	180	0.619
300	2.971	361	1.072

is specified. In case the functional unit indicates the fabric per square meter, the density (in grams per square meter) must also be known.

The cradle-to-gate analysis of the production chain from raw material extraction to manufactured textile demonstrates that acryl and PET have the least impact on the environment (followed by elastane and nylon). Cotton represents the highest environmental burden in all four single indicators (CO_2 equivalent, CED, Eco-costs 2012, and ReCiPe). For cotton fabric less than 150 dtex, weaving and spinning have the highest cradle-to-gate impact. For polymer fibers, the impact of spinning is comparatively low; however, weaving has the highest impact in less than 70 dtex textile production. Knitting has a factor of 20 lower impact than weaving for all fibers, so knitting is a better solution than weaving from an environmental point of view.

Dyeing and final finishing processes are case dependent, but calculations suggest ranges that do not exceed one third of the total of the preceding cradle-to-gate processes. The cradle-to-grave analysis in eco-costs for a woven textile, made out of 70 dtex yarn, shows that a cotton product has the worst environmental profile and a product made out of acryl the best. For the given specifications, weaving is the most significant life cycle stage followed by the manufacturing of the base material (and spinning for cotton). The total environmental burden over the complete life cycle is reduced at a higher yarn size due to the decrease in energy use (per kilogram textile) for the spinning and weaving processes of thicker yarns. As a consequence, the impact of weaving (and likewise of knitting) becomes less important and cotton and nylon change places in the ranking (breakeven point is around 100 dtex). In the use phase, the washing and drying of laundry has less relative impact than it is suggested in the classical literature (e.g., Laitala and Boks 2012; Collins and Aumônier 2002; BSR 2009), even when thicker yarns are used to manufacture the textile product, provided that "energy label A" machines are used.

LCA results of textile products over the whole value chain are highly case dependent, especially when the dyeing and finishing processes and the use phase and end-of-life are included in the analysis. Further LCI data studies on textiles and garments are urgently needed to lower the current uncertainties in LCA of textile materials and products.

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