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Research article

Environmental and social performance of valorizing waste wool for sweater production

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A B S T R A C T

The clothing industry has been active in recent years to develop more sustainable and circular business models, with extensive attention to fossil fibers and cotton, although wool has received little academic attention. This study follows the valorization process of conventionally discarded wool from a sheep farm in Sweden to produce a wool sweater. The aim is to highlight important environmental and social hotspots for valorizing the waste wool in a new supply chain for the clothing company. The study employs life cycle assessment (LCA) and social life cycle assessment (SLCA) with the PSILCA database to assess different supply chains. The LCA results illustrate that the supply chain valorizing waste wool significantly reduces environmental impacts compared to conventional supply chains of merino wool. The processing of the wool and sweater assembly contribute to the largest share of the environmental impacts and are sensitive to the choice of electricity mix employed for processing and manufacturing. The results from the SLCA suggest that the supply chains involving primarily European producers have fewer social risks than the conventional supply chains for wool. Large social risks are present in the shipping between production sites in Europe, and manufacturing facilities for the wool garments, pointing to the care required to ensure social responsibility along the supply chain. The SLCA results are sensitive to the cost assumptions made for activities along the supply chain. The results provide empirical evidence and highlight areas to improve the environmental and social implications for developing a new circular supply chain.

Introduction

The clothing industry has been identified to account for a large share of environmental impacts from personal consumption, primarily due to the current fast fashion paradigm and the environmental implications of producing different textiles (Peters et al., 2019). In recent years, there has been an increased interest in assessing the sustainability of clothing, with many efforts to provide footprints, sustainability assessments, and new business models (Khan and Islam, 2015; Lenzo et al., 2018; Radhakrishnan, 2015). The clothing industry has developed holistic assessment metrics to assess the social and environmental implications of its products throughout the life cycle, e.g., through the Higg Index (SAC, 2019). Furthermore, standards and benchmarking approaches are being developed through collaborative efforts with clothing industry representatives and the academic community, including the Product Environmental Footprint category rules for apparel (EC, 2013; 2019) and similar category rules through the Environmental Product Declaration (EPD, 2019) system to allow for comparisons.

Concurrently, the increased interest and prevalence of the circular economy in both industry and policy has led to many goals and targets being developed to address sustainability through circularity in the clothing industry ((EMF, 2017); Radhakrishnan, 2015). There is an increasing body of literature available reviewing the potential and implications of different methods to recycle, reuse, and repurpose textiles to reduce the environmental impacts through circular approaches (Sandin and Peters, 2018; Alhola et al., 2019; Peters et al., 2019; Zamani et al., 2017). In particular, clothing manufacturers have begun developing approaches to contribute to the circular economy through the investigation of new business models to contribute to a circular economy (Fischer and Pascucci, 2017; Holtström et al., 2019; Moorhouse and Moorhouse, 2017; Wilson, 2015; Zamani et al., 2017). These include collaborative consumption, recycling programs, and many design initiatives to address sustainability along the supply chain and life cy-

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cle (Holtström et al., 2019; Stål and Corvellec, 2018; Stål and Jansson, 2017; Urbinati et al., 2017). There have been several studies outlining the potential of these approaches for reducing the environmental impacts, exploring circular production methods for textiles and fibers (Peters et al., 2019; Schmidt et al., 2016) and end-of-life approaches for recycling and reusing clothing (see e.g., a review by Sandin and Peters, 2018). However, many of the assessments focus on fossil-based fibers (ibid.), while natural fibers such as wool have received less scientific attention (Woolridge et al., 2006). To our knowledge, there are no studies which assess the sustainability of upcycling wool wastes from raw material production into new textiles or garments, although several studies have reviewed the use of waste wool for new applications as growing media and nutrients (Zoccola et al., 2015; Górecki and Górecki, 2010; Patnaik et al., 2015)

Wool, despite its importance as a textile fiber and rising (re)popularity (IWTO, 2018; Sneddon et al., 2012), has little value in Sweden. In several recent studies, it was concluded that only 8% of Swedish wool is used for textile production, with over 75% of wool produced ending up as a waste product (Olofsson et al., 2010; Svenska Fåravelsförbundet, 2017). This is due to the current restrictions on the use of agricultural by-products, classifying wool as a waste product with no economic incentives to valorize the wool beyond disposal (Olofsson et al., 2010). Sweden also imports large shares of wool from neighboring countries, in addition to a substantial share of wool being imported from abroad for its large clothing sector, see, e.g., Olofsson et al. (2010) andBhaderovic and Zalkat (2018). As such, it is essential to further develop the market for this underutilized product and understand how to sustainably manage it in new supply chains; providing added value to sheep farmers and clothing manufacturers.

The sustainability of wool has been a subject of inquiry in a number of publications, primarily outlining the methodological complexity of applying LCA to wool production (Barber and Pellow, 2006; Lenzo et al., 2018; Woolridge et al., 2006; Wiedemann et al., 2020). Often these are confined to discussions on the potential implications of the allocation of environmental impacts between meat and production of (merino) wool (Wiedemann et al., 2015; Brock et al., 2013; Henry et al., 2015; Biswas et al., 2010). Few studies have outlined impacts for wool garments (Wiedemann et al., 2020; Lenzo et al., 2017) and assessed other types of wool other than merino wool, such as wool from other domestic races of sheep.

While much of the literature focuses on environmental sustainability, less focus has been placed on the social implications of textile production and consumption despite the many potential risks along textile supply chains (Zamani et al., 2018; Lenzo et al., 2017). This is due to the fact that social LCA is an emerging subject of inquiry in the field (Sala et al., 2013; Martin et al., 2018; Lenzo et al., 2017) and few social assessments of clothing have been performed. Nonetheless, social LCAs applied to textiles are emerging. Notably, Lenzo et al. (2017) have studied the social sustainability applied to an artisanal wool product and Zamani et al. (2018) reviewed the social hotspots for the Swedish clothing sector to identify potential indicators for use in future social LCAs.

Furthermore, Egels-Zandén (2016) studied the integration of social sustainability, and Leal Filho et al. (2019) studied the socio-economic benefits of textile production and recycling. Most of these studies employ the Social Hotspots Database (Benoit-Norris et al., 2012), while no scientific articles have employed the PSILCA database. As such, this study provides a novel assessment and critical review of the method.

Consumer products, such as clothing, have been found to have a large potential to reduce the environmental implications of personal consumption, though much of the literature on circular business models have not focused on consumer products (Bocken et al., 2018; Zamani et al., 2017). While many of the previous studies on circular production methods for clothing document theoretical examples and potential for such systems to contribute to the circular economy, creating expectations for their potential (Lazarevic and Valve, 2017), few studies provide empirical evidence of the sustainability of circular business models compared to conventional supply chains. As such, it is important to assess these developing systems and business models in order to ensure that considerations to improve their sustainability are taken into account early in the development and realization of supply chains (Bocken et al., 2018;); in addition to focusing on all three pillars of sustainability (De Angelis et al., 2018; Merli et al., 2018).

Given this background, and in response to the knowledge gaps highlighted, this article aims to assess the environmental and social performance of valorizing waste wool for producing garments to promote more sustainable decision making along the supply chain. This includes assessing the implications along the new supply chain and comparing it with conventional supply chains for wool and the manufacturing of garments, providing a novel contribution, as few previous studies of wool systems go beyond the farm gate. To our knowledge, this is the first academic study to review and employ the PSILCA database providing novel insights into the method for the SLCA community. By assessing the environmental and social performance of a circular business model for a consumer textile product, the study also provides valuable knowledge to the circular and sustainable business model literature, providing empirical evidence of the potential benefits of developing new supply chains to promote the valorization of waste.

Methods

Case Study

The study follows the valorization process of waste wool from a farm north of Stockholm, i.e., Norrby Gård, to the production and availability of a midweight sweater called 'Norrby Wool Sweater' for retail by Röj. Röjk's goal is to produce the sweater using more 'local' production systems and reduce environmental impacts through the use of waste wool, and provide a new market to this Swedish resource, in place of sourcing merino wool from abroad.

The waste wool, also called greasy wool, is collected from the sheep farm, Norrby Gård, north of Stockholm. As a meat producing farm, shearing of the sheep is mandatory several times a year. In Sweden, the wool has no economic benefit for the sheep farmers and incurs costs for shearing and disposing of the sheared greasy wool. As such, the greasy wool is typically incinerated or composted on the farms. In this new value chain, after shearing, the greasy wool is manually collected and sorted at the farm. Thereafter, it is shipped by truck to the port of Nynäshamn, where it is transported by boat to the island of Gotland for scouring (Röjk, 2019).

In the scouring process, the greasy wool is washed and sorted. The process requires machinery to separate, wash the wool, heat for the liquid baths, and to separate the fat (i.e., lanolin), and also requires detergents for washing. At the scouring facility in Gotland, no lanolin is captured. However, in the scenarios assessed, two different scouring paths were assessed. These include the current system, where the wool is scoured on Gotland, and the planned future scenario, where the wool will be scoured in Belgium, which allows for lanolin capture and a higher quality wool yarn.

From the scouring process, the wool is shipped to Lithuania, where it is spun into yarn. Furthermore, the yarn is produced with no dying or bleaching of the wool yarn to preserve the natural color. This yarn is then used to produce different weaves, also done in Lithuania. From the weaving process, the woven fabric is cut and assembled in the garment assembly plant in Estonia. The fi-

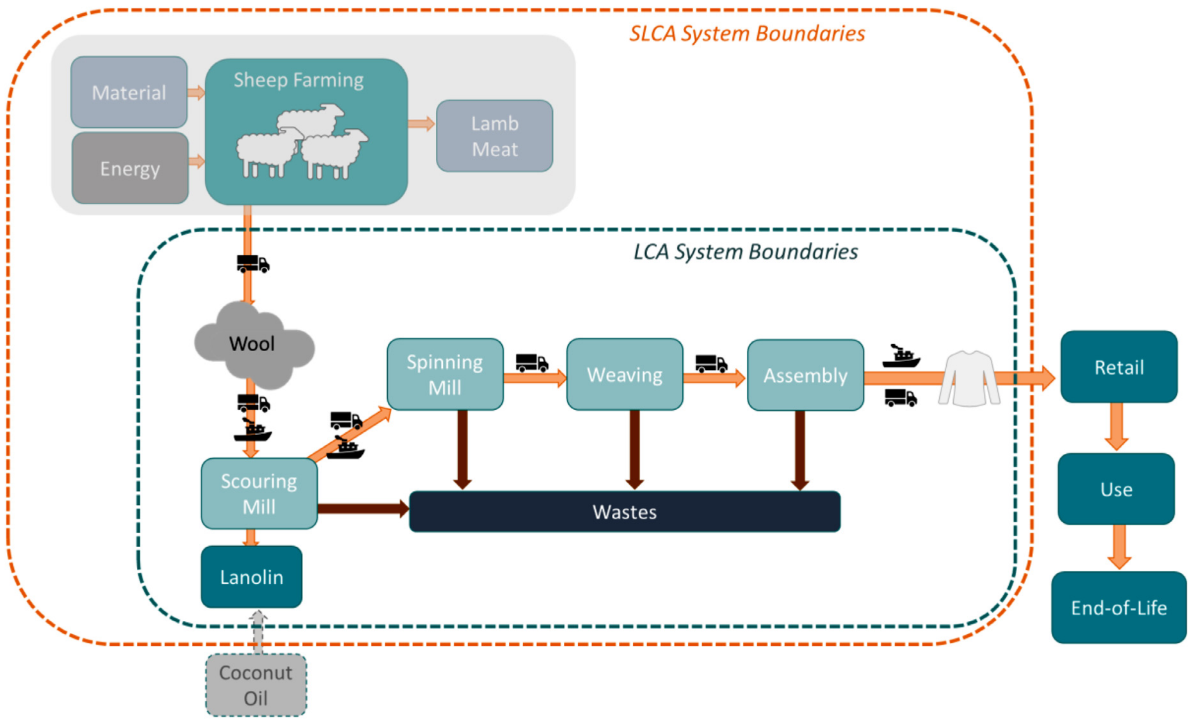

Figure 1. System boundaries of the study, including the processing steps from wool waste to sweater production.

nal product, a midweight sweater of roughly 600g wool, is then shipped back to Röjk in Sweden for retail. See a depiction of the product in the Appendix (Section 1) and further details of the supply chain in Figure 1. Additional knowledge of wool processing is extensively outlined in Barber and Pellow (2006).

Assessing Environmental and Social Sustainability

This project assesses the environmental and social performance of the valorization of waste wool for the Norrby Wool Sweater by Röjk. The following sections outline the environmental life cycle assessment (LCA) and the social life cycle (SLCA) assessment methods employed and the scenarios assessed to review different supply chain configurations due to potential changes in the supply chain and for comparison with conventional supply chains.

Goal and Scope

The functional unit for the assessment, in both the LCA and SLCA, is one mid-weight sweater produced from waste wool in the new value chain available for retail. The weight of each sweater is roughly 600 grams. As the study was performed to understand the impacts of the production system, and given the current lack of studies performing environmental and social life cycle assessments for wool products, a cradle-to-gate perspective is employed. This includes the acquisition of the waste wool, all processing of the wool to produce yarn, knitting, final assembly, and final availability at the suppliers' warehouse and webshop, only available as an exclusive product through the webshop. Impacts from retail, washing, and end-of-life processes are not included in the study, although they can be important to assess further to guide consumers to extend the life of their products (Wiedemann et al., 2020).

Scenarios Assessed

As aforementioned, the study reviews different supply chains and scenarios. These include two main scenarios for the LCA, i.e., 1) wool from Sweden (SE), scoured on Gotland and then shipped to Eastern Europe (EE), which includes Lithuania and Estonia, and 2) a supply chain including scouring in Belgium (BE) as Röjk is considering sending the wool to Belgium for scouring due to more efficient processes. For comparison to conventional supply chains of wool, the LCA and SLCA review several additional scenarios. This includes an Australian wool supply chain (AU-EE), and for the SLCA, this also includes the addition of an Uruguayan supply chain (UY-EE). These particular scenarios are included as Röjk suggested that they employ Australian and Uruguayan wool in other wool products, and as such, a comparative assessment could be provided for them to understand the implications of their supply chain choices. The supply chains reviewed are outlined briefly below. Further details on the supply chains, assumptions and data employed are more thoroughly described in the Appendix, Sections 1-2.

The Swedish-Baltic Supply Chain (SE-EE)

This supply chain includes waste wool originating from a Swedish (SE) farm, Norrby. From there, it is transported to Gotland to be scoured. The other main steps, spinning, and sweater production, are conducted in Eastern Europe (EE), i.e., Lithuania and Estonia, respectively. The product is then sent to the warehouse for retail.

The Swedish Belgian-Baltic Supply Chain (SE-BE-EE)

This supply chain is similar to the SE-EE supply chain aforementioned. However, instead of scouring the wool in Gotland, the wool is transported to Belgium for scouring and then to Lithuania, where it enters the same supply chain.

The Australian Supply Chain (AU-EE)

This supply chain includes Australian (AU) wool that is sheared and scoured in Australia, sent to Rotterdam, and then shipped to

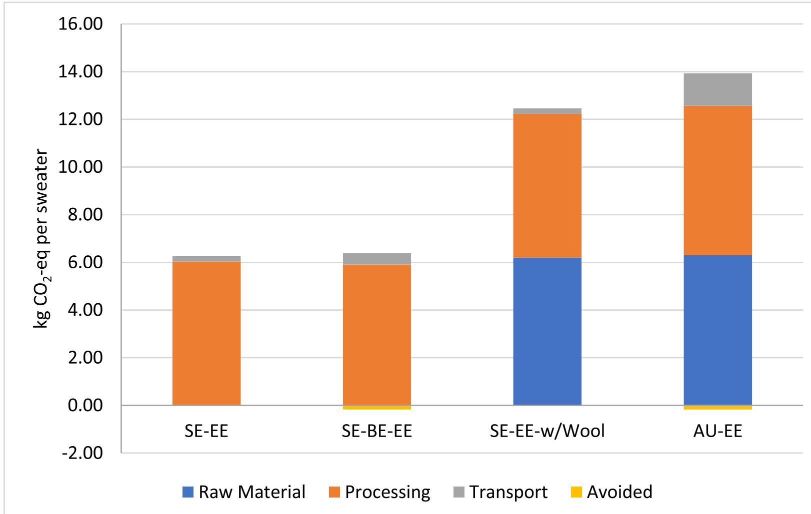

Figure 2. Contribution of different processes to the GHG emissions (Shown in kg CO_2-eq per sweater) SE-EE: Swedish wool, sweater production in Baltics, SE-EE: Swedish wool, sweater production in Baltics (including upstream wool impacts), SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics.

Lithuania for spinning, after which it enters the same supply chain as the SE-EE scenario described above.

The Uruguayan Supply Chain (UY-EE)

This supply chain includes Uruguayan (UY) wool that is sheared and scoured in Uruguay, sent to Rotterdam, and then shipped to Lithuania for spinning, after which it enters the same supply chain as the SE-EE scenario described above.

Environmental Life Cycle Assessment (LCA)

In order to assess the environmental performance of the valorized wool system, life cycle assessment was employed. Life cycle assessment (LCA) is a widely applied tool used to assess the potential environmental impacts and resource use of products and services throughout their life cycle (Finnveden et al., 2009) and has been used to study textiles and other garments in a number of previous studies (Lenzo et al., 2018; Peters et al., 2019; Roos et al., 2016).

In this article, the life cycle impact assessment (LCIA) method ILCD v 1.0.8 midpoint was employed due to its prominence in the field and holistic review of environmental impacts. The environmental impact categories available in the article are limited to greenhouse gas (GHG) emissions, acidification and eutrophication impacts, and resource depletion (including water and fossil resources). These were chosen to provide a screening of the potential environmental hotspots, and to assess both local and global environmental impacts for agricultural products for the improvement of the studied systems. Further results, including a broader array of environmental impact categories are also available in the Appendix (Tables A2-A5) for further details.

The LCA also includes avoided processes, e.g., the availability of the by-product, lanolin. The use and end-of-life phases of the wool sweater are not included in the assessment; see Figure 1. Additionally, the environmental impacts from sheep farming were not included for the waste wool. This is due to the fact that currently, there is no economic value in the waste wool, see Figure 2. However, environmental impacts from activities for sheering and associated transportation for the waste wool are included. Furthermore, the inclusion of impacts from sheep farming has been analyzed in the sensitivity analysis, assuming the wool will begin to receive economic value due to the new value chain being created. Previous studies have also shown that the raw material, wool, is a large impacting process in previous assessments and highly sensitive to allocation (Barber and Pellow, 2006; Lenzo et al., 2018; Woolridge et al., 2006; Wiedemann et al., 2020).

Life Cycle Inventory and Data

LCI data for all material and energy inputs and outputs were obtained from Ecoinvent v 3.5 (2018) and other relevant data from the literature. When data was not available for specific material and energy inputs, similar or corresponding products were used in their place. See Table 1, subsequent text and Table A1 in the Appendix for a review of the material and energy flows, and corresponding LCI datasets employed.

Impacts were included for the shearing, sorting, collection, storage, and transportation from Norrby Gård to the scouring plant. This includes electricity use and different transportation methods such as truck and boat, depending upon the location of the scouring plant. All transportation between facilities is assumed to be conducted by truck unless otherwise specified.

Energy, water, and detergent application for the scouring, spinning, and weaving processes were modeled based on inputs from Barber and Pellow (2006). The detergent was assumed to be fatty alcohol ethoxylate detergent. Losses in weight from one process to the next include waste fractions from wool sorting and by-products. The main by-product of the scouring process, lanolin, has been identified in a number of studies as a valuable output from the wool process (Barber and Pellow, 2006; Woolridge et al., 2006). It is assumed to replace coconut oil in cosmetics. In the scenarios which are scoured in Sweden, this is not included as there is no lanolin extraction. In contrast, for the scenarios with scouring in Belgium, it is assumed that 60% of the lanolin in the wool is extracted.

Social Life Cycle Assessment (SLCA)

In order to understand the potential social implications of the reviewed supply chains, a social life cycle assessment (SLCA) was also conducted. SLCA is a methodological framework that assesses the social and socio-economic impacts of products, both positive or negative, from a life cycle perspective. SLCA was developed

Table 1
Life Cycle Inventory for the SE-EE Supply Chain.

Process	Type	Name/Process	Amount	Unit
Farm	Inputs	Greasy Wool	150	kg
		Electricity	18	kWh
Scouring	Inputs	Greasy Wool for Scouring	150	kg
		Electricity	45	kWh
		Heat	525	MJ
		Water	0.9	m^3
		Detergent	2	kg
	Outputs	Lanolin	0	kg
		Wastewater	0.8	m^3
		Waste (Incineration)	38	kg
Spinning	Inputs	Wool for Spinning	113	kg
		Electricity	225	kWh
		Heat	338	MJ
	Outputs	Waste	4	kg
Knitting	Inputs	Wool for Knitting	108	kg
		Electricity	290	kWh
		Heat	4 328	MJ
	Outputs	Waste	5	kg
Assembly	Inputs	Wool for Spinning	103	kg
		Electricity	290	kWh
		Tag	0.90	kg
	Outputs	Waste	3	kg
Retail	Inputs	Amount to Retail	100	kg
		Plastic Wrapping	4	kg
		Cardboard	11	kg
	Outputs	Sweaters	167	units
Transportation	Shipping wool (Farm-Harbor), Truck	24 000	kgkm	
	Shipping wool (Harbor-Gotland), Boat	30 000	kgkm	
	Transport (Gotland-Öland), Boat	37 500	kgkm	
	Transport (Sweden-Lithuania), Truck	105 000	kgkm	
	Transport (Lithuania-Estonia), Truck	67 500	kgkm	
	Transport (Estonia-Sweden), Boat	40 000	kgkm	
	Transport (Domestic, Retail), Truck	10 000	kgkm	

based on the environmental LCA framework and includes the same major steps, but focuses on social impacts; see further details in the framework by UNEP, 2013) for SLCA. These social impacts are the result of positive or negative pressures on social endpoints. UNEP, 2013, p.43) define these social impacts as "consequences of social relations weaved in the context of an activity." The impacts that SLCA covers may directly influence many stakeholders along the supply chain, and are linked to the behavior of enterprises, and impacts on social capital (UNEP, 2013). The results can be used for the improvement of socio-economic conditions within the supply chain and all its stakeholders.

This assessment is conducted employing the PSILCA v 2.1 Professional in the program OpenLCA (Ciroth et al., 2015) by modeling the different supply-chains. The database is based on the EORA multi-region input-output database, which covers roughly 15,000 sectors and encompassing 189 countries and over 50 indicators (Lenzen et al., 2013). As the PSILCA database employs input-output data, secondary impacts due to imports of industries from other industries are traceable. The PSILCA database includes 65 indicators and addresses 19 subcategories for five stakeholders. The PSILCA 2.1 documentation by Ciroth and Eisfeldt (2017) presents an overview of all the subcategories and indicators present in the PSILCA database as well as their definitions. The indicators included in this study are a result of the PSILCA characterization method, called the "Social Impacts Weighting Method," that characterizes these 65 indicators in 49 overarching categories. Due to the limited scope of this research, five of these characterized indicators are included, namely Corruption and Bribery, Child Labour, Forced Labour, Social Responsibility along the supply chain, and Safety Measures. These were chosen based on consultation with the producer and from previous literature on relevant indicators for Swedish textiles and wool products (Zamani et al., 2018; Lenzo et al., 2017). The different indicators are assessed as "medium risk hours" to quantify the risks associated with products along their life cycle (Herrera, 2019). These risks are divided into six levels per hour worked (Ciroth 2015), and then converted to *medium risk hours* (MRH) using multipliers that are pre-defined per indicator; see further elaboration in Eisfeldt (2017).

The quality and certainty of this data varies per indicator and is available as pedigree matrices in the dataset itself. Further details on the construction of these matrices are available in Eisfeldt (2017, p.19). This research only uses the generic data from the PSILCA database; on-site data collection is not a part of this study. Ciroth and Franze (2011) and Ferrante et al. (2019) provide more information on techniques for on-site data collection for SLCAs and how to use this data as an alternative to generic data.

Social Life Cycle Inventory and Data

Similar to the LCA, the SLCA requires inventory data. For the PSILCA database, these are based entirely on the economic value of inputs and processes, input as USD. All economic data for the original supply chain (SE-EE) were supplied by Röjk. The economic data for other supply chains and processes were obtained from electronic sources; see the Appendix (Section 2) for further details on economic data used in the different supply chains. Some of the data supplied by Röjk was aggregated, and assumptions were made for data that was not available. Unlike the LCA, the system boundaries of the SLCA include wool production.

Transportation between the wool producer and the scouring facility included truck and ferry transport, while only the total cost was available. Here, the truck was assumed to incur 60% of the total transportation costs, with the rest attributed to the ferry. All transportation by land is assumed to be done by truck only. Transportation between the sweater producer and the warehouse in-

Table 2
Aggregate table of activities used in SLCA supply chains (SE-Sweden, AU-Australia, UY-Uruguay, BE-Belgium, US-United States, NL-Netherlands, LT-Lithuania, EE-Estonia,). Scenarios reviewed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, UY-EE: Uruguayan wool, sweater production in Baltics.

Process	Dataset	Country	Used in Supply Chain
Wool Production	Products of agriculture, hunting and related services – SE	SE	SE-EE, SE-BE-EE
	Shorn wool – AU	AU	AU-EE
	Wool – UY	UY	UY-EE
Transport (Wool -Scouring)	Land transport; transport via pipelines – SE	SE	SE-EE, SE-BE-EE
	Water transport – SE	SE	SE-EE, SE-BE-EE
	Land transport; transport via pipelines – BE	BE	SE-BE-EE
	Road Freight Transport – AU	AU	AU-EE
Scouring	Manufacture of Textiles-SE	SE	SE-EE
	Wool scouring – AU	AU	AU-EE
	Manufacture of textiles – BE	BE	SE-BE-EE
Transport (Scouring – Spinning)	Water transport - SE	SE	SE-EE
	Land transport; transport via pipelines – BE	BE	SE-BE-EE
	Water transport - AU	AU	AU-EE
	Water transport - US	US	UY-EE
	Land transport; transport via pipelines – NL	NL	AU-EE, UY-EE
Spinning	Manufacture of textiles – LT	LT	SE-EE, SE-BE-EE, AU-EE, UY-EE
Transport (Spinning – Production	Land transport; transport via pipelines – LT	LT	SE-EE, SE-BE-EE, AU-EE, UY-EE
Sweater Production	Manufacture of wearing apparel; dressing and dyeing of fur – EE	EE	SE-EE, SE-BE-EE, AU-EE, UY-EE
Transport (Production – Warehouse)	Water transport – EE	EE	SE-EE, SE-BE-EE, AU-EE, UY-EE
	Land transport; transport via pipelines – SE	EE	SE-EE, SE-BE-EE, AU-EE, UY-EE

cluded transportation by truck and boat, while only the total cost was available. Here, the truck was assumed to make up 20% of the total cost, with the remaining 80% by boat. All transportation within the different countries is assumed to be handled by organizations originating from that country. For example, between the wool producer and the scouring facility in the SE-EE supply chain, transportation is assumed to be conducted by a Swedish based transportation firm. Costs for transoceanic transport were based on the amount of wool that can be transported in a container, as reported by AWEX (2009), which served as input for calculating costs in the World Freight Rates Calculator (WFR, 2019).

The total cost for clean Australian wool was available, but the ratio between the costs for greasy wool and scouring was not. Therefore, the implemented ratio was 50/50. Given that no good representative activity for scouring in Uruguay was present, instead, the full price for Uruguayan wool as stated in Arrosa (2018) was allocated to the wool activity.

Costs for transportation by truck for the AU-EE and UY-EE supply chains were assumed to have similar costs to the Swedish shipping costs. As aforementioned, the costs of transportation between the wool producer and scouring facility in Sweden was split equally to transportation by truck and ferry. The land transportation share was then divided by the distance traveled as well as the weight it transported. The result was a cost in SEK/kg*km. This was then converted into USD and used for the cost calculation of the transportation in the UY-EE and AU-EE scenarios. All distances for road travel by the trucks were calculated using Google Maps.

The PSILCA database does not have detailed information for every country included in its database. As such, representative datasets were chosen. Since the PSILCA database uses the NACE system for activities, the closest aggregated activity replaced the specific activity. For example, “Manufacture of Textiles” activity represented the spinning activity since a more detailed activity was not available . Since this activity includes the production of rugs, ropes, and other textile products, this will influence the results. Table 2 below presents the activities used for each step in the different supply chains for the SLCA. As previously highlighted, the UY-EE supply chain does not include scouring, as the wool price taken for the scouring process in Uruguay is included in the wool production.

Results and Discussion

Life Cycle Assessment

The results illustrate that the valorized wool process GHG emissions were were roughly 6 kg CO_2-eq per sweater from a cradle-to-gate perspective, see Figure 2. The results suggest that the GHG emissions are not significantly different between the European supply chains. However, including the impacts of wool nearly doubles the GHG emissions per sweater, where the AU-EE supply chain is included as a reference. Similar results are found for the SE-EE scenario, including the wool, which produces similar results as Nolimal (2018) per sweater.

Similar results for the European supply chains are also illustrated for other impact categories, where the SE-EE and SE-BE-EE supply chains have lower environmental impacts in nearly all categories; see Table 3 below. However, it is worth noting that the water resource depletion in the SE-BE-EE supply chain is much larger than other supply chains. This is primarily due to the choice of the electricity system for process energy in the Belgian scouring and spinning process. A sensitivity to this choice is also included below. Further details and a broader listing of environmental impact categories available in the ILCD method are available in the Appendix, Tables A2-A5.

Analysis of LCA Results

As illustrated in Figure 2, the process emissions contributed to a large share of the overall emissions from the different scenarios. This is primarily due to electricity and heating in the processes for scouring and assembling the sweater, see also Figure 3. A slight increase in the GHG emissions from transportation can be seen in the SE-BE-EE supply chain compared to the SE-EE, which includes more transportation by truck. However, the GHG emissions from the transportation had no significant contribution in the SE-EE scenarios, while it was more significant in the reference supply chain with wool originating from Australia. Furthermore, in Figure 4, credits due to the use of lanolin were found to have no significant contribution to the overall results per sweater, although they partly negate the transportation emissions in the SE-EE scenarios. The overall contributions of the production and raw ma-

Table 3
Impacts per sweater for the different supply chains. SE-EE: Swedish wool, sweater production in Baltics, SE-EE: Swedish wool, sweater production in Baltics (including upstream wool impacts), SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics.

	GHG Emissions	Acidification	Freshwater eutrophication	Resource depletion - mineral, fossils and renewables	Resource depletion - water
	(kg CO_2-eq)	(Mole H+ eq.)	(g P eq.)	(g Sb eq.)	(m^3)
SE-EE	6.3	0.03	5.0	0.07	0.02
SE-BE-EE	6.2	0.02	4.0	0.04	0.21
SE-EE (including wool)	12	0.25	8.0	0.28	0.05
AU-EE	14	0.25	8.0	0.26	0.03

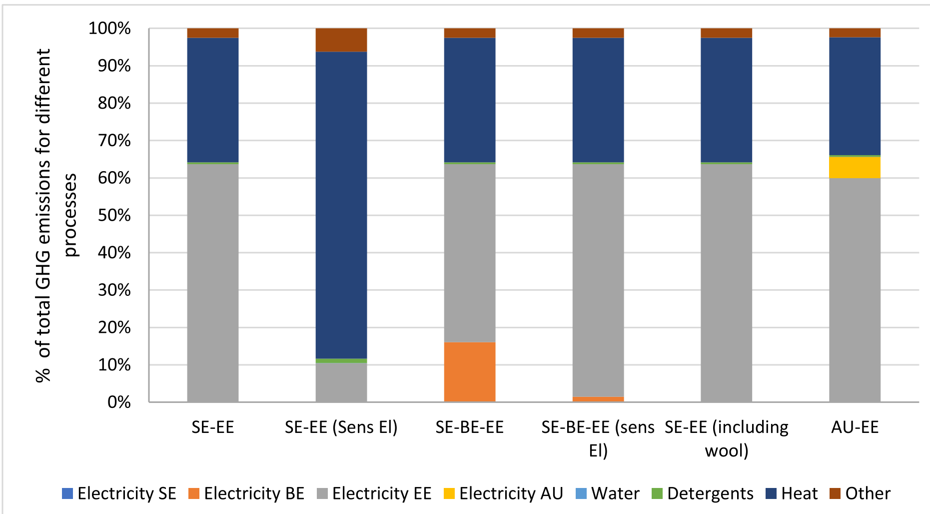

Figure 3. Contribution to processing emissions for the different scenarios, shown in percent greenhouse gas (GHG) emissions. Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics AU-EE: Australian wool, sweater production in Baltics, Sens el: Sensitivity analysis to electricity dataset employed. SE-Sweden, EE-Eastern Europe, BE-Belgium, AU-Australia.

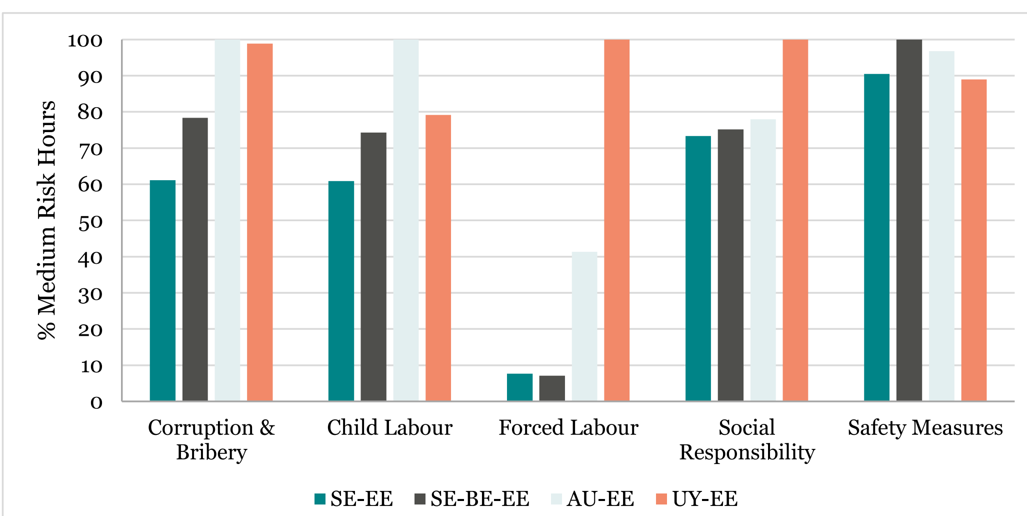

Figure 4. Normalised results of SLCA. The scenario with largest impacts is set to 100% for each impact category. Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, UY-EE: Uruguayan wool, sweater production in Baltics.

terial sourcing phases are in line with previous studies, see e.g., Lenzo et al., 2018, Biswas et al. (2010), and Brock et al. (2013).

Figure 3 depicts the origin of the process GHG emissions for the different supply chains. As shown, the largest share of emissions come from energy use in processing. Water, detergents, and other inputs had no significant contribution to the processing impacts; similar to results in Moreira Cardoso (2013), Barber and Pellow (2006) and Emanuelle (2017). Per kilogram of wool, the processing, and raw material each contributed to roughly 10 kg CO_2-eq. These results are slightly lower than those found in Biswas et al. (2010) and Brock et al. (2013), which illustrated greasy wool impacts of roughly 16-20 kg CO_2-eq per kg of wool and up to 40 kg CO_2-eq per kg of greasy wool were found in Weidemann et al. (2015). This is due primarily to not modeling

Table 4
Sensitivity to the choice of electricity system employed in the SE-EE and SE-BE scenarios. Results are depicted per sweater. SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics AU-EE: Australian wool, sweater production in Baltics, Sens el: Sensitivity analysis to electricity dataset employed.

Supply Chains	GHG Emissions	Acidification	Freshwater eutrophication	Resource depletion - mineral, fossils and renewables	Resource depletion - water
	(kg CO_2-eq)	(Mole H+ eq.)	(g P eq.)	(g Sb eq.)	(m^3)
SE-EE	6.3	0.03	5.0	0.07	0.02
SE-EE (Sens El)	2.7	0.01	4.0	0.08	0.01
SE-BE-EE	6.2	0.02	8.0	0.04	0.21
SE-BE-EE (Sens El)	5.3	0.02	8.0	0.04	1.3

Table 5
SLCA results for the chosen social indicators for the different supply chains. All results are expressed in Medium Risk Hours (MRH) per sweater. Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, UY-EE: Uruguayan wool, sweater production in Baltics.

Indicator	SE-EE	SE-BE-EE	AU-EE	UY-EE
Active involvement of enterprises in corruption and bribery	35	44	57	56
Child Labor, total	10	13	17	14
Goods produced by forced labour	4.8	4.5	26	63
Safety measures	37	41	40	37
Social responsibility along the supply chain	470	480	500	640

the sheep farming and relying only on data from Ecoinvent for the wool, as wool was assumed again to be a waste product in this study (Ecoinvent 2018). The results are in line with figures from Moreira Cardoso (2013) for the scouring and spinning, each contributing to around 2 kg CO_2-eq per kg wool. However, the aforementioned study did not include further processing, although they did identify that the dyeing and bleaching process also led to roughly 2-5 kg CO_2-eq per kg of wool. In this study, these impacts were avoided as no dyeing or bleaching process were included.

As the energy employed for processing, primarily electricity, had a large contribution to the overall impacts from the different supply chains, a sensitivity to the electricity system choice was conducted. In the scenario reviewing SE-EE (Sens El) scenario, the LCI data for electricity was changed to the Swedish electricity mix, which has much lower emissions than the mix employed in Eastern Europe. Table 4 shows that nearly all impact categories are reduced, and the GHG emissions per sweater are halved. Furthermore, the SE-BE-EE scenario had slightly lower impacts in nearly all impact categories except for the water resource depletion compared to the SE-EE scenario.

As an electricity LCI dataset for Belgium was not identified, the corresponding dataset for the Netherlands was employed. This assumption may affect the overall results. In order to test this choice, the scenario reviewing SE-BE-EE (Sens El) employs the electricity LCI data for France. As illustrated, this would significantly increase the water resource depletion. Despite reduced GHG emissions, no significant changes in acidification, eutrophication impacts, depletion of mineral, fossil, and renewable resources are highlighted. This is due to the prominent use of nuclear energy in France.

Social LCA

Figure 4 provides a normalized summary of the results of the SLCA, illustrating that the European supply chains have significantly less medium risk hours than the other supply chains (i.e., AU-EE and UY-EE) in three of the five tested indicators. These indicators are Corruption & Bribery, Child Labour, and Goods produced by Forced Labour, labeled ‘Forced Labour.’ In the Social Responsibility and Forced Labour categories, the UY-EE supply chain has considerably higher social impact risks.

As illustrated, no significant difference in the safety measures category is shown. However, the safety measures category shows slightly higher impacts in the SE-BE-EE supply chain compared to the others. Table 5 below presents further details of the medium risk hours (MRH) for each supply chain and social indicator review; see also Table A10 in the Appendix for further details.

Analyzing Upstream Supply Chains

The final stages of the sweater production are the same in all scenarios, which includes the knitting, assembling of the sweater, all transport between the Lithuanian and Estonian facilities and final transport to the retail warehouse in Sweden. Deducting this part of the supply chains allows for comparison of how the supply chains differ in upstream social implications of wool production, i.e., primarily from scouring and spinning.

Figure 5 illustrates these upstream impacts for the supply of wool and transportation to the weaving facility, again excluding the shared activities (spinning, production, transport). As shown, for three of the five indicators, the activities outside the shared supply chain are responsible for more than 50% of the impacts, while the expenditure in these parts of each supply chain are between 22.8 and 25.4%. This highlights the significance of the impact these processes have on the total results. Zamani et al. (2018) and De Brito et al. (2008) suggest similar outcomes when sourcing raw materials, but also producing textiles from outside Europe, which may have prevalent social issues due to relaxed social regulatory systems and management. See Table A10 in the Appendix for further details.

Investigating the sources of risk for SE-EE

Disaggregating the total risk allows for an analysis of the sources of risk for each supply chain. Figure 6 illustrates a normalized overview of the source countries for each indicator for the SE-EE supply chain. As shown, a number of countries are responsible for different types of risk indicators. China contributes to a large share of the Forced Labour and Child Labour risks, while risks stemming from Estonia are significant in the categories Social Responsibility and Corruption and Bribery. For all indicators, the five largest source countries are responsible for over 50% of the total

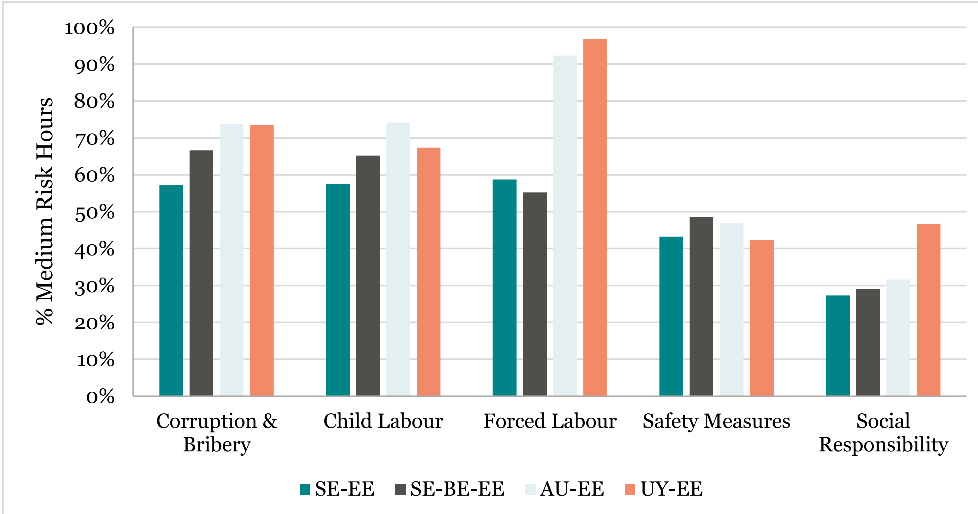

Figure 5. Share of total impact outside shared supply chain. Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, UY-EE: Uruguayan wool, sweater production in Baltics.

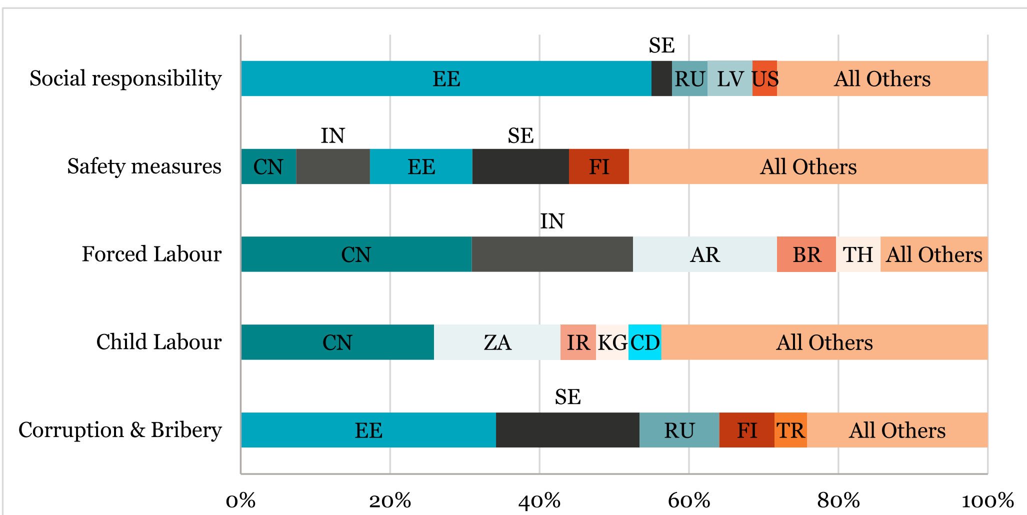

Figure 6. Normalized overview of the source countries per indicator for the SE-EE supply chain (EE-Estonia, SE-Sweden, RU-Russia, LV-Latvia, US-United States, CN-China, IN-India, FI-Finland, AR-Argentina, BR-Brazil, TH-Thailand, ZA-South Africa, IR-Iran, KG-Kyrgyzstan, CD-DR Congo, TR-Turkey).

risk. Further details on the sources for the other supply chains reviewed are available in the Appendix (Table A11).

Analyzing Country of Origin for Forced Labour

Upon further analysis, it was found that the results are dependent upon how the different economic systems are interconnected in the MRIO employed in PSILCA. As such, this section analyzes the effect of these on European economic activities, which are dependent on outside economies.

Figure 7 illustrates the interconnectedness of the global economy and that economies that are geographically far away can still have a significant secondary effect for the wool sweaters assessed. Further details are provided in Table A15 of the Appendix. Again, this is similar to findings in Zamani et al. (2018), who highlight the ‘unexpected results’ for impacts in other countries and processes than those included in the assessment. As illustrated, while the SE-EE supply chain does not include activities originating in India or China, activities in these countries represent over 50% of the total contribution to forced labor risks for this supply chain. Furthermore, the largest share of risks for forced labor throughout the UY-EE supply chain originate from Argentina, followed by China and Brazil; see Figure 9. The share of risks originating from Argentina are larger than the sum of all other countries, illustrating how interconnected the UY-EE economy is with Argentina. For the AU-EE supply chain, the largest share of the risks for Forced Labour throughout the supply chain originates from China, followed by India and Thailand. While Argentina is again identified as one of the five economies with the largest impact overall, its impact is far smaller here than it is for the UY-EE supply chain. For the Forced Labour impacts for the SE-EE and SE-BE-EE supply chains, China is illustrated to have the most substantial contribution to forced labor impacts. This is followed by Argentina and Brazil. In the SE-EE supply chain, Estonia also has a significant share of the forced labor risks. The results are similar for the SE-BE-EE chain, although Thailand and India are highlighted as the largest contributor to MRH.

Analyzing the Source Activities per Indicator

To further exemplify and analyze where the largest impacts originate, this section examines the contributing activities. Figure 8 provides an overview of the five activities with the largest impact

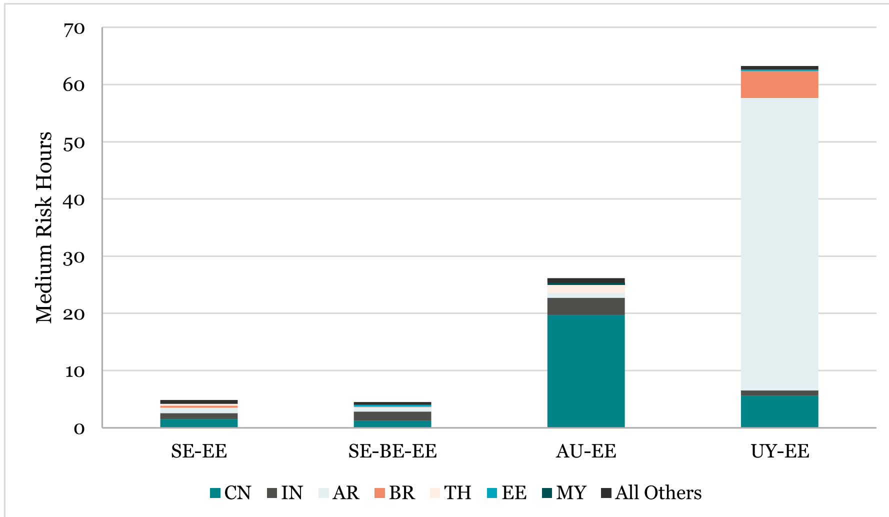

Figure 7. Country of origin for results for impact category Goods produced by Forced Labour for each supply chain (CN-China, IN-India, AR-Argentina, TH-Thailand, EE-Estonia, MY-Malaysia). Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics AU-EE: Australian wool, sweater production in Baltics.

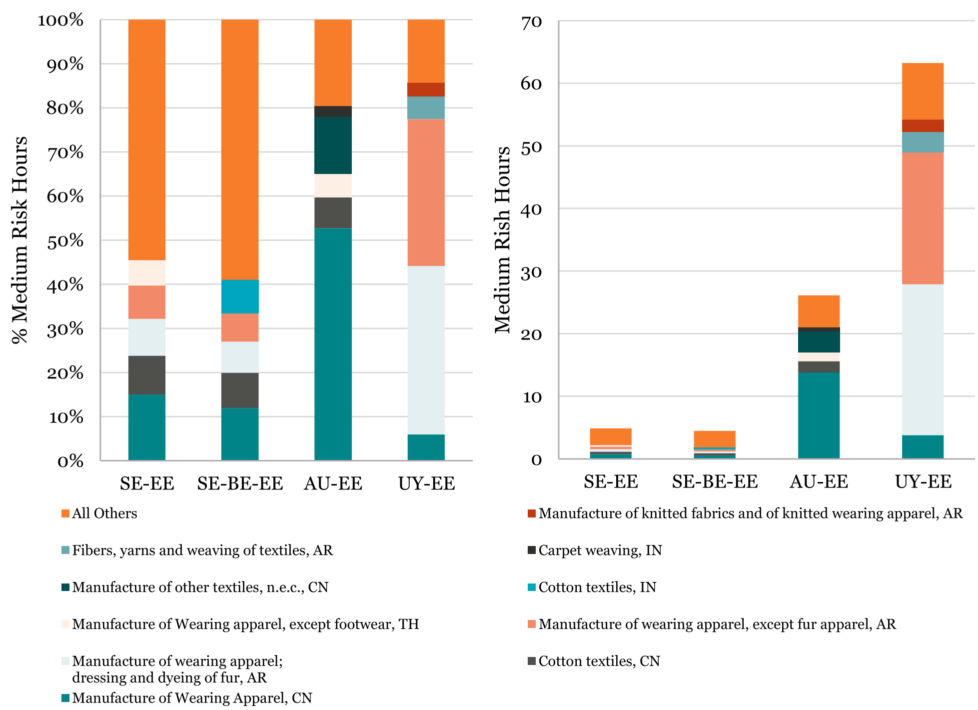

Figure 8. Activities with the largest impacts on Goods produced by Forced Labour for each supply chain (CN-China, IN-India, AR-Argentina, TH-Thailand). Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics. UY-EE: Uruguayan wool, sweater production in Baltics.

in the indicator Forced Labour for each supply chain, and a summation of all smaller activities as 'All others.'

As illustrated, the differences among the supply chains are significant. Figure 8 shows a large share of the risks for forced labor originates from the manufacturing of textiles. As aforementioned, a large share of the risks may originate from counties not associated with the process. For example, the UY-EE supply chain risks are significantly related to manufacturing activities in Argentina, illustrating the interdependence of trade toward the results; further details are provided in Table A15 in the Appendix. The differences between supply chains are less significant for the potential MRH in corruption and bribery, as is shown in Figure 9 below.

Figure 9 highlights the contribution of transportation activities to the impact category, Active involvement of enterprises in corruption and bribery. As illustrated, six of the eight largest risks directly result from transportation activities (and are not aggregated in All Others). The SE-EE supply chain involves the least transport, while all other supply chains show a larger share of transport activities, both in relative and absolute terms. The AU-EE and UY-EE supply chains show that the transport from the Rotterdam harbor to the knitting facility (Land transport; transport via pipelines, NL) represents over 30% of the total risks. Further details for other social impact categories are found in the Appendix (Table A17).

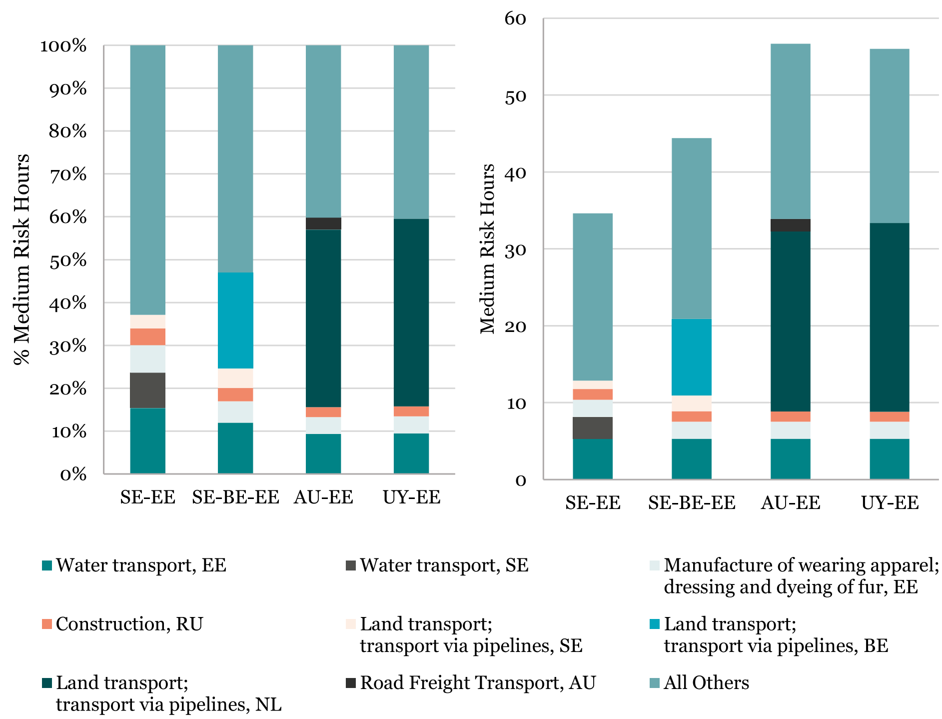

Figure 9. Activities with largest impact on Active involvement of enterprises in corruption and bribery for each supply chain. (EE-Estonia, RU-Russia, SE-Sweden, BE-Belgium, AU-Australia, NL-Netherlands). Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, and UY-EE: Uruguayan wool, sweater production in Baltics.

Table 6
Increase in Medium Risk Hours (MRH) for each indicator for each supply chain per dollar (USD) spent. Scenarios assessed include SE-EE: Swedish wool, sweater production in Baltics, SE-BE-EE: Swedish wool, Belgian scouring, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics, UY-EE: Uruguayan wool, sweater production in Baltics. The Shared Supply Chain denotes the manufacturing processes shared by all sweaters in the Baltic.

Indicator (MRH)	SE-EE	SE-BE-EE	AU-EE	UY-EE	Shared Supply-chain
Corruption & Bribery	0.85	1.3	1.6	1.8	0.20
Child Labour	0.26	0.35	0.50	0.40	0.06
Forced Labour	0.12	0.10	0.95	2.7	0.03
Safety Measures	0.69	0.85	0.74	0.68	0.28
Social Responsibility	5.4	5.9	6.2	13	4.5

Sensitivity to Cost Assumptions

In further analysis, it was found that the results are sensitive to the assumptions made for the costs associated with different processes along the supply chain. Table 6 provides an analysis of the increase of Medium Risk Hours for each indicator per dollar spent for each of the supply chains. Once again, the shared supply chain was also highlighted to illustrate the contribution of the upstream impacts in the supply chains reviewed.

Table 6 above shows that the increase in MRH per dollar spent varies significantly between supply chains for some indicators. As illustrated in Forced Labour and Child Labour indicators, the AU-EE and UY-EE supply chains show a significantly higher increase per dollar than the European supply chains. In four of the five indicators, a European supply chain performs best. The exception being the Safety Measures indicator, where the UY-EE supply chain performs best.

As shown in the Results section, some single activities have a large impact on the results of some supply chains; most notably

• Manufacture of wearing apparel, CN in the AU-EE supply chain for Goods produced by forced labor;

• Transport activities in corruption and bribery for all but the SE-EE supply chain;

• Manufacture of wearing apparel; dyeing and dressing of fur, in Estonia for the social responsibility for all supply chains

As shown in Figure 8 above, the process “Manufacture of wearing apparel, CN” influences the total risk in Goods produced in forced labor significantly, especially in the AU-EE supply chain. Further investigation of the processes at hand showed that the scouring process had a significant connection to this process. For each USD spent in this process, 0.157 USD is connected to this particular process. This is more than ten times higher than the next similar process from a different country (Hong Kong), and the largest of all connected process. The next two largest processes are also from China, Woolen Textiles (0.07 USD/USD) and Knitting Mills (0.05 USD/USD).

The transportation activities were also significant for corruption and bribery. Road transportation from Belgium and Netherlands contributed to a large share of the total risk in corruption and bribery for the SE-BE-EE, AU-EE, and UY-EE supply chains. For the Belgian process, 65% of the impacts stemmed directly from the Belgian transportation process, the other 35% being from other processes it interacted with. For the Dutch process, 81% of the total risks were associated with the transportation process itself, the other 19% being from processes it interacts with. As a result, the Netherlands became the largest country of origin for corruption

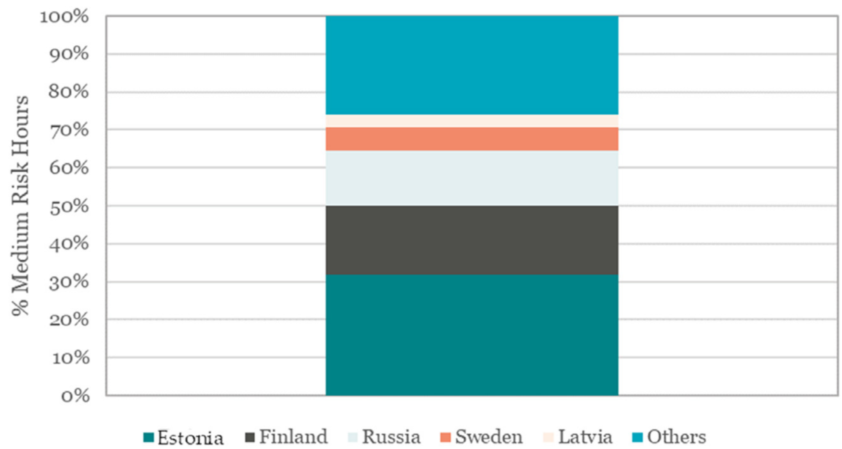

Figure 10. Overview of origin of risk in Social Responsibility for the knitting process. Illustrated in the percentage of total medium risk hours.

and bribery risks for the AU-EE and UY-EE supply chains. This indicates that the supply chains are sensitive to land transportation in Europe, which may involve bribery and corruption. Transportation by boat, on the other hand, was not as significant as land transportation. Given that the share of costs per amount of wool for a sweater is much lower for transportation by boat, it results in fewer risks. However, some limitations on the assumptions for transportation processes were outlined earlier. These are further analyzed below.

All four supply chains highlight the process 'Manufacture of wearing apparel; dyeing and dressing of fur, EE' to have a significant impact on the Social Responsibility indicator. This activity contributed to between 37% and 48% of the total risks for each supply chain. As 60-61% of all costs occur during this process, it is not unexpected that this process shows up as a major source of risks, highlighting an important area for improvement in supply chains, including animal-based textiles. Further analysis highlighted that only 19% of the total risk originates from the said process, while the other 81% originates from other related processes. These included the Finnish and Russian construction industry, as well as the Russian transport industry. In total, 31% of all risk for this process originates from Estonia, with large shares also originating from Finland and Russia, see Figure 10.

Limitations

SLCA is a developing methodology with several limitations (Benoît, 2009; Hobson et al., 2018), some of which are also reflected in this study. As the SLCA was dependent upon economic inputs, the results are sensitive to the assumptions made for costs for different activities and processes along the supply chain, similar to process-related data for LCA. As illustrated, this was particularly important for social impacts from transportation, and further details on costs for transportation by truck in Eastern Europe and transportation by boat would greatly improve the precision.

The results highlighted an interaction between processes that are irrelevant for the given supply chain, where processes and activities in China, India, South Africa, and the Democratic Republic of Congo are present in the different social risks identified. Many of the activities identified are intertwined with economic processes in countries with better labor laws, due to dependencies on resources and cheap labor, as such, there are indirect connections to these regions (De Brito et al., 2008). Once again, similar findings were also outlined in Zamani et al. (2018), highlighting unexpected impacts in countries outside the supply chain. As Tsalidi et al. (2020) affirm, this may be partly due to the choices made in the modeling, where processes and activities in neighboring countries are employed if processes and activities in the studied supply chain are not available in the databases. Therefore, a significant limitation for reviewing specific supply chains are the ripple effects of the SLCA, also highlighted in (Benoit-Norris et al., 2012). Furthermore, as the database employs general data, it outputs general results that may not always be entirely relevant for the product assessed. As such, more in-depth choices may increase the accuracy of the results. This calls into question how much of the social impacts can be attributed to the activities in the supply chain, and how much is noise generated by the generalized data.

Finally, the modeling of the supply chain using PSILCA was not entirely representative of the supply chain, as site-specific and more detailed data processes and activities are not available, leading to general results. This is important to highlight as Röjk has handpicked all factories in the current SE-EE supply chain**,** which may have improved performance compared to the results obtained. This can also be the case in many frontrunners in the clothing industry to promote more sustainable supply chains and may not be representative of actual developments.

Conclusions

As a discarded product from sheep breeding, the valorization of wool was found to have many benefits over the conventional supply chains to produce wool sweaters. In this paper, we have explored the environmental and social sustainability of this new value chain. The results of the LCA suggest that the new value chain has significant improvements compared to importing wool, with the environmental impacts in nearly all impact categories halved compared to conventional supply chains. As in previous studies, the results are sensitive to the allocation of environmental impacts to the wool and the electricity system employed. As the processes associated with the wool sweater production (e.g., scouring, spinning, knitting, etc.) were found to have the largest environmental impacts, the results pinpoint that further scrutiny could be focused on ensuring these producers employ sustainable energy systems to improve the sustainability of the sweaters produced. The potential changes in the supply chain to include scouring in Belgium in place of Gotland were shown to have only minor implications for the overall environmental impacts. However, the potential for extraction of lanolin could offset transportation emissions from the supply chain.

The results also suggest that Röjk and other clothing producers, beyond optimizing their production system for better environmental performance, should also review the potential social hotspots from their supply chains. The SLCA illustrates that the valorization of the wool in the new value chain has many reduced social risks compared to conventional supply chains for wool. This study points to the potential areas for improvement, including e.g., ensuring the logistic firms and textile production firms employed in this supply chain have suitable social conditions and better their social responsibility. Furthermore, the large social risks from sourcing wool from abroad underscore that care should be taken to ensure socially sustainable retailers when choosing suppliers of wool from outside Europe, both for Röjk and other producers of wool products. Furthermore, as the assessment relies heavily on the use of economic data for different processes and activities, the results suggest that the social impacts are dependent upon many assumptions and details provided by the producers. More precise assumptions regarding prices and more disaggregated or adapted data would improve the accuracy of the results for this research. Nevertheless, the results suggest that social sustainability standards are adequate in Europe and that these standards result in a lower risk of social issues for European-produced wool. While this study did not focus on the use phase, future research could further focus on the extension of the lifetime of the products through more sustainable washing and storage.

Overall, the results provide input to Röjk, and other clothing producers, the potential of valorizing raw materials in new European supply chains, such as previously discarded wool to produce new products. Furthermore, this study provides empirical evidence on sustainable and circular business models in the clothing industry and for consumer products. It can also promote further support for the clothing industry and to policy-makers to promote and reconsider barriers to the use of agricultural by-products to realize their value and potential for promoting a circular economy and address social responsibility along the supply chain. The study also employed the novel PSILCA database and methodology, providing important knowledge to the SLCA literature and studying supply chains beyond economic and environmental implications. In conclusion, the results suggest that, compared to conventional supply chains for wool to produce sweaters, the use of the waste wool contributes to a circular economy, and goals and targets for more sustainable production in the clothing industry, improving the environmental and social performance of the assessed sweater.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2020.11.023.

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