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CARBON FOOTPRINTING

Sustainable management in the slow fashion industry: carbon footprint of an Italian brand

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Abstract

Purpose Environmental impacts associated with the fashion industry concern society and require commitment to sustainable development goals from leading companies. The role of the luxury sector in setting trends and negotiating power within the supply chain can lead this industry towards sustainability. This study constructs a comprehensive operational flux inventory attributed to an Italian luxury garment brand, aiming to investigate and propose feasible strategies to reduce potential impacts coupled with their products.

Methods Under the operational control criteria, a whole year of activities was tracked using mainly primary data from its management system. According to ISO 14064–1:2019, potential greenhouse gas emissions were classified, organized, and processed into six categories. The analysis, at the company level, covered the product's complete life cycle, i.e., from cradle to the grave. The ecoinvent database considered preferentially local geography, and the cut-off system approach, therefore assigning emissions to the primary user.

Results and discussion Results showed that the only unit in central Italy where the headquarter is located (excluding retail stores), producing 485,193 women's clothing in a year, emitted 9804 t CO_2 eq. Most of these impacts (69% or 6752 t CO_2 eq) can be associated with indirect emissions related to raw products and materials, and about 93% of this amount results from the high-quality products used by the company. Transportation represents 14% of the total emissions, while the use phase accounts for about 13%. As a final step, six different mitigation scenarios were proposed and analyzed by focusing on non-core production activities, i.e., upstream, and downstream operations, and consumers' habits. Once combined, these strategies can potentially reduce by about 25% the study case company overall emissions.

Conclusions As a conclusion, exploring possible alternatives through environmental assessment tools can support strategies for achieving impact reduction. While aggressive changes can be done in non-core activities with excellent results, changes perceived by the customers can also be well desired to mark innovation and advances in the business mindset.

Keywords Carbon footprint · Circular economy · Sustainability · Slow fashion · Sustainable business

1 Introduction

As one of the most important industries with revenue of US $ 3 trillion or 2% of the global gross domestic product (Fashion United 2020), the apparel sector represents a threat from an environmental perspective. The fashion industry employs around 1.7 million people in 176,000 European businesses, with 90% classified as small companies (European Commission 2019), consequently, the sector's high-impact demands urgent actions (Cegarro-navarro and Buzzi 2021; Niinimäki et al. 2020) as concerns arise from the unsustainable production and consumption levels (Kim et al. 2021; Muthu 2020; United Nations 2020; Wiedemann et al. 2020). The textile industry generates 1.2 billion tonnes of greenhouse gas (GHG) per year (United

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Nations Economic Commission for Europe 2020), while the overall fashion sector accounts for a staggering 2.1 billion tonnes of GHG emissions (McKinsey and Company and Global Fashion Agenda, 2020). Only clothing accounts for 2 to 10% of the global environmental impact of EU consumption (EPRS 2019).

In this context, the challenge of the business model transition is happening through the use of new (Adıgüzel and Donato 2021; Claudio 2007) and certified materials (Ellen MacArthur Foundation 2017), the development of advanced demand forecasting technologies (Hinkka et al. 2015), the reduction of waste, the extension of the clothing lifespan (including second hand) (Carbon Trust 2011; Roos et al. 2015), recycling, and upcycling practices (Adıgüzel and Donato 2021; Kim et al. 2021; Schmidt et al. 2016), among others. Finally, these methods and their results are communicated to a growing conscious society as sustainability reports are available on the brands' websites, the Fashion Pact, Corporate Social Responsibility, and the Environmental Profit and Loss.

The Fashion Pact depicts the commitment of one-third of this sector with the acceleration of sustainability practices aiming to net-zero carbon emissions by 2050 (The Fashion Pact 2020). Three action pillars encompass the United Nations Fashion Industry Charter framework for Climate Action, reducing the impact of the materials by 25% by 2025 and achieving 100% of renewable energy by 2030. Unfortunately, the first collaboration year coincided with the COVID-19 pandemic, which affected the market. However, the report stated that signatories have already reduced about 350,000–450,000 tons of CO_2 eq emitted.

According to the European Union Commission (European Commission 2011), Corporate Social Responsibility (CSR), in growing use by the apparel industry (Kozlowski et al. 2014), reports economic, ecological, and social impacts of an organization in compliance with the sustainability triad. The CSR is detailed by Vatamanescu et al. as a strategic communication tool between corporations such as Kering and Moët Hennessy Louis Vuitton and stakeholders (Cegarro-navarro and Buzzi 2021).

Environmental Profit and Loss reports aim to associate economic performance with the ecological impact of companies' activities to complement the accounting balance (Arena et al. 2015). According to Arena et al., BSO Origin could have been the pioneer of such methodology, but it was limited to their direct burdens and combining the cost of preventing, repairing, and the value lost by society due to the impacts. Further developments, such as the Puma report, for example, expand the boundaries of the supply chain (Puma 2018).

Supply chains in fashion are usually long and distributed in several countries, complicating tracking environmental and labor practices, besides demanding more transport (Niinimäki et al. 2020). Therefore, in terms of emissions, it translates into a counter-productive pattern regarding sustainability. Even if the fashion industry is conscious of the value of being green, operational costs and economic performance are considered obstacles (Tebaldi et al. 2022).

An essential aspect of life cycle studies in the fashion sector is the availability of a comprehensive database. Munasinghe et al. (2021) reported that most studies do not follow the complete life cycle chain and proposed mapping sector's life cycle assessments (LCA) through a systematic literature review and further adjust the information found by meta-analysis extraction into a single functional unit regarding their energy and water use, and GHG emissions. The authors found that recycled cotton and flax have the lowest impact, while the dyeing process substantially increases the environmental burden of any item (Munasinghe et al. 2021). From their research, Munasinghe et al. concluded that most LCA focus on the raw material extraction phase as a critical step and found research gaps in non-woven fabric production, fabric and clothing manufacturing (smart textiles), retailing, dry cleaning, ironing, use phase (with wide variance in brands standards and users' behaviors), and landfill steps.

However, research studies have shown that a company's specific environmental impact depends on the firm's characteristics and product. Indeed, the fashion sector can be divided into two segments. "Fast Fashion" is commonly associated with excessive emissions (Cegarro-navarro and Buzzi 2021; Peters et al. 2021) since the large-scaled collections are produced with high frequency (Kozlowski et al. 2014), using materials and labor (Claudio 2007; Kozlowski et al. 2014; UNEP 2018) from poorly regulated countries (Niinimäki et al. 2020), (Lenzo et al. 2018), and have a short lifespan (Cimatti et al. 2017; Claudio 2007; EPRS 2019), generating vast amounts of waste. This market segment meets customers who cannot afford high-end products and consume low-durability items in more quantities (Cimatti et al. 2017; EPRS 2019). On the other hand, "Slow Fashion" (Cimatti et al. 2017) concept is expanding among retail companies, pushed by the younger consumers' demands (Cegarro-navarro and Buzzi 2021; Gazzola et al. 2020; Kim et al. 2021), and costumers' sense of identity and ownership (Castagna et al. 2022). The mindset is to reduce the production scale by endorsing local materials and crafting (EPRS 2019), substituting materials for less impacting ones (Kozlowski et al. 2014), or even using materials and design solutions that would facilitate their recycling processes (Peters et al. 2018). Allied to these practices, extending the outfits' lifespan is highly recommended (Abdelmeguid et al. 2022).

In this view, the luxury market, which is often responsible for establishing trends, could play a significant role in boosting the sector's overall sustainability. Indeed, innovative apparel industries continuously develop strategies for optimizing non-core activities and creating new materials to meet their concerns (Adıgüzel and Donato 2021). The most updated concept of luxury is associated with a unique customer experience besides quality, tradition, and style (Brun et al. 2008). Moreover, the goods' high-quality materials, traditional craftsmanship, and extended durability are compatible with sustainable practices. Therefore, it can play a vital role in the sustainability pattern, particularly since, according to Adıgüzel and Donato (2021), the younger generations, responsible for 85% of global luxury demand growth, are deeply concerned about sustainability. Kim et al. reported that around half of the Millennials and Generation Z would spend an extra 10% or more on sustainable products. The businesses are also moving towards services that can add value beyond fabricated goods, such as clothes rentals (Johnson and Plepys 2021), online second-hand shops, upcycling, recycling, etc. Since brand reputation and continuity are critical aspects of business progress (Brun et al. 2008; Cegarro-navarro and Buzzi 2021), it seems inevitable that sustainability is on the apparel sector's agenda (Muthu 2020).

Finally, Brun et al. (2008) underlined the value of the product's geographical origin, making Italy an industry reference. Italy is the first European country in the personal luxury goods market worth 19 billion euros (Coppola 2020), led by multi-brands companies such as Luxottica, Gucci, Prada, Armani, and Max Mara. According to Fashion United (2020), Italy's clothing and textile sectors employ 350,000 people. Besides these large groups, the sector comprises smaller enterprises (Brun et al. 2008) that usually involve local companies strongly connected to the region's economy. The environmental impact of these smaller realities is often difficult to map and quantify and yet of paramount importance given the large numbers involved.

In this view, the present study presents the complete inventory of the 2019 operations of a traditional slow fashion small-to-medium enterprise based in central Italy (Umbria) and the corresponding GHG emissions with insights on improving its environmental performance. The case of the luxury garment brand is representative of the small-scaled players capable of establishing changes. Moreover, it is particularly relevant for its geography, integration with the community, and influence in counter hand of the perverse dispersed production chain and low-labor-cost business model. The base year was selected as representative before the pandemic slowdown of the production.

According to the Directorate-General for Environment of the EU Commission, Greenhouse Gas Protocol is the most widely employed international accounting tool for quantifying emissions (European Commission 2021). The ISO 14064: 2019 (ISO 2019) specifies the framework for quantifying inventory and reporting an organization's greenhouse gas emissions. The revision, which replaces the 2006 version, divides emissions into six categories instead of the previous three scopes. These categories are divided into direct GHG emissions and removals and indirect GHG emissions from energy, transportation, products used by the organization, the use of products from the organization, and other sources.

2 Methodology

The ISO 14064–1:2019 methodology was employed to quantify GHG emissions of a small-to-medium fashion enterprise based in central Italy (Umbria) during the product's complete life cycle stages. The study applied an attributional approach in accordance with ISO 14044:2006 and ISO 14046:2014 (detailed in the following sections), carried out at the company level from the cradle to the grave (Muthu 2014). Therefore, the emissions are not confined to the factory emissions, including product performance during its use and disposal phases. Boundaries were defined after a site visit and meetings allowing us to understand the operations.

Documents, bills, and other factory detailed data were collected to construct a complete inventory of the industry's inbound and outbound fluxes. The use and end stage were estimated according to general recommendations from the company specialists and complementary literature research. The corresponding input from the ecoinvent database was used considering local Italian geographical boundaries. When not available, European or Global datasets were employed. The calculations were carried out using the SimaPro 9.1.1.1 software, loaded with ecoinvent 3.6 (Wernet et al. 2016), and the cut-off system approach, which assigns emissions to the primary user, i.e., recycled items are considered burden-free.

The potential GHG emissions were classified and processed in six categories (ISO 2019):

Direct GHG emissions and removals
Indirect GHG emissions from imported energy
Indirect GHG emissions from transportation
Indirect GHG emissions from products used by the organization
Indirect GHG emissions associated with the use of products produced by the organization
Indirect GHG emissions from other sources

All the impacts were also calculated in aggregate, and subcategories were created as recommended by ISO 14046 for better visualization and comparison purposes (ISO 2019).

2.1 Goal and scope

This study aimed to measure direct and indirect GHG emissions related to a luxury fashion factory production and distribution activities in 2019. The unit has 166 employees and exports around 72% of its production to 40 countries.

Its stores are divided into “shop in shop” (2 in Italy, 12 in Europe, 2 in the USA, and 40 in Asia) and flagship stores (5 in Italy, 13 in Europe, 1 in the USA, and 2 in Asia). The business core is its cashmere products, and the company usually produces two labels and two collections per year for a total of about 1600 items. The goal was to (i) identify the most important emission sources and propose improvement strategies to reduce the company’s environmental impact, (ii) compare the obtained environmental impact of the small-to-medium company with reference to large enterprises, and (iii) uncover the connections with local smaller companies that benefit from the company’s existence.

2.2 Boundaries

Impacts were reported for 1 year of a luxury fashion company production, which corresponds to 485,193 garments among dresses, coats, shirts, trousers, knit, bags, shoes, and others. The entire list of items produced can be found in Table 3 in the Appendix.

The boundaries (Fig. 1) were limited to the organization’s operational control criteria (ISO 2019). Therefore, the system considers raw materials’ production and transportation from the supplier to the factory, and the transportation of the raw material and semi-finished products within the company production chain, including all sorts of packaging and related transportations. Retail shops were excluded due to the inherent difficulty in accurately specifying their operations.

Also, the factory’s electricity and methane consumption are included, along with impacts related to company vehicles, work visits, employees’ transportation (estimated), and visitors to the outlet retail unit within the factory (estimated). Transportation of returns managed by the company, waste treatment and transportation to the disposal site, and estimated washing and storage of the product during its use and end-of-life are also considered.

The company’s production system follows the research findings of Brun et al. (2008), to ensure the consistent delivery of high-quality products. Internally, the company handles every aspect of the production process, including design, material selection, and prototype creation. Skilled Italian artisans are exclusively responsible for crafting the collection, with a significant portion of production taking place in the Umbria region. The sourcing of materials predominantly involves Italian companies, as depicted in Fig. 2. However, due to the extensive range of components used, determining the exact origin of all raw materials is impractical. To address this, a combination of European or global mixes was chosen to prevent underestimating emissions. Although this decision introduces some uncertainty in emission factors associated with specific countries, individually assessing each country was not feasible. As a result, emission factors representing a European or global average were utilized to avoid underestimations.

It is worth noting that different countries have varying regulations, leading to diverse practices that impact the overall performance of the finished garments. Notably, a small percentage of the finished textiles (2.6%), yarn (0.2%), and leather (8.1%) are explicitly identified as sourced from abroad. To maintain stringent quality control, the company incorporates transportation for every raw material used during the production process.

2.3 Company inventory

In the Appendix section (Table 3), we present the data collected with the specific source. The company inventory was built by using the following inputs from the company:

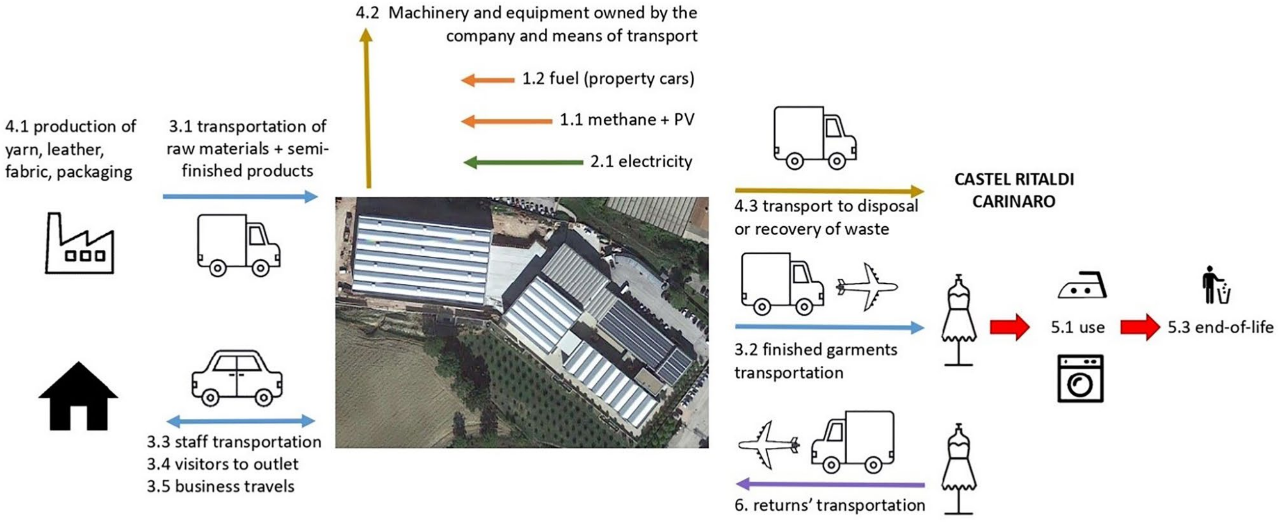

Fig. 1 System boundaries scheme, numbers correspond to ISO categories

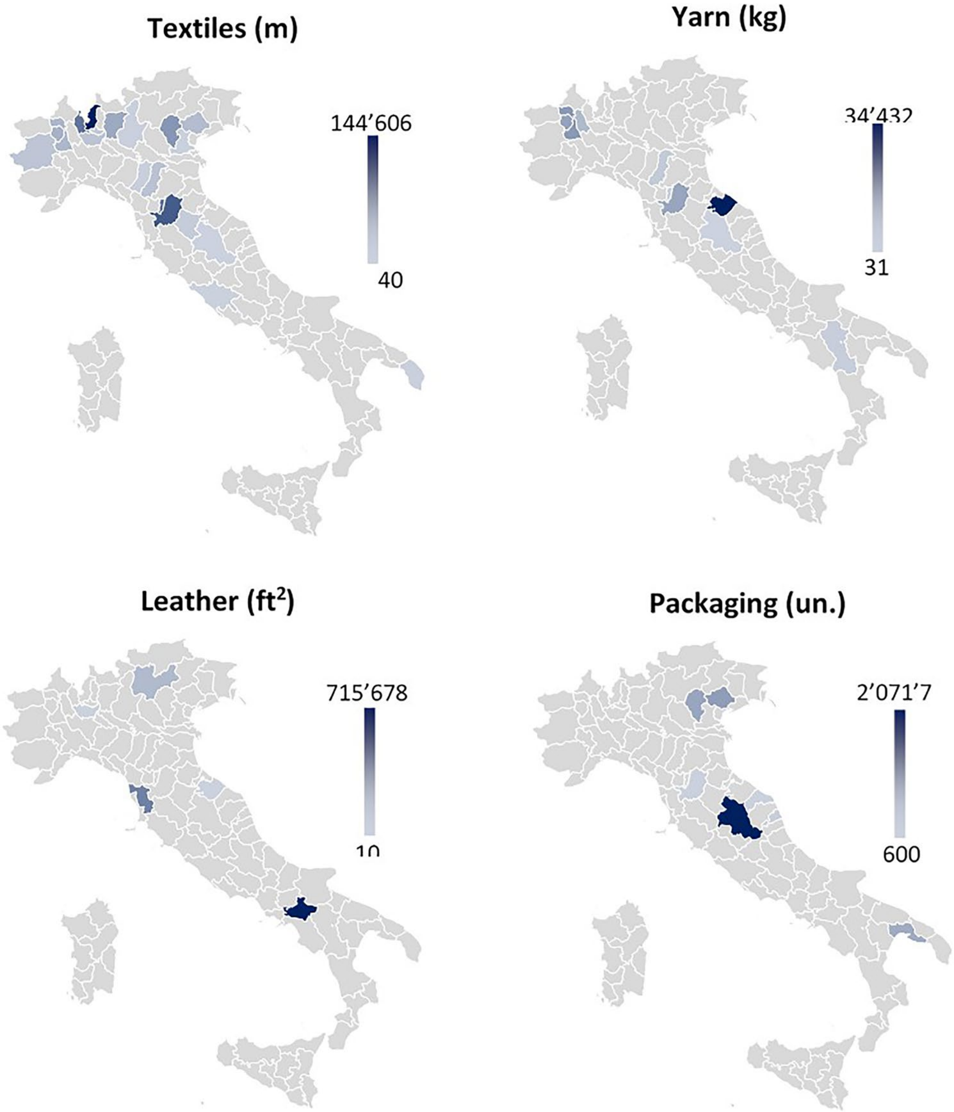

Fig. 2 Suppliers' locations and material amounts according to data provided by the company

Electricity, fuel, and gas bills
The waste Environmental Declaration
A list of their purchased materials (yarn in kg, leather in ft^2, textiles in m^2, packaging in unit) with supplier's names and material's specifications;
A list of all hired shipping with origin and destination, from which we identified raw materials, semi-finished products, finished materials, and returns
The inventory of their building structure, fleet, and machinery
Staff's average daily distances with the corresponding means of transportation
Receipts to estimate the amount of outlet visitors
Garment production data (number of pieces, average weight, typology)
Products expected lifespan
Recommendations for the use stage such as washing and ironing requirements

Category 1 accounted for the methane consumption, the production and consumption of photovoltaic energy (1.1), and the fuel consumed by the company's property cars (1.2) from billing. Category 2 considered the imported energy consumption (2.1), including the losses as collected from the electricity bills.

Category 3 represents the collection of the most significant indirect emissions, selected in accordance with the guidance outlined in ISO 14064–1:2019 (ISO 2019). The selection process carefully considered the intended use of the GHG inventory, as described in Sect. 2.1. To evaluate the significance of indirect emissions, specific criteria were established based on the principles of relevance, completeness, consistency, accuracy, and transparency. The primary focus was on identifying emissions with a substantial quantitative magnitude. To identify and assess the categories of indirect emissions, a rigorous screening process was undertaken, involving the expertise of both internal and external specialists, sector-specific guidance, literature reviews, and third-party databases. Particular attention was given to the magnitude of GHG emissions associated with each category. The defined criteria were then applied to select the significant indirect emissions, taking into account various factors such as estimated magnitude, data accuracy, cost, as well as other criteria including risk, opportunity, and user needs. This thorough and comprehensive evaluation process allowed for a justified determination of the significance of both indirect emissions and removals.

As a result, the impacts identified in category 3 encompassed a range of indirect emissions from various sources. These included third-party fleet transportation of textiles to artisans (3.1) and of finished products to retail (3.2), transportation of employees (3.3), transportation of outlet visitors and business travels (3.5). Subcategories 3.1 and 3.2 meticulously track the impact of shipping services, utilizing documentation provided by the three couriers utilized by the company. This documentation detailed crucial information such as origin, destination, weight, and type of expedition. To determine transportation typologies, the ecoinvent database was consulted, taking into consideration factors such as distance, weight, and the information available on each courier's website. Transport between shops was excluded from consideration as it is managed directly by the retailers themselves.

Regarding the transportation of clients to other shops selling the products, this aspect presents a complex and multifaceted information. The company's retail shops are situated in diverse settings, including commercial streets without car access, department stores, and shopping malls. Evaluating the transportation of clients to all these locations would involve accounting for a wide range of transportation modes and travel distances. Given the intricacies and variations involved, the decision was made to exclude this aspect from the study in line with the selection criteria for indirect emissions. Although this decision may have some influence on the results, attempting to account for all possible scenarios would introduce significant complexity and uncertainty.

Subcategory 3.3 encompasses and quantifies the environmental impacts associated with the daily commuting of the 166 employees at the production site. The estimation of indirect emissions was built based on specific information provided by the company and considered the average distance traveled twice per day (18.32 km) for 233 days by 80% of employees commuting daily to work by car, while the remaining 20% were assumed to make four trips per day of the same length. The original model considers the process "market for transport, passenger car RER," which assumes the use of an ideal car for which a weighted final impact is calculated, taking into account the prevalence of internal combustion engines and electric motors in Europe. The selected process represents an average impact calculated by considering different car classes (EURO 3, EURO 4, and EURO 5), various engine sizes (small, medium, and large), and different types of fuel (gasoline, diesel, and natural gas). The weighting of impacts associated with electric cars is based on a medium-sized vehicle. In 2019, the outlet store located at the factory building received 3005 visitors, as documented by receipts. An average distance input of 300 km, representing a round trip from Rome to the retail outlet, was assumed. The same journey was considered for visitors from outside Italy, assuming Rome to be the primary destination. Since the means of transportation were unknown, the study utilized the Market for transport in passenger car in EU as an estimation of the fleet mix. It is important to note that in this case, the primary travel motivation for visitors to the retail outlet was not considered.

Category 4 listed all indirect impacts associated with the products used by the organization: raw materials (yarn, leather, textiles) and packaging purchased (4.1), company-owned machinery (4.2), waste treatment (4.3), transportation of non-core services (4.5). Yarn and textile composition was assumed according to the suppliers and the company information. The yarn was firstly reported by weight, while textiles and leather by area. Therefore, both these data were converted to weight values for better readability and comparison. As found in the literature, yarn and textile dyeing were considered equal to 50% of the total weight purchased (Beton et al. 2014). The weaving process was modeled using the "Weaving, synthetic fiber {GLO}, weaving of synthetic fiber, for industrial use, Cut-off, U" process on the ecoinvent. This process was included for elastin, polyester, acrylic, polyamide, viscose, and wool—including cashmere and merino wool. The company provided detailed data regarding their machinery, which was also checked during the field visit. Waste amounts, typology, and destination were documented in an Environmental Declaration form. Finally, extra transportation was obtained from the delivery services documents that specified origin and destination.

The use phase scenario in category 5 encompassed various activities such as washing, drying, and ironing (5.1). To determine the end-of-life scenario (5.3), we referred to the CONAI 2019 report on the treatment of unsorted waste in Italy (ISPRA 2013). Our calculations were based not only on relevant literature but also primarily on the company's indications regarding the estimated lifespan and recommended usage for each product type. The end-of-life stage was defined as the product being treated as unsorted waste once the use phase concluded, without any recycling considered. In Table 4 in the Appendix, we have presented the information provided by the company regarding the average weight of each product, the estimated lifespan in years, seasonal use, and washing recommendations (frequency of washing). Table 5 in the Appendix provides the company's information regarding the washing and ironing methods specific to each product type. To estimate ironing time and energy consumption, we referred to the study by Beton et al.

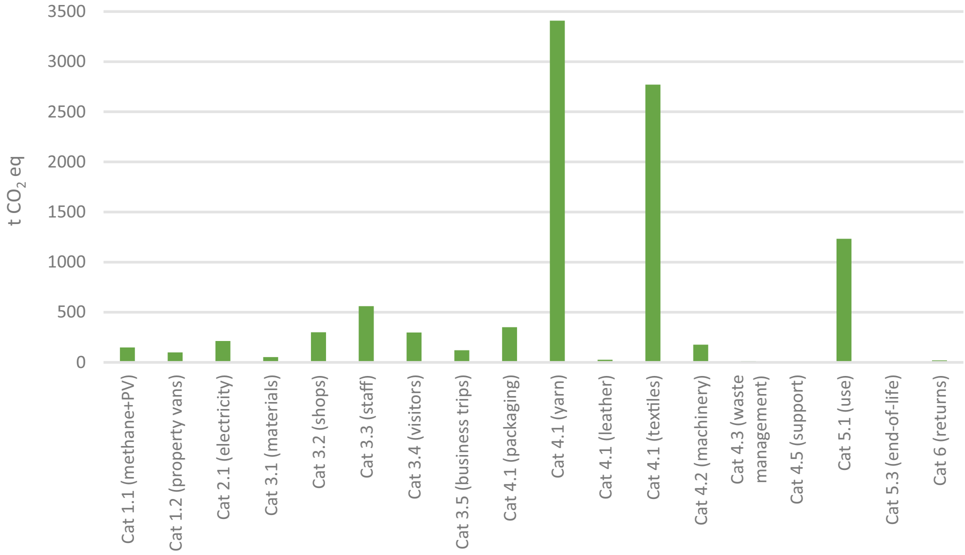

Fig. 3 Total emissions in 2019 detailed by subcategories

(2014). Notably, the calculation did not include the impact of the home-laundry journey. The electricity consumption for washing and ironing tops, pants, skirts, and knits was calculated by considering half the impact of dry cleaning and half the impact of washing by hand or in a washing machine.

Category 6 considered transporting finished and unsold products back to the company. The evidence is the courier's shipping list with retail as the collection point and the factory headquarters as the destination address.

3 Results and discussions

The total GHG emissions were 9804 t CO$_2$ eq. Most of the emissions (68.9%) derive from category 4 (indirect GHG emissions from products used by the organization), followed by category 3 (indirect GHG emissions from transportation 13.6%), and category 5 (indirect GHG emissions associated with the use of products produced by the organization) amount to 12.6%. Similar literature studies for larger enterprises (Høst-Madsen et al. 2014) also show the prevalence of material production emissions, with the largest impacts found in tailoring (24%) and raw material production (39%).

Figure 3 shows the main contributors to subcategory 4.1, where yarn is responsible for 34.8% and textiles responsible for 28.3% of the overall impacts generated by category 4. The use phase (subcategory 5.1) accounts for 12.6% of the total. However, this category varies significantly based on consumer habits. Therefore, the use step is often excluded from thematic reports such as the Environmental Profit & Loss, the Danish apparel sector natural (Høst-Madsen et al. 2014), and the PUMA Carbon Footprint (Puma 2018). The Environmental Assessment of Swedish fashion consumption (Sandin et al. 2019) made several assumptions regarding user behavior, including the number of uses and washes, washing methods, transportation means and distances, and lifespan. The study also developed various scenarios based on these assumptions. Similarly, the Business for Social Responsibility report (Business for Social Responsibility 2009) highlighted the impact of user behavior on energy consumption during the use phase. Munasinghe et al. (2021) expressed similar concerns about this phase, emphasizing how the frequency of washing can affect the lifespan of a product. Interestingly, the Sandin et al. (2019) report identified the use phase as the primary source of emissions, while raw materials were found to have the second-largest impact, which contrasts with other studies. According to the International Carbon Flows report, approximately 50% of the emissions associated with a cotton t-shirt occur during the use phase. It is conceivable that the analyzed fashion products utilize materials with a higher environmental impact, and it is likely that the garments receive more appropriate care due to their economic value.

The most used product among yarns is wool (regular, cashmere, and merino), with 64.7% of the total purchase in weight. Mainly associated with sheep farming and fiber cleaning, it corresponds to 74.6% of emissions. Generally speaking, this is a good result since wool is recognized as versatile, durable, and has low washing requirements (Wool LCA Technical Advisory Group 2016; Wiedemann et al. 2020). Wiedermann et al. (2020) highlighted that Australia, New Zealand, South America, and South Africa produce the finest quality wool. However, there are gaps in research regarding the long extension of the wool chain (Wool LCA Technical Advisory Group 2016). Wool production starts on farms in around 100 countries, while wool processing takes place in other countries such as China, Italy, and the UK, and often manufacturing of the fabric and apparel is done in Asian countries (Wool LCA Technical Advisory Group 2016).

The second most purchased product is cotton (13%), followed by silk (7%). However, silk is the second major contributor with a total of 661.3 t CO_2 Eq. (19.4%). Cotton is the third product in emissions with 50.6 t CO_2 eq or 1.5%. According to Muthu, cotton cultivation demands water, energy, land, fertilizers, and chemicals, resulting in sensible alteration of different environmental aspects and human health (Høst-Madsen et al. 2014; Muthu 2020).

The most purchased textiles are wool (regular, cashmere, and merino) (23%), followed by organic cotton (19%), and regular cotton (11.4%). Silk is the fifth most used textile in weight (9.3%) but is the first one in emissions with 1153.5 t CO_2 Eq. (41.6%), followed by wool (regular, cashmere, and merino), with 40.3%. Long silk fibers that form the yarn (Astudillo et al. 2014; Munasinghe et al. 2021) have a greater environmental impact compared to other fibers. Regarding silk production, Muthu (2020) highlighted that despite the pros of planting mulberry trees, there are adverse outcomes from using fertilizers, pesticides, emissions on water due to degumming, and the use of formalin and bleach powders, energy, water, and chemicals in the reeling step.

Quantis (2018) report found that 36% of the GHG emissions during material preparation occur during the dyeing and finishing step, 28% during yarn preparation, 15% during fiber production, and 12% during textile production. Assembly, distribution, and disposal correspond to the rest of the emissions. Bevilacqua et al. (2011) demonstrated a prevalence of emissions on electrical and thermal energy and transportation during the textile production chain. In part, the differences can be attributed to the region where the material is produced, impacting the energy mix and waste treatment (Quantis 2018). The LCA for five garments in Sweden (Roos et al. 2015) resulted in most emissions during the fabric production, followed by the use phase and fiber production. The Fashion on Climate report pointed out that more than 70% originated from upstream activities (38% from material production, 8% from yarn preparation, 6% from textile preparation, 15% from wet processes, 4% from cutting), 20% during the use phase, 6% from transport and retail, and 3% for the end of use (Berg et al. 2020).

4 Sensitivity analysis

4.1 Analysis of alternative scenarios

Scenario analysis was implemented to evaluate mitigation planning. Local sensitivity analysis (Igos et al. 2019) was performed for the most impactful categories varying a single input simultaneously. Simulations assumed emission reduction strategies from upstream operations, consumers' habits, and downstream operations. The first strategy (scenarios 1, 2, and 3) consisted in implementing different raw material content as recycled inputs and partially substituting high-impacting materials with similar ones. The second strategy (scenario 4) relates to consumer behaviors at the use stage. The third strategy (scenarios 5 and 6) considered remodeling systems that are not directly connected to the business value-creation, such as employees' transportation and packaging inputs. Table 1 resumes the six investigated alternative scenarios.

4.1.1 Upstream operations scenarios

Textile selection is a critical area with significant potential for mitigation opportunities (Munasinghe et al. 2021). To explore these opportunities, alternative strategies were examined by focusing on different material compositions and comparing them to the original scenario (SO). The investigation specifically looked into various mixtures of wool, silk, and different types of silk fibers, as these inputs were found to contribute significantly to the company's overall environmental impact. Similar strategies involving the partial use of recycled materials and material substitution have been reported in studies by Quantis (2018), Moazzem et al. (2021), and Roos et al. (2015).

Alternative scenario 1 (SA_1) involves substituting 30% of virgin wool with recycled wool. In this scenario, the emissions associated with the use of new wool are reduced to 39.71 kg CO_2 eq/kg, considering recycled materials as burden-free according to the polluter pays principle introduced in the Product Category Rules (PCR) for construction products and services (EPD 2018), all the impacts due to the upstream processes are imposed to zero. On the

Table 1 Summaries of scenarios

Scenario	Description	Life cycle stage
1	Substitution of 30% virgin wool for recycled wool, considered as burden-free	Upstream operation
2	Long-fiber silk was replaced by a mixture of long (70%) and short-fiber silk (30%)	Upstream operation
3	50% reduction of silk and wool + increase in viscose and cotton	Upstream operation
4	10% reduction of the washing frequency	Use phase
5	Change of packaging inputs for sustainable alternatives	Downstream operation
6	50% of car-pooling + 50% fleet substitution to electric cars	Downstream operation

other hand, alternative scenario 2 (SA_2) compares the original long-fiber silk with a mixture of 70% long-fiber silk and 30% short-fiber silk. As a result, the impact of silk yarn decreases from 134.25 kg CO_2 eq/kg to 94.25 kg CO_2 eq/kg. Figure 4a demonstrates the significant sensitivity of the model, and particularly of category 4.1, to these parameters, which were initially assessed based on the information provided by the company. Combining these two scenarios could potentially reduce the company's overall impact by approximately 937.8 t CO_2 eq: 739.4 t CO_2 eq for SA_1 and 198.4 t CO_2 eq for SA_2.

Lastly, alternative scenario 3 (SA_3) proposes the partial substitution of silk and wool with low-impact alternatives. Specifically, SA_3 simulates a 50% reduction in the weight of silk and wool, with a corresponding increase in the use of viscose (a semi-synthetic fiber that can be used as a substitute for silk) and cotton (as a replacement for wool). Figure 4b illustrates a 37% reduction in the 4.1 category emissions in this new scenario, corresponding to a total reduction of 1,031 t CO_2 eq for these two components.

4.1.2 Consumers' habits scenario

The use phase of the garments exhibits large variability (Munasinghe et al. 2021; Muthu 2020; Quantis 2018; Wiedemann et al. 2020). Consumer habits, brand recommendations, and geographical factors contribute to this variability (Claudio 2007). Literature suggests that customers' care practices have a significant impact on the overall life cycle emissions (Moazzem et al. 2021). Abdelmeguid et al. (2022) consider these habits as a "soft aspect" that should be addressed before tackling structural challenges in the industry, such as innovation, regulation, stakeholder engagement, and financial pressures.

The original scenario was developed considering average garment weights for various types (e.g., jackets, trousers, dresses), washing, drying, and ironing recommendations, estimated washing frequency, and the expected lifespan provided by the company (refer to the Appendix). The emissions attributed to this phase represent a somewhat overestimated situation, in line with the findings of Roos et al. (2015). According to the Climate on Fashion report, the use phase is responsible for 20% of the overall emissions.

For the slow fashion segment, longer garment lifespans result in increased washing frequency. Water consumption, detergent type and quantity, and drying energy were determined based on data from the ecoinvent database, while ironing time per garment and iron energy consumption were obtained from the literature (Thomas et al. 2012b). Alternative scenario 4 (SA_4) considers a conservative 10% reduction of the washing frequency, assuming that garments are handled according to brand instructions despite the associated high cost. The results, which were recalculated based on linear proportionality, indicate emissions of 123.35 t CO_2 eq., accounting for 1.25% of the total emissions.

4.1.3 Downstream operation scenarios

Scenario 5 (SA_5) considered the change of packaging inputs for possibly more sustainable alternatives. Table 2

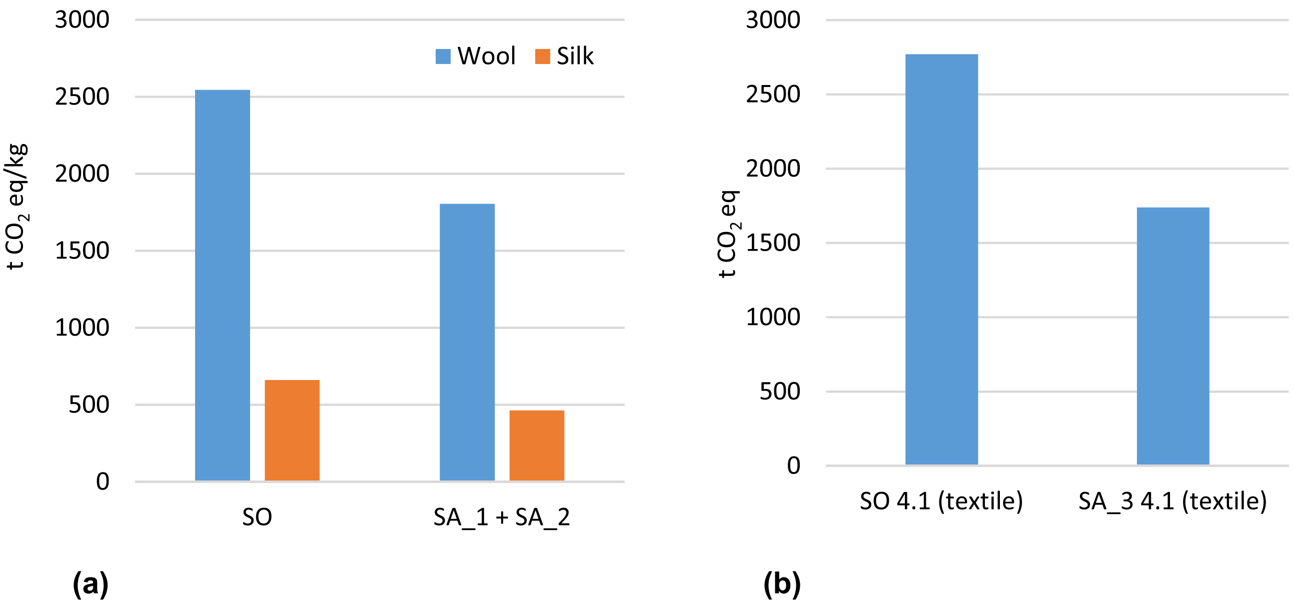

Fig. 4 **a** Environmental impact for category 4.1, scenarios 1 and 2: wool recycled content addition, and silk yarn composition modification. **b** Environmental impact for category 4.1, scenario 3: wool and silk substitution scenario

Table 2 Scenario 5 summary

Original input	Modified input for scenario 5
Paper, woodfree, coated {RoW}, market for, Cut-off, U – (0% recycled, 90% from chemical pulp)	Graphic paper, 100% recycled {RER}, production, Cut-off, U
Corrugated board box {RER}, production, Cut-off, U – (94% recycled)	Containerboard, fluting medium {RER}, containerboard production, recycled, Cut-off, U
Solid bleached board {RER}, production, Cut-off, U – (0% recycled)	Solid unbleached board {RER}, production, Cut-off, U
Paper, woodfree, coated {RER}, paper production, woodfree, coated, at integrated mill, Cut-off, U – (0% recycled, 90% from chemical pulp)	Paper, woodfree, uncoated {CA-QC}, paper production, woodfree, uncoated, 100% recycled content, at non-integrated mill, Cut-off, U

summarizes the main modifications with respect to the reference scenario.

The first substitution is related to the paper tags originally modeled as "Printed paper, offset {RoW}, offset printing, per kg printed paper, Cut-off, U," i.e., considering brand new paper with no recycled content, although made of woodfree paper, containing at least 90% of the fibers in form of chemical pulp. SA_5 considers 100% recycled graphic paper in substitution for the original input.

The second input modification refers to cardboard boxes used for protecting the garments for shipping. Also in this case, it was assumed that 100% of the corrugated board box was produced using recycled materials. Similarly, SA_5 also considered a 100% recycling rate for the lighter paper used in fine bag packaging.

Finally, the rigid solid bleached board paper used for fine packing was substituted with an unbleached board. The simulation results showed a reduction of 6.56 t CO_2 eq emitted, shown in Fig. 5a.

The alternative scenario 6 (SA_6) proposes modifications to subcategory 3.3, i.e., employee commuting. The original scenario considers the ecoinvent process "market for transport, passenger car RER" that includes a mix of EURO 3, EURO 4, and EURO 5, sizes, and fuel types. SA_6 considers the practice of car-pooling for 50% of the commuters and the substitution of % of the fleet to electric cars, which reduces 66% of the impacts (368 t CO_2 eq) compared to the original scenario (Fig. 5b).

The implementation of all six strategies together, as in Fig. 6, could reduce the emissions from 9804 t CO_2 eq (scenario SO) to 7338 t CO_2 eq (alternative scenarios SA), or 25%.

4.2 Limitations of the study

The limitations of this work, like in other life cycle assessment studies, mostly concern the simplifications and data used for the calculations and modeling choices (Dahllöf, 2004; Muthu 2014). High-quality primary information was obtained from the company, but information regarding transportation means, the origin of the products within a long production chain (Lenzo et al. 2018; Muthu 2020; Niinimäki et al. 2020; United Nations 2020), and the electric energy required for producing the textiles were estimated based on the assumptions declared in this document. The calculations were based on the ecoinvent database, which also has gaps in this industry typology. Additionally, the use and disposal steps are subject to many variables and uncertainty.

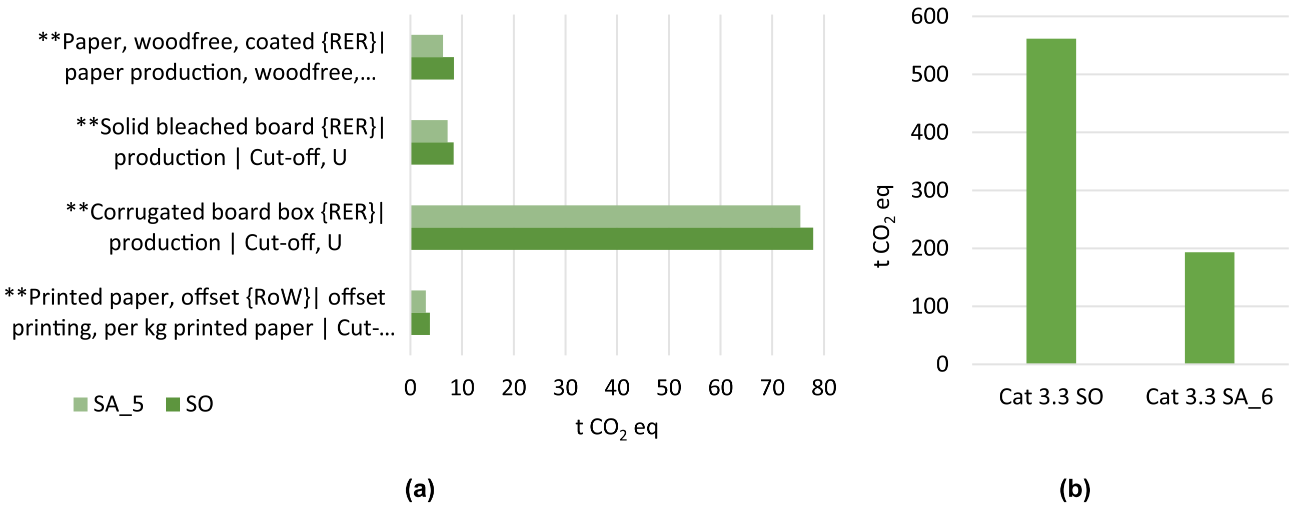

Fig. 5 **a** Scenario 5, subcategory 4.1, packaging material alternatives. **b** Scenario 6, subcategory 3.3, alternative employee's transportation

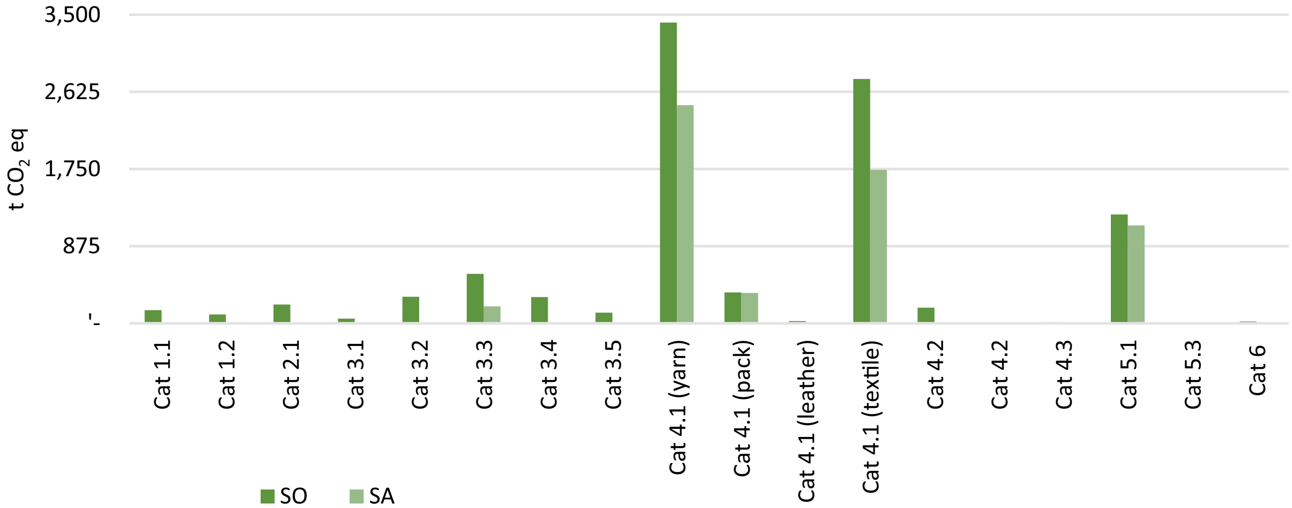

Fig. 6 Combination of all scenarios proposed

5 Conclusions

The United Nations established that member States must reduce global carbon emissions by 45% from 2010 levels by 2030. In a context where the business's reputation and the continuity of its operations depend on achieving these goals, decarbonizing supply chains, quantifying, and reporting their performances is critical for emissions reduction. The luxury sector's role in setting trends and negotiating power within the supply chain can guide the industry towards sustainability.

This study concerns the calculation and analysis of the GHG emissions of an Italian luxury fashion company, as representative of many small-to-medium enterprises that must face the ecological transition of the global market while preserving the intrinsic value of local artisanal production. The aim is to identify the most significant sources of emissions and propose appropriate mitigation strategies while maintaining the unique network of local producers and artisans involved in the sector.

The study identified cumulative emission of approximately 9804 t CO_2 eq. Category 4, which encompasses all indirect emissions resulting from products and materials directly used by the organization, accounted for the highest emissions (71%). In more detail, the analysis of the subcategories highlighted the predominant role of category 4.1 (production of the raw material and packaging), accounting for 69% and is directly related to the market segment where consumers perceive the value of the product.

Since the production of the raw materials is resource-demanding and, associated with their transportation (also among the manufacturers), produces most of the emissions, the extended lifespan of a high-quality product is aligned with the sustainability practices even if it has an impact the use phase. During that stage, the high variability can be managed through consumers' awareness of reducing emissions during the use and prolonging the products' life.

A dedicated analysis of possible alternatives can support strategies to reduce the company's impacts. Actions can be applied in the whole operations chain. While aggressive changes can be made in non-core activities with excellent results, such as energy sources and transportation mean, the changes perceived by customers can also be desirable to showcase innovation and advancements in the business mindset.

The company has already implemented several actions to reduce its environmental impact, and the present work is part of this strategy. For example, the company relies on optimized systems to forecast sales and minimize returns or over-production, besides automated storage, ensuring that stocks are fully mapped. Furthermore, the company is improving the use of organic cotton and natural cashmere, substituting regular plastic bags with biodegradable ones. In addition, the renewable energy use in their plant will be incremented.

Further studies, with detailed product mapping, could include a social hotspot assessment as the company aims the value of the local supply chain. Additionally, this study could be extended to trending strategies such as upcycling and clothing library initiatives, i.e., practices that prolong the life of garments.

Appendix

Table 3 Inventory and data sources

Subcategory	Description	Quantity	Unit	Data source	Primary	Secondary	Proxy
1.1	Natural gas, high pressure (IT), market for, Cut-off, U (higher calorific value of 38.52 MJ/m3)	5.49E+04	m^3	Billing	x		
1.1	Heat, district or industrial, natural gas (Europe without Switzerland), market for, Cut-off, U	2.11E+06	MJ	Billing	x		
1.1	Electricity, low voltage (IT), electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted, Cut-off, U	1.11E+04	kWh	Company	x		
1.2	Diesel (Europe without Switzerland), market for, Cut-off, U (density of 0.85 kg/l)	2.25E+04	kg	Receipt	x		
1.2	Energy, from diesel burned in machinery/RER Energy	2.30E+08	kcal	Receipt	x		
2.1	Electricity, low voltage (IT), market for, Cut-off, U	5.14E+05	kWh	Billing	x		
3.1	Market for transport, freight, lorry 3.5–7.5 metric ton, (RER), EURO4, Cut-off, U	1.05E+08	kgkm	Billing + delivery company + SimaPro	x	x	
3.2	Market for transport, freight, lorry 3.5–7.5 metric ton, EURO4, (RER), Cut-off, U	5.65E+08	kgkm	Billing + delivery company + SimaPro	x	x	
3.2	Market group for transport, freight, light commercial vehicle, (RER), Cut-off, U	6.55E+05	km	Billing + delivery company + SimaPro	x	x	
3.2	Market for transport, freight, lorry 7.5–16 metric ton, EURO4, (RER), Cut-off, U	3.30E+07	kgkm	Billing + delivery company + SimaPro	x	x	
3.2	Market for transport, freight, aircraft, unspecified, (GLO), Cut-off, U	1.43E+07	kgkm	Billing + delivery company + SimaPro	x	x	
3.3	Transport, passenger car (RER), market for, Cut-off, U	1.70E+06	km	Company	x		
3.4	Transport, passenger car (RER), market for, Cut-off, U	9.02E+03	km	Receipts + assumption	x		x
3.5	Transport, passenger car (RER), market for, Cut-off, U	3.65E+04	km	Receipt	x		
4.1	Bio—Yarn, cotton (RoW), production, open end spinning, Cut-off, U	8.51E+02	kg	Receipt + supplier website	x	x	
4.1	Bleaching and dyeing, yarn (RoW), Cut-off, U	3.51E+04	kg	Receipt + literature	x	x	
4.1	Elastane fiber production (polyurethane added dry spinning)	5.65E+02	kg	Receipt + supplier website + literature	x	x	
4.1	Fiber, flax (RoW), fiber production, flax, retting, Cut-off, U added spinning	1.85E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Fiber, polyester (RoW), polyester fiber production, finished, Cut-off, U	1.42E+03	kg	Receipt + supplier website	x	x	
4.1	Fibee, viscose (GLO), fiber production, viscose, Cut-off, U added spinning	1.76E+03	kg	Receipt + supplier website	x	x	
4.1	Metallic yarn	1.41E+02	kg	Receipt + supplier website + literature	x	x	

Table 3 (continued)

Subcategory	Description	Quantity	Unit	Data source	Primary	Secondary	Proxy
4.1	Polyamide fiber production (nylon added melt spinning)	4.23E + 02	kg	Receipt + supplier website + literature	x	x	
4.1	Wool fiber (with spinning), scouring and combing	4.54E + 04	kg	Receipt + supplier website + literature	x	x	
4.1	Yarn, cotton (RoW), production, open end spinning, cut-off, U	9.11E + 03	kg	Receipt + supplier website	x	x	
4.1	Yarn, silk (RoW), yarn production, silk, long-fiber, cut-off, U	4.93E + 03	kg	Receipt + supplier website	x	x	
4.1	Bitumen adhesive compound, cold (GLO), market for, cut-off, U	2.00E + 01	kg	Receipt + supplier website	x	x	
4.1	Bitumen adhesive compound, hot (RER), production, cut-off, U	3.10E + 01	kg	Receipt + supplier website	x	x	
4.1	Cleft timber, measured as dry mass (DE), hardwood forestry, oak, sustainable forest management, Cut-off, U	7.01E + 02	kg	Receipt + supplier website	x	x	
4.1	Corrugated board box (RER), production, Cut-off, U	8.78E + 03	kg	Receipt + supplier website	x	x	
4.1	Fiber, polyester (RoW), polyester fiber production, finished, cut-off, U	4.15E + 03	kg	Receipt + supplier website	x	x	
4.1	Injection molding (RER), processing, Cut-off, U	1.71E + 04	kg	Receipt + supplier website	x	x	
4.1	Limestone, crushed, washed (RoW), production, Cut-off, U	7.64E + 02	kg	Receipt + supplier website + literature	x	x	
4.1	Packaging film, low-density polyethylene (RER), production, Cut-off, U	9.10E + 02	kg	Receipt + supplier website	x	x	
4.1	Paper, woodfree, coated (RER), production, at integrated mill, Cut-off, U	8.17E + 03	kg	Receipt + supplier website	x	x	
4.1	Permanent magnet, for electric motor (GLO), production, Cut-off, U	4.13E + 02	kg	Receipt + supplier website	x	x	
4.1	Polyamide fiber production	5.53E + 03	kg	Receipt + supplier website	x	x	
4.1	Polyethylene, LLDPE, granulate, at plant/RER	1.86E + 04	kg	Receipt + supplier website	x	x	
4.1	Polylactide, granulate (GLO), production, Cut-off, U (Ecopure)	1.86E + 02	kg	Receipt + supplier website	x	x	
4.1	Polypropylene, granulate (RER), production, Cut-off, U	9.13E + 02	kg	Receipt + supplier website	x	x	
4.1	Polystyrene, extruded (RER), production, CO_2 blown, Cut-off, U	1.35E + 03	kg	Receipt + supplier website	x	x	
4.1	Polyurethane, flexible foam (RER), production, Cut-off, U	5.24E + 02	kg	Receipt + supplier website	x	x	
4.1	Polyvinylchloride, bulk polymerized (RER), production, Cut-off, U	1.45E + 04	kg	Receipt + supplier website	x	x	
4.1	Printed paper, offset (RoW), offset printing, per kg printed paper, Cut-off, U	1.39E + 03	kg	Receipt + supplier website	x	x	
4.1	Solid bleached board (RER), production, Cut-off, U	8.56E + 03	kg	Receipt + supplier website	x	x	
4.1	Steel, low-alloyed (RER), steel production, converter, low-alloyed, Cut-off, U	4.28E + 03	kg	Receipt + supplier website	x	x	

Table 3 (continued)

Subcategory	Description	Quantity	Unit	Data source	Primary	Secondary	Proxy
4.1	Textile, knit cotton (RoW), textile production, cotton, circular knitting, Cut-off, U	2.41E+02	kg	Receipt + supplier website	x	x	
4.1	Textile, non-woven polypropylene (RoW), textile production, spun bond, Cut-off, U	6.89E+03	kg	Receipt + supplier website	x	x	
4.1	Thermoforming of plastic sheets (RoW), processing, Cut-off, U	1.86E+04	kg	Receipt + supplier website	x	x	
4.1	Tissue paper (RER), production, Cut-off, U	2.73E+03	kg	Receipt + supplier website	x	x	
4.1	Weaving, synthetic fiber (GLO), for industrial use, Cut-off, U	9.81E+03	kg	Receipt + supplier website	x	x	
4.1	Wool fiber	1.27E+02	kg	Receipt + literature	x	x	
4.1	SITC-61, leather, leather manufactures, n.e.s., and dressed furskins, import/kg/CH S	4.91E+03	kg	Receipt + company data	x	x	
4.1	Batch dyeing, fiber, cotton (RoW), batch dyeing, fiber, cotton, Cut-off, U	4.30E+04	kg	Receipt + literature	x	x	
4.1	BIO—textile, knit cotton (RoW), textile production, cotton, circular knitting, Cut-off, U	1.63E+03	kg	Receipt + literature	x	x	
4.1	Bleaching, textile (RoW), bleaching, textile, Cut-off, U	4.30E+04	kg	Literature		x	
4.1	Textile (added weaving) Elastane fiber production (polyurethane added dry spinning)	1.91E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) fiber, viscose (GLO), fiber production, Cut-off, U added spinning	9.10E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) fiber, viscose (GLO), fiber production, Cut-off, U added spinning (cellulose acetate)	2.79E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) polyacrylonitrile fibers (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S added spinning	4.10E+01	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) polyamide fiber production (nylon added melt spinning)	5.59E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) polyester fiber production (polyethylene added melt spinning fiber)—polyethylene terephthalate	4.87E+02	kg	Receipt + supplier website + literature	x	x	
4.1	Textile (added weaving) wool fiber (with spinning), scouring and combing	1.97E+03	kg	Receipt + supplier website + literature	x	x	
4.1	Textile flax based on “textile, jute (RoW), textile production, weaving, Cut-off, U”	6.07E+03	kg	Receipt + literature	x	x	
4.1	Textile, jute (RoW), textile production, jute, weaving, Cut-off, U	1.44E+02	kg	Receipt + literature	x	x	

Table 3 (continued)

Subcategory	Description	Quantity	Unit	Data source	Primary	Secondary	Proxy
4.1	Textile, knit cotton (RoW), textile production, cotton, circular knitting, Cut-off, U	9.80E + 03	kg	Receipt + supplier website	x	x	
4.1	Textile, non-woven polyester (RoW), textile production, needle punched, Cut-off, U	5.36E + 03	kg	Receipt + supplier website	x	x	
4.1	Textile, non-woven polypropylene (RoW), textile production, spun bond, Cut-off, U	9.20E + 01	kg	Receipt + supplier website	x	x	
4.1	Textile, silk (RoW), textile production, silk, Cut-off, U	7.96E + 03	kg	Receipt + supplier website	x	x	
4.1	Vinyl acetate (RER), production, Cut-off, U	5.50E + 02	kg	Receipt + supplier website	x	x	
4.2	Washing machine (GLO), market for washing machine, Cut-off, U	8	p	Company	x		
4.2	Dryer (GLO), market for dryer, cut-off, U	4	p	Company	x		
4.2	Elevator, hydraulic (GLO), market for elevator, hydraulic, Cut-off, U	7	p	Company	x		
4.2	Refrigerator (GLO), market for refrigerator, Cut-off, U	4	p	Company	x		
4.2	SITC-74, general industrial machinery, and equipment, n.e.s., and machine parts, n.e.s., import/kg/CH S	1.03E + 04	kg	Company	x		
4.2	Building, multi-storey (GLO), market for, Cut-off, U	4.82E + 02	m^3	Company	x		
4.2	Light commercial vehicle (GLO), market for, Cut-off, U	6	p	Company	x		
4.2	Passenger car, diesel (GLO), market for, Cut-off, U	8.19E + 02	kg	Company + literature	x	x	
4.3	Waste paper, sorted (RoW), treatment of waste paper, unsorted, sorting, Cut-off, U	6.52E + 03	kg	Billing	x		
4.3	Toner module, laser printer, color (RoW), treatment of used, recycling, Cut-off, U	107	p	Billing	x		
4.3	Waste polyethylene terephthalate, for recycling, sorted (Europe without Switzerland), treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting, Cut-off, U	1.22E + 04	kg	Billing	x		
4.3	115 Waste treatment, Waste water treatment, other, EU27	3.08E + 02	kg	Billing	x		
4.3	Municipal waste collection service by 21 metric ton lorry (GLO), market for, Cut-off, U	1.39E + 06	kgkm	Billing	x		
4.3	Process-specific burdens, inert material landfill (RoW), process-specific burdens, inert material landfill, Cut-off, U	1.05E + 03	kg	Billing	x		
4.3	Process-specific burdens, hazardous waste incineration plant (RoW), processing, Cut-off, U	1.49E + 02	kg	Billing	x		

Table 3 (continued)

Subcategory	Description	Quantity	Unit	Data source	Primary	Secondary	Proxy
4.3	Process-specific burdens, hazardous waste incineration plant (RoW), processing, Cut-off, U	9.40E+02	kg	Billing	x		
4.5	Transport, freight, lorry 3.5–7.5 metric ton, euro4 (RER), market for transport, freight, lorry 3.5–7.5 metric ton, EURO4, Cut-off, U	3.24E+06	kgkm	Billing+delivery company+SimaPro	x		
4.5	Transport, freight, lorry 3.5–7.5 metric ton, euro4 (RER), market for transport, freight, lorry 3.5–7.5 metric ton, EURO4, Cut-off, U	8.38E+06	kgkm	Billing+delivery company+SimaPro	x		
5.1	Tap water (Europe without Switzerland), market for, Cut-off, U	1.84E+07	kg	Company+SimaPro	x	x	
5.1	Non-ionic surfactant (GLO), market for non-ionic surfactant, Cut-off, U	1.56E+04	kg	Company+SimaPro	x	x	
5.1	Tetrachloroethylene (RoW), production, Cut-off, U	4.59E+04	kg	Company+SimaPro	x	x	
5.1	Washing, drying and finishing laundry (GLO), Cut-off, U	9.81E+05	kg	Company+SimaPro	x	x	
5.1	Electricity, low voltage (RER), market group for, Cut-off, U	5.01E+05	kWh	Company+SimaPro	x	x	
5.1	Heat, district or industrial, natural gas (GLO), market group for, Cut-off, U	2.50E+06	kWh	Company+SimaPro+Literature	x	x	
5.1	Electricity, low voltage (RER), market group for, Cut-off, U	2.45E+05	kWh	Company+SimaPro+Literature	x	x	
5.3	Process-specific burdens, inert material landfill (RoW), Cut-off, U	1.56E+04	kg	Legislation			x
5.3	Process-specific burdens, municipal waste incineration (Europe without Switzerland), Cut-off, U	3.90E+04	kg	Legislation			x
6	Transport, freight, lorry 3.5–7.5 metric ton, euro4 (RER), market for transport, freight, lorry 3.5–7.5 metric ton, EURO4, Cut-off, U	3.34E+07	kgkm	Billing+delivery company+SimaPro	x		
6	Transport, freight, light commercial vehicle (RER), market group for transport, freight, light commercial vehicle, Cut-off, U	1.01E+06	kgkm	Billing+delivery company+SimaPro	x		
6	Transport, freight, lorry 7.5–16 metric ton, euro4 (RoW), market for transport, freight, lorry 7.5–16 metric ton, EURO4, Cut-off, U	4.47E+06	kgkm	Billing+delivery company+SimaPro	x		
6	Transport, freight, aircraft, unspecified (GLO), market for transport, freight, aircraft, unspecified, Cut-off, U	1.83E+06	kgkm	Billing+delivery company+SimaPro	x		

The x indicates if the data source is primary, secondary or proxy

Table 4 Inputs for the use phase regarding lifespan and washing estimated by the company

Product	Pieces	Average weight (kg)	Lifespan (years)	N. months used	Days of use (year)	Washing frequency (days)	N washes among life	Amount of washing (kg)
	Primary data	*Primary data*	*Secondary data*	*Secondary data*	*Secondary data*	*Secondary data*	*Secondary data*	*Secondary data*
Dresses	38,108	0.558	4	4	120	30	16	340,178
Giacche	23,760	0.708	5	4	120	40	15	252,173
Coats and Outwear	17,800	0.99	5	5	150	60	12.5	220,382
Leather	5054	0.979	8	3	90	90	8	39,571
Shirts	31,500	0.447	2	8	240	7	68.6	964,822
Top	21,880	0.183	2	6	180	7	51.4	206,116
Pants	68,976	0.356	2	6	180	30	12	294,872
Skirts	18,867	0.395	2	6	180	30	12	89,381
Knit	132,765	0.291	3	6	180	30	18	694,776
Jersey	63,417	0.194	3	5	150	7	64.3	789,053

Table 5 Company recommendations for type of washing and ironing

Product	Type of washing	Type of ironing	Time of ironing (h) (Thomas et al. 2012a)	Hours × ironing per piece	Hours × 0.75 kW (Thomas et al. 2012a) × tot article = kWh
	Primary data from the company		Secondary data from literature		
Dresses	Dry	Iron	0.075	1.2	34,297
Giacche	Dry	Iron	0.04	0.6	10,692
Coats and outwear	Dry	Iron	0.05	0.63	8344
Leather	Washing machine	No ironing	-	-	-
Shirts	Hand wash	Iron	0.043	2.95	69,660
Top	Hand/dry	Iron	0.043	2.21	36,290
Pants	Dry/washing machine	Iron	0.072	0.43	22,348
Skirts	Dry/washing machine	Iron	0.072	0.43	6113
Knit	dry / hand	Steam	0.04	0.72	71,693
Jersey	washing machine	Iron	0.05	Included	(Wernet et al. 2016)

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Author contribution Fabiana Frota de Albuquerque Landi: conceptualization of the study, methodology, visualization, data curation, writing—original draft; Claudia Fabiani: conceptualization of the study, methodology, writing review and editing, supervision; Benedetta Pioppi: conceptualization of the study, writing review and editing; Anna Laura Pisello: writing review, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to confidentiality reasons but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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