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Measuring the Value of Blockchain Traceability in Supporting LCA for Textile Products

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Abstract: The efficiency of sustainability assessments of textile products is generally prevented because of a lack of available and reliable data across complex and globalized supply chains. The purpose of this study is to evaluate how blockchain traceability data can improve the Life Cycle Assessment (LCA) of textile products and to measure the actual value of exploiting this specific traceability data. To do so, a case study consisting of two LCAs modeling the production of wool top lots in China was conducted. A first LCA was conducted with generic data and the second with the added value of specific blockchain traceability data. Based on the second LCA, different wool top lot composition scenarios were then modeled to account for the environmental impact of different farming practices. Two main results were obtained: the environmental impact of wool top lots can vary up to +118% between two batches depending on their composition, and the specific data changes drastically from the impact calculated with generic data, with +36% calculated impact for the same wool composition of batches. Therefore, it was concluded that blockchain traceability data could be a strong asset for conducting LCA at the batch level by providing differentiated data on batch composition and origin and providing readily available specific data for a more representative assessment.

Keywords: LCA; blockchain; traceability; textile; wool

1. Introduction

From climate change to loss of biodiversity, from impacts on human health to impacts on ecosystems and resources, industrial activity has been acknowledged as one of the main drivers of our impact on the environment [1]. Therefore, industrial companies nowadays observe the need to align with various and ambitious sustainability objectives set to address the environmental emergency faced by humanity. They face both the toughening of environmental regulations and increased expectations from consumers about the sustainability of the products they buy. The textile sector is especially facing growing demand for more sustainable products from consumers, and the potential of a soon-to-come general environmental display on textile products has already been experimented and is part of a law project in France [2]. Driving change towards a more sustainable production comes by acknowledging, measuring, and managing the overall impact industrial stakeholders have regarding various environmental sustainability topics.

The most common method used to assess the environmental impact of industrial products throughout their value chain is the Life Cycle Analysis (LCA) method [3]. LCA accounts for emission and resource consumption toward all activities involved in the life cycle of a product and characterizes them into meaningful environmental indicators such as climate change, ecosystem quality, health of the human population, and resource

depletion [4]. However, it requires a large amount of specific and reliable production data to model all the inputs and outputs of an industrial system adequately at different production stages. It is very sensitive to the variation of such data [5]. Because of increasingly complex and globalized supply chains of industrial sectors, including the textile sector, product life cycle data is often scattered, lacks transparency, or is simply unavailable [6]. Approximately 80% of the time and resources allocated to LCA projects are used for data collection [7].

The lack of data accessibility and reliability throughout supply chains has recently encouraged industrial companies to invest in traceability systems, which were helped by the emergence of blockchain technology and its multiple benefits for supply chains [8]. The main characteristics of blockchain, including transparency, immutability, and accountability, have caused it to become one of the main enablers of decentralized product traceability systems [9]. First used by companies to monitor their product's quality, security, or authenticity, blockchain traceability has recently been studied to monitor environmental sustainability by supporting life cycle inventories in LCAs. Indeed, the decentralized characteristics of blockchain traceability systems could answer data collection problems in LCA and therefore help make impact assessment more representative of various industrial practices [10]. This refined impact assessment could drive a more sustainable supply chain management in the textile sector with the capability to measure the impact variation of different batches of raw materials, depending on the supplying and transformation stakeholders involved in the production process.

This research paper aims to evaluate how blockchain traceability could improve LCA results' representativity in textile products by enhancing primary data collection and quantifying this improvement potential against a generic LCA. An experiment was conducted on wool top lots with the objective to measure how blockchain traceability enables the refinement of the LCA data collection and calculation of environmental impact at the level of product batches.

The paper is structured as follows. First, a literature review is conducted to analyze the opportunities of using blockchain traceability in enhancing LCA (Section 2). Section 3 describes the proposed research method on how to integrate blockchain traceability into the LCA process and introduces the case study. Results are presented and discussed in Section 4. The study's main limitations and the potential to integrate blockchain traceability and LCA are discussed in Section 5.

2. Literature Review

Generally, the impact of supply chain activities accounts for up to 90% of the environmental impact of product processing companies [11]. Therefore, to enhance the sustainability of the supply chain (Sustainable Supply Chain, SSC) and identify the main lever for sustainable production, it is imperative to collect accurate and reliable data upstream of the production. The main challenge in establishing an SSC is the increasing complexity of globalized and fractured value chains [6]. The geographical dispersion of value chains increases the risk of vulnerability and makes traceability of products, tracking of production events, and risk management extremely complex [12]. According to UNECE [13], only 34% of apparel products commercialized worldwide have traceability, and among these, only 6% have total traceability going up the whole value chain. This complexity also prevents the measurement and management of environmental impact at different stages of production [11].

To ensure the sustainability of dynamic supply chains, a system needs to be readily adaptable, allowing for frequent and simultaneous capture of diverse information across different continents [14]. It also needs to handle the fragile information from other actors with a decentralized system that would not be subject to localized failure [15]. The main challenges currently facing the establishment of sustainable supply are therefore transparency, accountability, and traceability. These limitations related to the difficulty of accessing data from activities across the supply chains thus affect the effectiveness of LCAs, which experience a significant gap between their theorization and their actual

application [16]. The primary data used in LCA allow the characterization and differentiation of the specific activities and industrial processes from industrial/sectorial averages. Therefore, the difficulty of collecting specific data, particularly during the LCI phase, is problematic because it only allows for an approximate quantification of the impact, which is representative of the average of a whole industry rather than specific to the value chain of a production system.

Moreover, because LCA results might be highly sensitive to given input data, the quality of the data must be documented and maximized [5]. Finally, a commonly discussed topic concerns the temporal evolution of life cycle inventories of industrial processes and activities, which suffer from high inertia in being updated. For example, some studies have shown a significant temporal variation in LCA impact scores [17].

A blockchain traceability platform integrated with an impact calculation methodology would provide transparent and traceable data along a product's value chain and easily map all inputs in fragmented and complex supply chains [16]. This would allow impact calculations to be based on more reliable data, improving their value and representativeness [7] and facilitating the ecodesign process. The properties of the blockchain, such as immutability, integrity, and data persistence [11], as well as the decentralization of this network, would also allow easier access to data by all users of the network and establish trust between actors who are usually distrustful of each other [18], making it easier to make data available for LCA. A study was conducted with large Australian companies in the materials sector to ask them about the blockchain's contribution to improving LCA methods [7]. The majority of the executives interviewed believe that this technology plays a major role in overcoming the complexity of LCA projects, which are becoming necessary in assessing the environmental impact of industrial products. Also, several papers have been proposing model integration between blockchain traceability and LCA. For instance, Zhang et al. [16] proposed an integrated framework and a multi-layer system architecture of a blockchain-LCA model. Similarly, to operationalize a system linking LCA and blockchain technology, Rolinck et al. [19] proposed a blockchain-based data management model to simplify the realization of LCAs and discussed its application for aviation maintenance.

To ensure that blockchain technology is relevant to address environmental traceability in the industry, the choice of this specific technology is to be clarified. First of all, it is important to note that different decentralized digital methods registering virtual transactions exist, called Distributed Ledger Technologies (DLT). For example, the Tangle technology uses a directed acyclic graph to hold the transactions [20] as well as the Hashgraph technology [21]. A SWOT analysis was conducted on those different technologies [21], and it appeared that, compared to Tangle and Hashgraph, the main advantage of blockchain technology was its level of maturity and successful implementation in the industry, other DLTs being still largely experimental. However, blockchain technology is frequently considered a very energy-intensive technology, raising questions about its applicability for environmental traceability [22]. To go beyond this myth, the heterogeneity of blockchain technologies is to be assessed. For example, it stood out that private blockchains with a Proof of Authority (PoA) consensus have a negligible energy consumption compared to Bitcoin and its Proof of Work (PoW) consensus, the work of miners being the main source of high energy consumption [22].

Overall, the scientific literature shows an increasing interest in exploring the potential contribution of blockchain-based traceability systems to improve and refine LCA inventories. Still, published research papers remain rather theoretical on the subject. There are still few articles that consider its operationalization by proposing integration models or system architectures. Research analyzing the implementation of such LCA blockchain-based traceability systems in an industrial environment has not been proposed yet. One of the obstacles to the operational implementation of LCA-blockchain systems in the industry is undoubtedly the lack of quantified cost/benefit analysis of such projects. As such, this research paper focuses on measuring the benefits of an LCA-blockchain platform in an

industrial context to guide decision-makers to evaluate its implementation within their scope of activity.

3. Research Method

To measure the contribution of blockchain traceability data on the realization of LCA, the project was conducted in two stages on a real case study aiming to assess the environmental profile of batches of worsted wool manufactured in China from the Chargeurs Luxury Materials company.

First, a so-called *generic LCA* was conducted following ISO 14040s standards on a product system defined jointly with the industrial partner. The goal and scope of the LCA is described in the corresponding section (Section 3.1). The first generic LCA was modeled using generic data from the Ecoinvent v.3 database and basic primary data from the industrial partner based on this product system. The list of data sources for each life cycle stage will be later presented in Table 1. In a second stage, a *specific LCA* was performed with specific production data provided by the Blockchain traceability platform of the industrial partner. The approach to performing an integrated LCA-blockchain traceability is described in Section 3.2.

3.1. Case Study

This research project was conducted in partnership with two companies. The first one, Crystalchain, is a company expert in the blockchain traceability of industrial products. It develops and implements a blockchain traceability platform linked to visualization and activity management tools for its industrial clients. The research partner has made available all of its traceability tools used for generic data collection. Crystalchain uses a private blockchain platform with a PoA consensus, significantly lowering the overall energy consumption compared to other blockchains, as explained in the literature review. It is based on the Ethereum technology, which was the first technology to propose the creation of smart contracts and decentralized applications and now has a large community of users.

The second company, Chargeurs Luxury Materials (CLM), is a world leader in wool processing, which has already implemented an operational blockchain traceability platform provided by Crystalchain. CLM provided the specific production data required to perform the LCA.

The objective of the case study was to perform a cradle-to-gate LCAs of combed wool batches, i.e., from the production of wool at the farm to the baling of batches of combed wool ready for spinning. The functional unit was defined as "1 kg of combed wool top lots at factory gate".

The scope of analysis focused on the combing factory owned by CLM in China with wool supply from three upstream farms: two farms in Australia and one in New Zealand. Since CLM owns only the combing plant, we were not able to obtain specific production data from the supplier farms. Therefore, we used generic inventory data from three wool production farms in Australia and New Zealand found in the scientific literature from an LCA study by Cardoso (2013) [23]. The representativeness of these three farms, with different characteristics and production modes presented in Figure 1, was validated by CLM managers. The latter confirmed that these three farm archetypes represent the wide variety of production methods of their suppliers.

Table 1. LCA processes and data source.

Stage	PROCESS NAME	Inputs/Outputs	Generic LCA Source	Specific LCA Source
Farming wool production	Sheep Breeding ǀ Farm 1, Conventional, NZ	Fertilizers	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Pesticides	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Animal Feed	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Agriculture machinery	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Water	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Electricity	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Direct Emissions	Cardoso [20]; Table 12	Cardoso [20]; Table 12
		Greasy wool ǀ farm 1	Cardoso [20]; Table 11	Cardoso [20]; Table 11
	Sheep Breeding ǀ Farm 2, Intensive, NZ	Same as farm 1	Same as farm 1	Same as farm 1
		Greasy wool ǀ farm 2	Cardoso [20]; Table 11	Cardoso [20]; Table 11
	Sheep Breeding ǀ Farm 3, Extensive, AU	Same as farm 1	Same as farm 1	Same as farm 1
		Greasy wool ǀ farm 3	Cardoso [20]; Table 11	Cardoso [20]; Table 11
Transport	Transport to Combing Mill ǀ from farm 1	Greasy wool ǀ farm 1	Cardoso [20]; Table 11	Cardoso [20]; Table 11
		Transport by boat	CLM China Factory 2020	CLM China Factory 2020
		Transport by train	CLM China Factory 2020	CLM China Factory 2020
		Transport by truck	CLM China Factory 2020	CLM China Factory 2020
		Transported greasy wool ǀ farm 1	CLM China Factory 2020	CLM China Factory 2020
	Transport to Combing Mill ǀ from farm 2	Same as farm 1	CLM China Factory 2020	CLM China Factory 2020
		Transported greasy wool ǀ farm 2	CLM China Factory 2020	CLM China Factory 2020
	Transport to Combing Mill ǀ from farm 3	Same as farm 1	CLM China Factory 2020	CLM China Factory 2020
		Transported greasy wool ǀ farm 3	CLM China Factory 2020	CLM China Factory 2020
Combing Mill Processing	Wool Blend Composition	Transported greasy wool ǀ farm 1	Same as specific	Crystalchain Traceability
		Transported greasy wool ǀ farm 2	Same as specific	Crystalchain Traceability
		Transported greasy wool ǀ farm 3	Same as specific	Crystalchain Traceability
		Greasy wool blend	Same as specific	Crystalchain Traceability
	Wool Processing ǀ Standard flow	Greasy wool blend	Same as specific	Crystalchain Traceability
		Electricity	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Steam	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Water	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Wastewater	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Packaging	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Chemicals	Cardoso [20]; Table 15, col.1	CLM China Factory 2020
		Wool waste		Crystalchain Traceability
		By-product (lanolin sold)		CLM China Factory 2020
		Wool top ǀ standard	Cardoso [20]; Table 15, col.1	Crystalchain Traceability
	Wool Processing ǀ Superwash	Electricity		CLM China Factory 2020
		Steam		CLM China Factory 2020
		Water		CLM China Factory 2020
		Wastewater		CLM China Factory 2020
		Packaging		CLM China Factory 2020
		Chemicals		CLM China Factory 2020
		Wool waste		CLM China Factory 2020
		Wool top ǀ Superwash		Crystalchain Traceability
	Wool Processing ǀ Recombing	Electricity		CLM China Factory 2020
		Packaging		CLM China Factory 2020
		Wool waste		CLM China Factory 2020
		Wool top ǀ recombed		Crystalchain Traceability
	Wool Processing Group	Wool top ǀ standard flow		Crystalchain Traceability
		Wool top ǀ Superwash		Crystalchain Traceability
		Wool top ǀ recombed		Crystalchain Traceability
		Wool top ǀ processed	Cardoso [20]; Table 15, col.1	Crystalchain Traceability

Farm 1 : average conventional agriculture	Farm 2 : intensive conventional agriculture	Farm 3 : extensive organic agriculture
Location : New Zealand **Stock rate :** 1.2 sheep/ha **Wool production :** 67t/year	**Location :** Australia **Stock rate :** 12 sheep/ha **Wool production :** 47.5t/year	**Location :** Australia **Stock rate :** 0.1 sheep/ha **Wool production :** 28.5t/year
Energy used per sheep : low **Water used per sheep :** low	**Energy used per sheep :** average **Water used per sheep :** average	**Energy used per sheep :** high **Water used per sheep :** high
Fertilizers used : low **Pesticides used :** low **Chemical treatments used :** low	**Fertilizers used :** high **Pesticides used :** average **Chemical treatments used :** average	**Fertilizers used :** no **Pesticides used :** no **Chemical treatments used :** no

Figure 1. Farms characteristics.

Table 1 lists all the LCA processes modeled and the data sources used to quantify all the inputs and outputs of every process for each of the two LCAs carried out. The third column discloses the data sources used to quantify each of the inputs and outputs modeled in the generic LCA. The fourth column does the same for data used in the specific LCA. Three main data sources have been used in this study:

- The paper of Cardoso [23] (specific tables used from this reference is in Table 1);
- The factory data collected from the industrial partner, CLM (CLM China Factory 2020); and
- The blockchain-based traceability platform of Crystalchain.

The constructed LCA model can be visualized in the following Figure 2. All the greasy wool is processed following a standard flow during the combing mill processing stage. Then, depending on the batch and customers' specific requirements, it can also be processed through a Superwash process or a recombing process, or directly packed to ship to the spinner for the next transformation stage. In the following figure, the same colors are used to identify the different processes and our results (discussed in Section 4) to easily visualize each stage's impact.
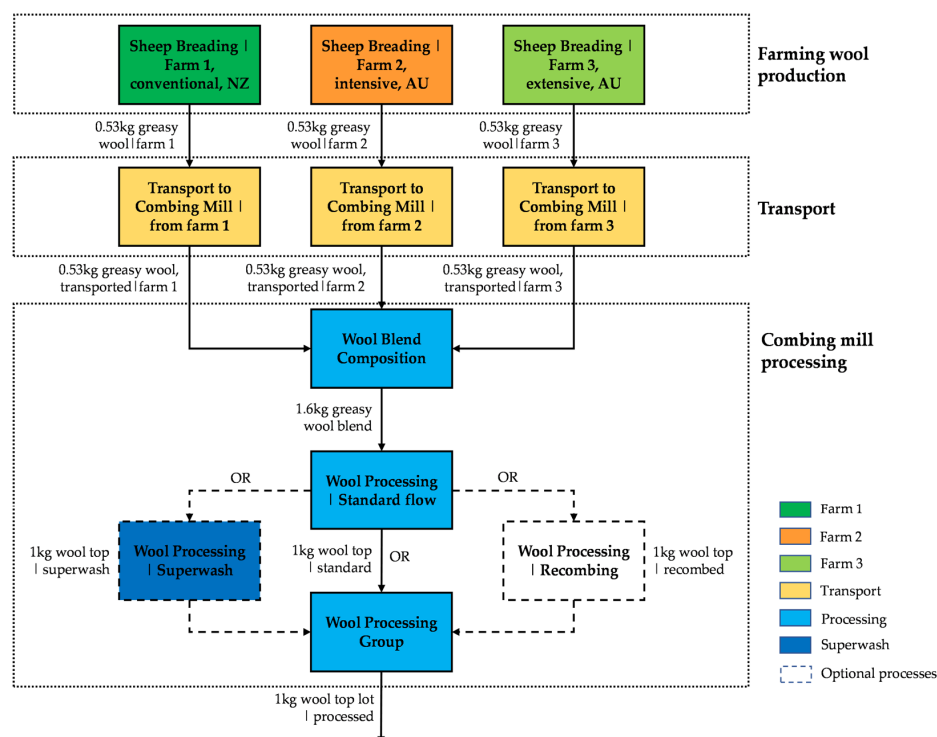
Figure 2. Product system of the LCA model structured in three main life cycle stages: farming wool production, transport, and combing mill processing. The functional unit is 1 kg of combed wool top lot at the factory gate.

3.2. Integrated LCA-Blockchain Traceability Approach

Hereby we describe a systematic approach to integrate blockchain traceability into the LCA process in order to provide specific data such as production volumes, energy and water consumed, chemicals used, waste generated, packaging used, raw material purchases, and direct emissions generated. The first *generic LCA* could be adapted, refined, and specified into a *specific LCA*. Figure 3 presents the different steps necessary to build this second *specific LCA*.
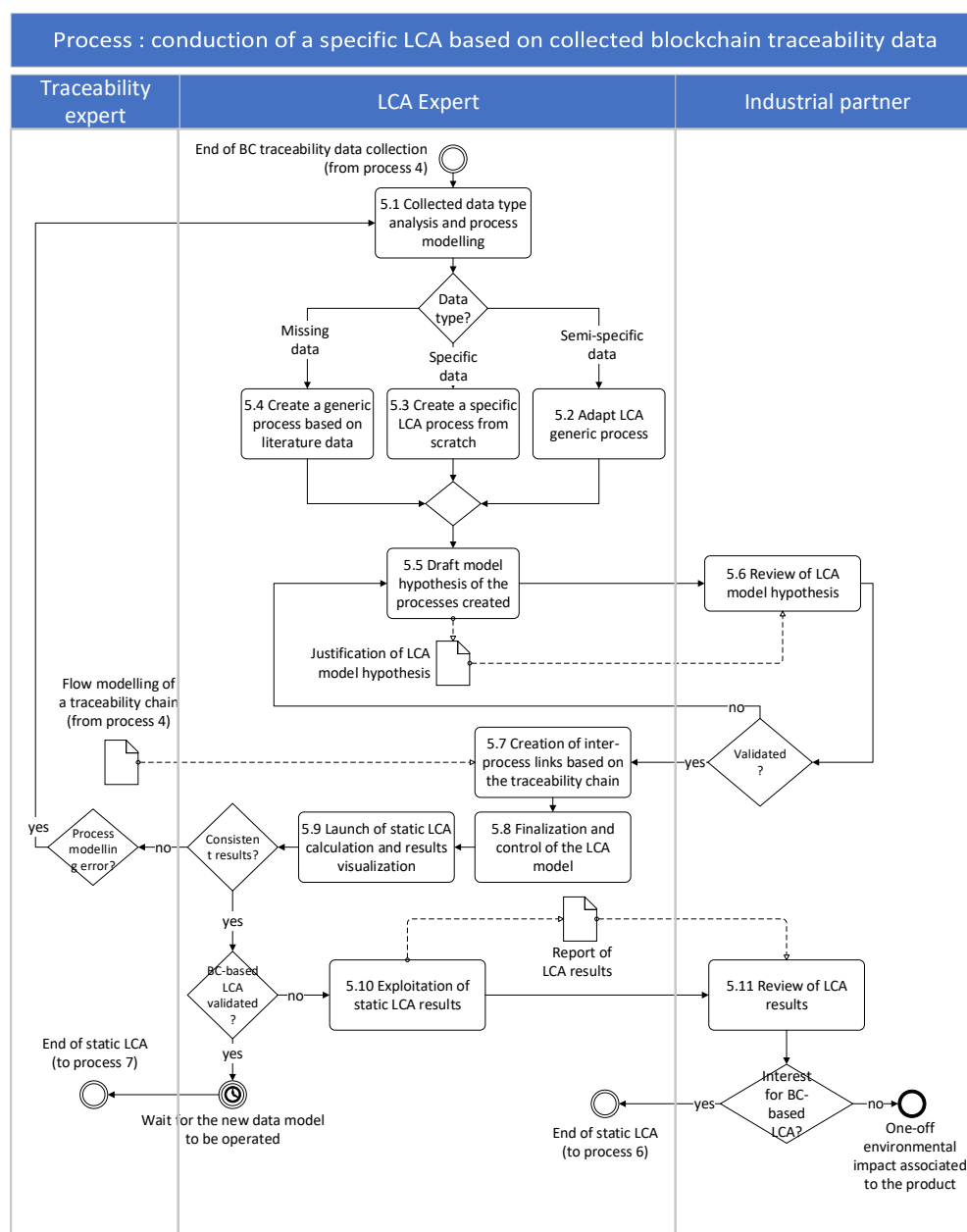

Figure 3. Blockchain data preparation activities.

The results of this *specific LCA* were compared to those of the *generic LCA* to quantify the contribution of an integrated LCA-blockchain traceability calculation approach. It should be noted that this second specific model is not 100% derived from data collected on the blockchain platform but also from data sent by the client by email. Indeed, at the time of our study, CLM did not have access to all of the data needed to establish an LCA. For example, data on energy consumption or chemicals used were not available on the platform.

To perform the LCA, we used OpenLCA. Ecoinvent v.3 was used to model cradle-to-gate inventory of the unit processes corresponding to those shown in Figure 2. The ReCiPe endpoint 2016 characterization method was used (H, A). Indeed, this impact assessment method proposes 18 impact indicators covering a wide range of environmental issues.

Moreover, it allows visualizing the results at the level of environmental problems, environmental damages, and at the level of a single impact score.

To maintain the confidentiality of the industrial partner's data, all results will be expressed as a 100% comparative normalization.

4. Results and Discussion

The LCA results are structured in two sub-sections. The first sub-section compares the *generic LCA* and the *specific LCA*. This comparison aims to evaluate and quantify the importance of specific traceability data of the impact scores. The second sub-section provides a number of sensitivity and scenarios analysis on the *specific LCA* only.

4.1. Comparative Results between Generic and Specific LCA

The scope of the LCA model is the same for both the *generic LCA* and the *specific LCA*, the only difference being the contribution of CLM specific data for the specific LCA. First of all, relative variation of impact scores was within 20% for all impact categories, except for fossil resource depletion (FRD), with a relative difference of up to 50% (Figure 4). Second, most of the environmental impact is associated with farming wool production, for which we could not obtain specific data, as we can see in Figure 4. The agricultural processes for both models are identical as they rely on generic data from Cardoso (2013). Both models also assume the same wool composition supplied from conventional agriculture (farm 1). However, the data sources used to model combing mill processing are clearly different in the two models. Figure 4 presents a comparative contribution analysis between the two LCAs for the selected impact categories.
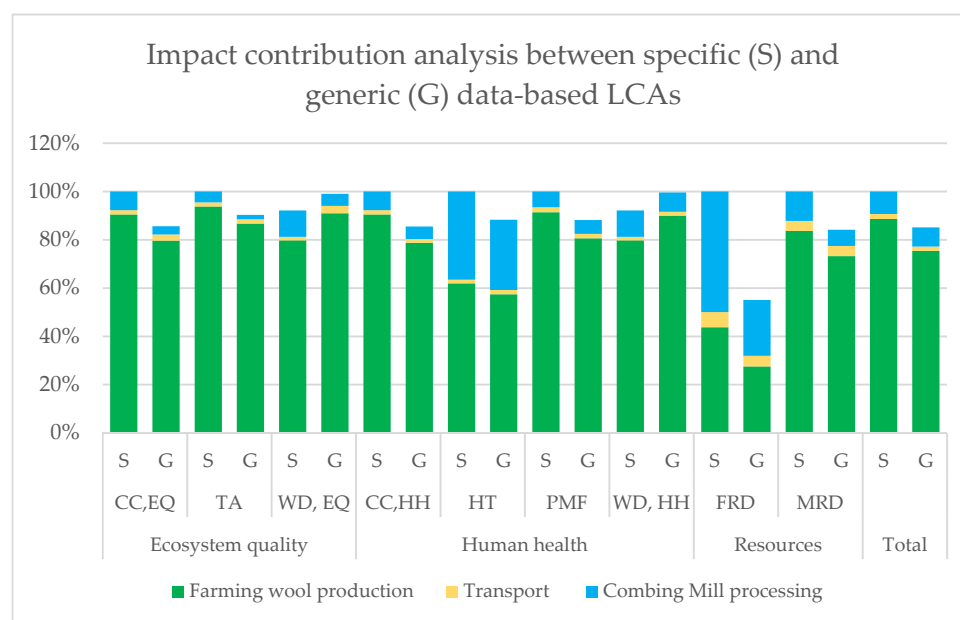
Figure 4. Impact contribution analysis for the *generic LCA* and the *specific LCA* with ReCiPe impact assessment methodology with the functional unit: 1 kg of combed wool top at factory gate. Acronyms: CC,EQ: Climate Change, Ecosystem Quality; TA: Terrestrial Acidification; WD,EQ: Water depletion, Ecosystem Quality; CC,HH: Climate Change, Human Health; HT: Human Toxicity; PMF: Particulate Matter Formation; WD,HH: Water Depletion, Human Health; FRD: Fossil Resources Depletion; MRD: Mineral Resources Depletion.

The "Total" column of Figure 4 presents the relative difference between the generic and the specific LCA obtained by aggregating all damage indicators into a single score using the hierarchical weighting factors of ReCiPe (40% Human health, 40% Ecosystem quality, and 20% resources) as implemented in OpenLCA.

Despite the invariability of the agricultural process, the observed variability in the impact scores for the different categories between the two LCA models can be explained by two main causes:

- Firstly, the provision of specific data for the combing mill processing stage makes it possible to specify in a more representative way the energy and the specific chemicals and packaging used in the CLM process;
- Also, the specific data provided more accurate loss rates of wool during coming mill processing. Losses are reported during washing, with the masses of organic matter, and lanolin eliminated is accounted for in the mass of greasy wool in input. Additional losses are reported at the sorting because of too short fibers and due to the different wool scraps. From the traceability data on annual production volumes, a yield of 0.7 could be estimated at the combing processing, which differs from the yield of 0.85 initially determined for the generic LCA. These differences in yields change the environmental impact proportionally, as the lower the yield, the more greasy wool must be sourced to produce 1 kg of worsted wool. The difference in the modeling of the yields between the two LCAs explains the difference in the impact obtained for the farming wool production.

To better compare this gap between generic and specific LCAs, we can define a variability rate:

$$\tau_{var} = 100 * \frac{Score_{specifique} - Score_{generique}}{Score_{generique}}$$

which measures the proportional difference of the specific from the generic for each impact category. The rates of change by category are presented in Figure 5.
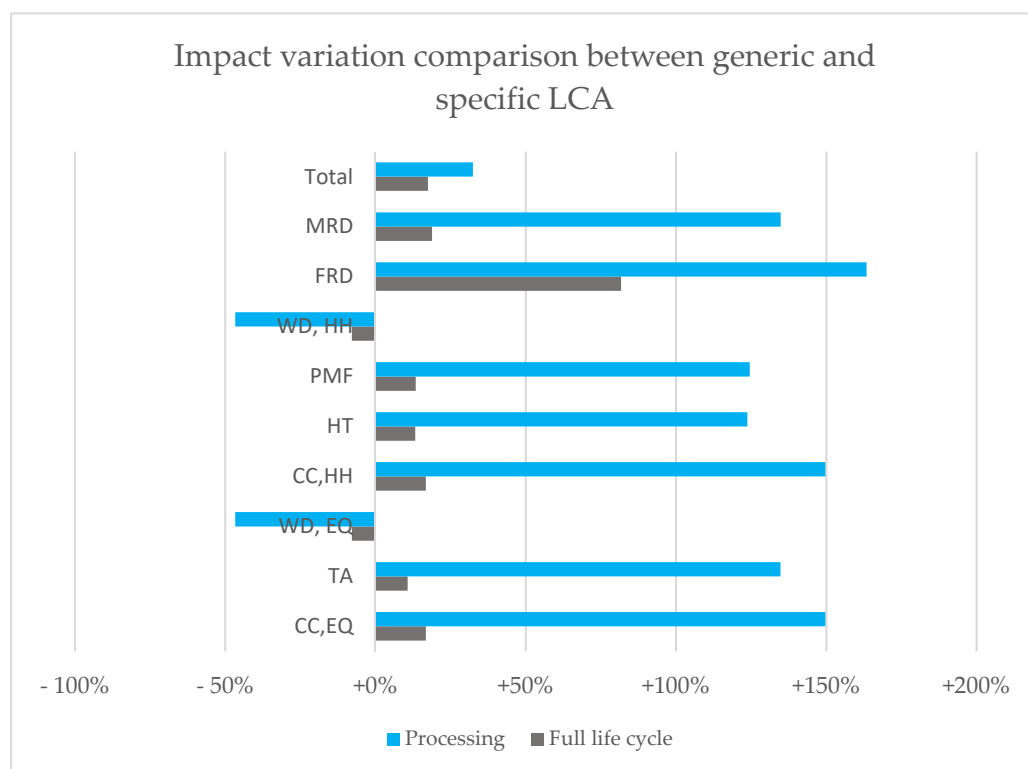
Figure 5. Impact variability rate of targeted (group of) processes between *generic LCA* and *specific LCA* models. See Figure 4 for the definition of the acronyms.

The variability in impact scores for the combing mill processing life cycle stage increased by +36% when supplied by traceability data and +20% overall when taking into account the full life cycle (farming wool production + transport + combing mill processing). In the climate change impact category, the variation is up to +150% within the combing mill processing life cycle stage.

4.2. Sensitivity Analysis on Different Production Scenarios in the Specific LCA

In this sub-section, we perform sensitivity analysis on:

1. The composition of batch of wool fiber supplied from different origins. The baseline results were obtained assuming a supply of 100% from conventional agriculture (farm 1). The percentages of wool fiber in a batch from farms 1, 2, and 3 vary.
2. The presence of an additional non-mandatory process of Superwash in the combing mill processing. This process uses a lot of water and chemicals to treat the wool in order to extend the lifetime of wool during the consumer's use phase.

The sensitivity analysis is combined into the five scenarios presented in Table 2.

Table 2. Scenario analysis as a function of the composition of a batch of wool fiber and the presence (or not) of the non-mandatory process of Superwash in the combing mill processing.

N°	Name	Farm_1	Farm_2	Farm_3	Standard	Recombing	Superwash
1	Wool mix	0.33	0.33	0.33	1	0	0
2	Conventional wool	1	0	0	1	0	0
3	Intensive wool	0	1	0	1	0	0
4	Extensive wool	0	0	1	1	0	0
5	Extensive wool + Superwash	0	0	1	0	0	1

The scenarios are based on six different parameters. The first three parameters (Farm_1, Farm_2, and Farm_3) quantify the proportion of wool sourced from each of the three farms presented in Figure 1 in the total wool blend composition. For example, in scenario 1, Farm_1 = 0.33 means that 33% of the wool blend is composed of wool sourced from farm 1. In scenarios 1 to 4, only those three parameters are modified to compare the impact of different wool blend compositions. The last three parameters (Standard, Recombing, and Superwash) are used to select one of the three processing paths described in Figure 2. Therefore, the difference between scenario 4 and scenario 5 is to underline the impact of an additional Superwash process on the overall impact of wool top lots. The wool blend composition is the same between both scenarios. It is important to note that no scenario considering the recombing step was proposed because its impact was considered negligible compared to all other processing steps.

By performing a contribution analysis of the single score results (obtained by ReCiPe endpoint 2016 characterization method (H, A)), we observe that over 58% of the total weighted impact score for each scenario was due to the climate change impact category (see Appendix A). Based on this observation, a contribution analysis by life cycle stage of the climate change impact category has been performed for each of the five modeled scenarios, as presented in Figure 6.
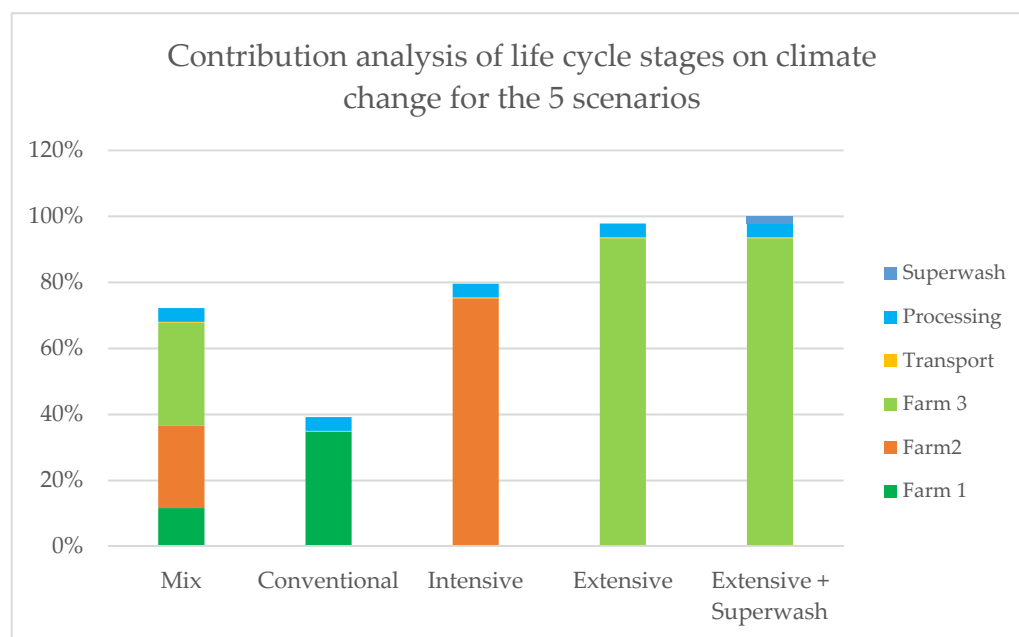
Figure 6. Contribution analysis by life cycle stage on the climate change impact category for the five scenarios defined in Table 2.

It can be observed that in all the scenarios, the upstream agricultural stage of sheep rearing—or farming wool production in the chart legend (including Farm 1, Farm 2, and Farm 3 stages)—contributes more than 90% of the total climate change impact scores. The balance, i.e., less than 10%, is due to the combing mill processing and transport life cycle stages (including Superwash, Processing, and Transport stages in the chart legend). The transport stage has an almost insignificant contribution to climate change, assuming that the transport is done by boat. The first interpretation of these results is that the need to obtain specific production data is particularly important for the agricultural phases of wool products, given their predominant impact. A first limit to the use of blockchain traceability systems for the LCA calculation of wool products can therefore be posed: if the system is not implemented at the wool farming suppliers, the value contribution of blockchain traceability to perform an LCA will be strongly reduced since it will only characterize the transformation stages in a precise manner and will leave a strong uncertainty on the upstream LCA calculation. Thus, an important verification criterion before using LCA-blockchain would be to ensure sufficient adoption of the traceability system on the most contributing upstream life cycle stages of the value chain.

We can see that scenario 2 of pure conventional agriculture (100% of farm 1, the same scenario used to compare generic and specific LCA) represents only 39% of the impact on climate change of scenario 5. In other words, the impact of scenario 5 is +156% compared to scenario 1. The interpretation that can be drawn from these results is that knowledge of both the composition of the wool batches and the optional transformation processes that they undergo is decisive for a good characterization of the impact of the product. In other words, the different batches of wool, which have on average the same characteristics when leaving the factory, can have highly random impacts, varying from more than simple to double.

Figure 7 compares the relative impacts of the five scenarios on different impact categories.
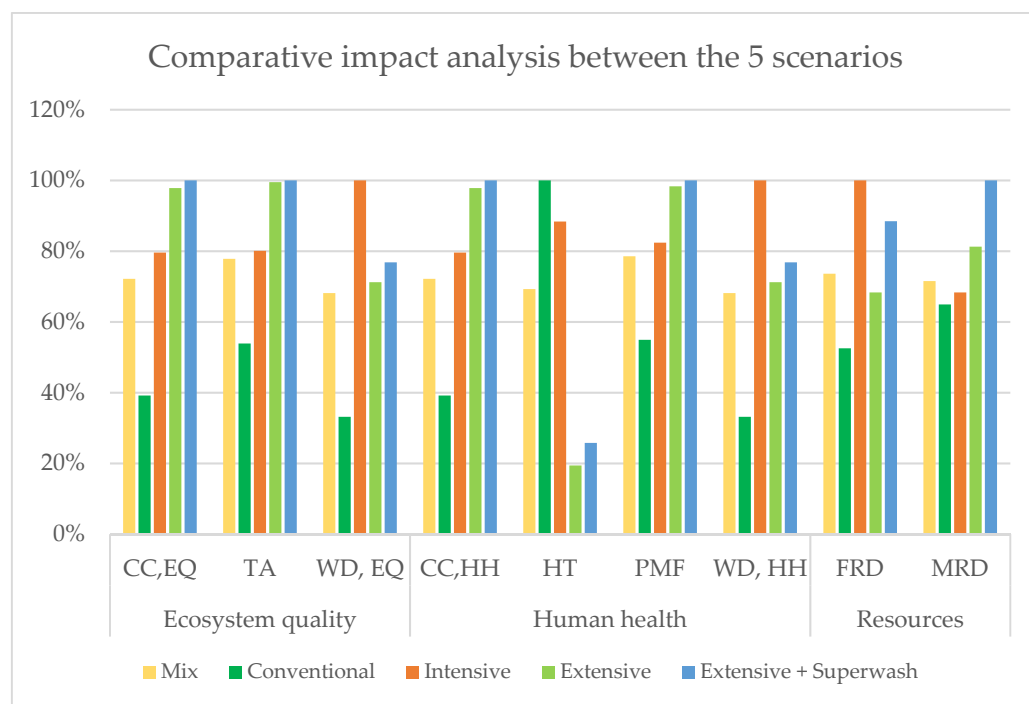
Figure 7. Impact scores expressed in relative terms per impact category. See Figure 4 for the definition of the acronyms of each impact category.

Figure 7 shows that there is an important variation in impact scores between the different scenarios. This variation ranges from +50% for the mineral resource depletion (MRD) indicator between the Conventional and the Extensive + Superwash scenarios and up to +450% for the human toxicity (HT) indicator between the Conventional and the Extensive scenarios. However, this last result must be considered significant since the category of impact on human toxicity has high uncertainty, and only differences over an order of magnitude can be considered significant. Variability across all categories suggests that the parameters modulated in the different scenarios can significantly modify the impact values obtained.

4.3. Outlook

The results obtained allow us to make three statements about the production of worsted wool:

1. The highly specific data provided by the blockchain traceability systems allow the impact of wool lots to be characterized in a much more granular and representative way than generic data. Indeed, the generic data do not provide a sufficient understanding of the impacts at stake in a production system, since the specificity of the data leads to an almost systematic increase in the impact on the different indicators. Therefore, specific traceability data provides a more accurate picture of the impact of production.
2. Blockchain traceability systems are only relevant for LCA calculation if implemented on the upstream agricultural production process, which is the most important stage of the life cycle for the environmental impact of combed wool batches.
3. The impact of worsted wool batches is highly dependent on the origin of the raw materials in the batch, and the optional transformation processes followed. This information can be provided in a differentiated way for every batch by blockchain traceability platforms.

Therefore, it can be argued that blockchain traceability facilitates the creation of LCA inventories and makes it possible to associate each chain of traceability, and therefore each product batch, with a unique environmental impact. It remains to be seen what need

this segmentation of impacts by product batch meets. First of all, we can think of the imminent environmental display of textile products, both at the French environmental labeling level [2] and at the European level with product environmental footprint category rules (PEFCR) [24]. It will soon be legally mandatory to communicate an ABCDE rating representing the environmental impact of its products. Thus, blockchain traceability could be a facilitator for the compliance of industrial actors on this point while providing a lever for improving the environmental impact of new products. Also, differentiating the impact by batch could be an interesting strategic decision support tool for raw material and product buyers. Understanding and evaluating the impact of each single batch according to their origin could make it possible to control and manage the company's sustainable strategy in almost real-time, communicate the company's responsible commitment to its customers, and provide the knowledge necessary for the eco-design of future products. We could even imagine the future use of classification and segmentation algorithms to determine the importance of strategic choices on the impact of industrial products by using the LCA-blockchain results of each product batch as a massive database.

5. Conclusions

This research paper aimed to evaluate how blockchain traceability could improve LCA results' representativity in textile products by enhancing primary data collection and quantifying this improvement potential against a generic LCA. Two main results were obtained: the environmental impact of the wool top lots can vary drastically depending on their composition and the origin of the wool (up to +118% on the overall environmental impact between two batches of different compositions) and the specific data provided by traceability strongly changes the perception of the impact of wool top lots compared to generic data for a fixed wool composition (+36% of calculated impact on the processing step with specific data). From these results, we can conclude that blockchain traceability data could provide a better understanding and characterization of the impacts of a product by unit lot. This increased understanding could help improve the environmental sustainability of the supply chain, guide the product eco-design, and increase transparency on product life cycle impact to the customer.

However, several limitations from an LCA perspective must be mentioned. First, the absence of specific production data for the upstream agricultural phase did not allow us to characterize this life cycle stage in a granular way, although it is the main contributor. This necessarily impacted the level of interpretability of the results obtained. Also, our study has a limited scope, so the conclusions reached cannot be generalized to other cases. There is no guarantee that the conclusions drawn here can be applied to other textile sectors and even less to other industrial sectors. In addition, the final processing, distribution, use, and end-of-life stages of wool products were not modeled in this study.

To address these limitations, several avenues for future research can be envisioned. First, further study on the categorization of farm inventories according to their agricultural practices and location could generate more accurate impact measurement and provide a reference data set of supplier farms in case of unavailability of specific data in the traceability model. Also, other studies quantifying the contributions of blockchain LCA on other textile chains and other industrial sectors would determine whether the conclusions put forward in this article can be generalized. Carrying out large-scale implementation of an LCA-blockchain traceability system could also validate the different hypotheses and findings put forward in this article. The question of trust and data quality entered on the blockchain are other essential questions that need to be addressed in future research.

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Appendix A

This Appendix A discloses the contribution of different impact categories to the single score calculated with the ReCiPe endpoint 2016 (H,A) methodology. The results are shown for each of the five different scenarios in Figure A1.
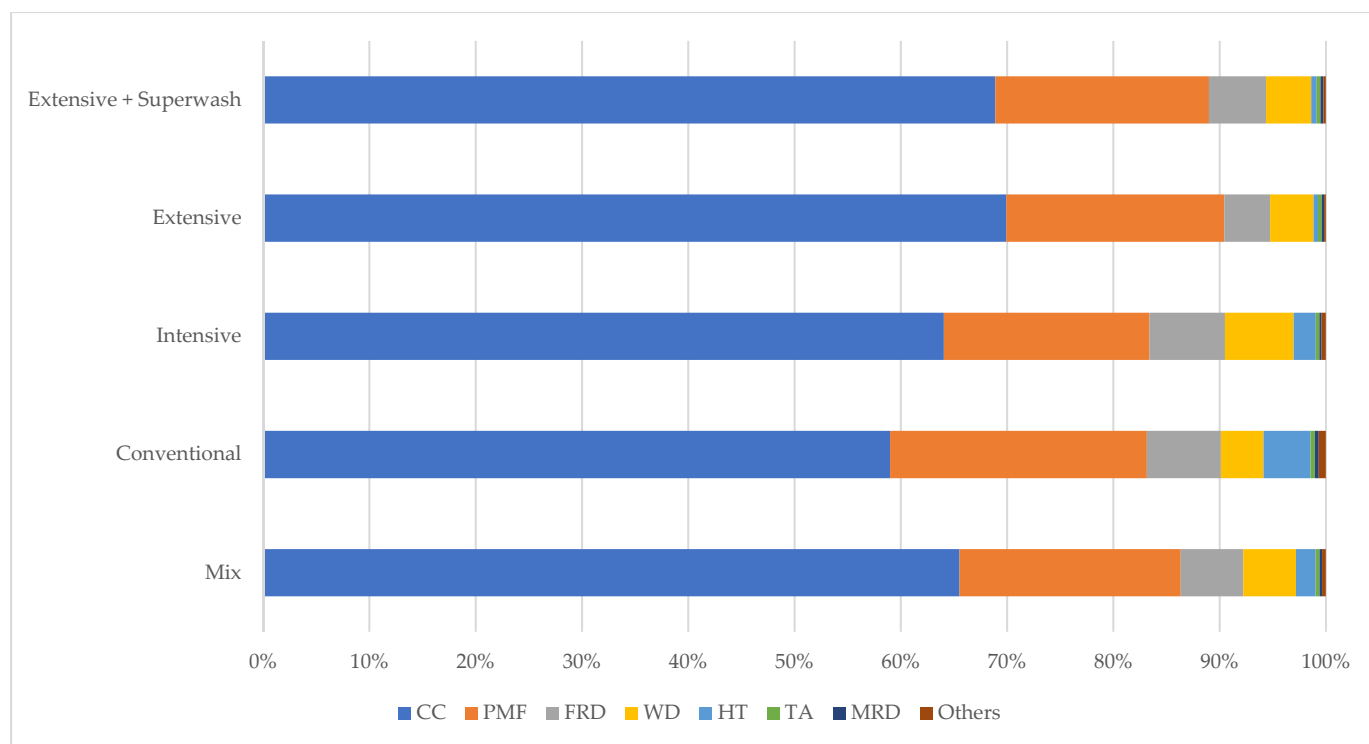
Figure A1. Contribution of impact categories to the single score for the 5 different scenarios. The abbreviations of impact indicators are the following: CC: Climate Change; PMF: Particulate Matter Formation; FRD: Fossil Resources Depletion; WD: Water Depletion; HT: Human Toxicity; TA: Terrestrial Acidification; MRD: Mineral Resources Depletion; Others: all other categories from ReCiPe endpoint 2016 methodology.

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