MANUSCRIPT

Abstract

The textile sector accounts for the fourth-highest usage of primary raw materials and water (after food, housing, and transport), the second-highest usage of land, and the fifth highest Green House Gases (GHG) emissions (EEA, 2017). While Life Cycle Assessment (LCA) has been widely used to assess the environmental impact of fashion, most studies are constrained by the lack of reliable data. Blockchain technology may enable better traceability by making origin and journey more transparent. The potential to integrate LCA and blockchain has been discussed in other sectors, but specific protocols in the fashion sector are largely missing. This study aims to address this by a) exploring the use of LCA to measure the impact reduction potential of circular strategies and b) proposing a protocol for the integration of LCA and BC to accurately assess circular practices. Using leather handbags as a case study, an LCA study is conducted comparing two circular scenarios against a baseline to quantify potential benefits from circular strategies. Subsequently, it builds a blockchain-based LCA framework to unleash circularity opportunities through enhanced traceability and data sharing. Results point to substantial environmental benefits from the circular strategies, for example, circular scenario 2 (reuse markets/ second-hand leather bag) was estimated to cause between 34.8% and 53.8% lower impacts while circular scenario 1 (leather alternative) contributed to impact reduction of more than 35% of the impacts in most impact categories (10 out of 18). The results also highlight the contribution of blockchain technology to enable traceability and reliable data for identification of environmental hotspots and accurate quantification of circular potential.

Keywords: circular economy, fashion, circular fashion, Block Chain, life cycle assessment.

1. Introduction

The environmental sustainability of the fashion industry has become a growing concern for consumers and policymakers in recent years. The sector accounts for the fourth-highest usage of primary raw materials and water (after food, housing, and transport), the second-highest usage of land, and the fifth highest GHG emissions (EEA, 2017), and has been classified by the European Commission's Joint Research Centre (JRC, 2015) as a "priority group, which makes a significant contribution to environmental impacts in Europe". Based on a linear system, the fashion industry not only extracts massive amounts of natural resources to produce textiles and accessories, but also generate annual waste streams worth USD 460 billion (Ellen MacArthur Foundation [EMF], 2017). By 2030, clothing consumption is expected to rise by 63% from 62 million tonnes today to 102 million tonnes (Global Fashion Agenda [GFA] & Boston Consulting Group [BCG], 2017).

This all call for a transition to a circular fashion economy, in which fashion products are designed and produced in a way that maximises their use and minimises environmental pressures from production to disposal (EMF, 2017). Such a systemic change within the industry faces several barriers, starting with a lack of transparency and traceability within complex global fashion supply chains (Fashion Revolution, 2020). This barrier also presents a major challenge to reliable data collection, which is essential for accurately measuring and managing environmental impacts of products (Zhang et al., 2020). One emerging solution is blockchain technology (BC), which enables traceability and access to reliable data all the way from raw material sourcing to the end consumer, and even further to secondary markets or disposal (Rusinek et al., 2018; Cognizant, 2018). Blockchain technology, in essence, can be described as a distributed system (e.g. database) that records transactions and information on a ledger held by a peer-to-peer network. The technology provides all network participants with a copy of the distributed ledger, without the need of a central authority to access information (Swan, 2015).

What makes the technology unique is not only the decentralised character of the registers in the network, but also the transparency of transactions. The consensus mechanisms and use of cryptographic technology contribute to the immutability of the database, making it very difficult to tamper with.

This research proposes a framework on how blockchain technology and LCA can be combined for traceable, circular fashion value chains, using leather handbags as a case study. Leather is one of the most environmentally problematic materials used by the fashion industry (Chrobot et al., 2018; GFA & BCG, 2017; Gottfridsson & Zhang, 2015), and is widely used in handbags and other fashion accessories (Grand View Research, 2018). At the same time, this product category presents ample opportunities for circular measures, which range from secondary markets and the use of alternative materials, which are relatively well established for handbags (BCG, 2019; Pithers, 2019). Although many recent reports and studies propose general pathways for circular fashion, there is still insufficient understanding of implementation frameworks for measurable monitoring systems for circular strategies. Contributing to address this gap, this research aims to fulfil the following objectives:

1) Understand the strengths and weaknesses of using LCA as a tool to: a. identifying environmental hotspots and b. assessing opportunities for circular fashion strategies.
2) Build understanding around the integration of blockchain technology and LCA to promote circular fashion strategies.

To fulfil the research objectives, this study is organised into five sections. Following this section, Section 2 presents the literature review. Section 3 describes the research methodology of the study. Section 4 presents and discusses the results, recommendations, and limitations of the environmental impact assessment and the blockchain-based LCA framework. Lastly, Section 5 concludes this study by highlighting key findings and areas of future research.

2. Literature review

2.1. Environmental impacts of fashion and fashion accessories

The fashion industry was responsible for 4% of global GHG emissions in 2018 (McKinsey & GFA, 2020) and dyeing and treating processes accounts for approximately 20% of total industrial water pollution (Kant, 2012). During production stages, vast amounts of natural resources are used, including land, water and agrochemicals to grow cotton, oil to produce synthetic fibres, chemicals to dye and finish textiles, and energy to power all stages from raw material extraction to cutting and sewing into finished products (JRC, 2014). While the production phase of textiles is the main contributor to the industry's total ecological impacts, impacts from the transport, retail, use, and end-of-life phases also pose significant burdens in terms of GHG emissions and waste generation (JRC, 2014; Van der Velden et al., 2014; McKinsey & GFA, 2020). Several LCA studies have been conducted to measure the environmental impacts of fashion textiles over its entire lifecycle. In Chrobot's et al (2018) study, main impacts during the production stage are driven by the processes of dyeing and finishing, yarn preparation, and fibre production. Dyeing and finishing require fossil-based energy and large amounts of chemicals, and account for a large fraction of the total industrial water pollution (Kant, 2012). Fibre production, on the other hand, has the highest impact on freshwater use and ecosystem quality, due to the cultivation techniques with high reliance on agrochemicals and water (Zhang et al., 2015).
One important material in fashion and fashion accessories is leather, which has associated higher impacts per kilogram of material than cotton and artificial fibres (GFA & BCG, 2017). LCA studies suggest that leather production contributes significantly to eutrophication, acidification, climate change, and water scarcity (ibid.; Gottfridsson & Zhang, 2015). Chobrot

et al. (2018) compared leather shoes with synthetic and textile shoes, to conclude that while leather shoes make up 25% of overall footwear production, they account for as much as 30% to 80% of environmental impacts, depending on the impact category. Main hotspots in terms of impacts are associated with cattle-raising and slaughtering processes. Raising cattle is highly land-use intensive and generate GHG emissions from land-use change, agrochemicals use, and enteric fermentation (Gerber et al., 2013; Herrero et al., 2009). As leather hides are usually by-products from the meat and dairy industry, allocated of impacts to leather production is a key step (De-Rosa Giglio et al., 2018). In terms of leather processing, the tanning process is the most impactful (Notarnicola et al., 2011). This phase is characterised by the use of the tanning agents in order to achieve the desired chemical and physical properties of leather (China et al., 2020) releasing as a result pollutants to water (e.g. Cr(III), chlorides, sulphides) and air (e.g. VOCs, PM), of which Cr(III) is most concerning due to its common conversion to the highly carcinogenic Cr(VI) in wastewater (China et al., 2020; Van Rensburg et al., 2020). New bio-based alternatives to conventional metal based tanning agents may reduce toxicity but chrome-based tanning remains to be by far the most common tanning method (De-Rosa Giglio et al., 2018).

Environmental impacts of fashion products in downstream stages are dependent on several variables such as consumer care, lifespans, and selected disposal routes. Activities such as that washing, drying and ironing, and synthetic fibre shedding during washing drive impacts during the use stage (Laitala et al., 2018; van der Velden et al., 2014), although leather products use-phase impacts tend to be lower. The fast fashion trend has also resulted in a reduction of the average lifespan of fashion items (EMF, 2017), which has fallen to only 3 years in the UK (WRAP, 2017). Main disposal routes for fashion items, around 75%, are still landfill and incineration (JRC, 2014; EMF, 2017), with only around 25% of apparel collected for reuse and recycling globally, and less than 1% of global textiles recycled back into clothing (Juanga-Labayen et al., 2022). Trade flows of secondary fashion items are also not unproblematic as the largest fraction of apparel collected for reuse is exported to Eastern European and developing countries (Ljungkvist et al., 2018), creating issues down the line in terms of inadequate disposal. The standard practice of blending materials in fashion items complicates the separation of different fibres and materials (Payne, 2015). Consequently, less than 1% of fashion waste is used back in the sector, as most of it is downcycled into lower-quality applications, such as insulation materials (Fletcher, 2008).

2.2. Circular fashion as a solution to mitigate fashion's impacts

Awareness of the impacts of fashion have enticed commitment and action towards a more sustainable fashion sector (EMF, 2017; Roos et al., 2015) which has also resulted in increased attention by the literature. The Circular Economy framework has been applied to the fashion industry to map avenues for 'clos(-ing) the loop of fashion' (Circular Flanders, n.d.) and moving away from a linear system to a restorative system. The Circular Economy is a system approach which tries to reduce dependency on primary materials, reduce energy intensity and eliminate waste by keeping products and materials in use an/ or repurposing them at the end of life (see, e.g. Ghisellini et al., 2016 or Geissdoerfer et al., 2017 for a review of the concept).

There are several contributions that map out CE strategies in fashion. Chen et al. (2021) offer a review of key strategies across key stages of the supply chain; Brydges (2021) investigates key CE strategies of Swedish based fashion companies and brands to conclude that while initiatives to address waste are started to be embedded into business practices integrated strategies covering all life cycle stages are less common. Several contributions have focused on Circular business models. These contributions cover ways to recover and recycle textiles (Ma et al., 2019; Bukhari et al., 2018; Jonsson et al., 2021), the design of circular textiles

(Moorhouse and Moorhouse, 2017; Smith et al., 2017) and the role of consumer/ user in circular textiles (Wagner and Heinzel, 2020; Koszewska, 2019). Resale and rental models have also been explored as a way to disrupt the disposable nature of current fashion trends through lifetime extension (Sweet & Wu, 2019). The functioning of secondary textile markets has also been investigated. Sandin and Peters (2018) highlight environmental gains of reusing textiles compared with recycling, assuming secondary textiles displace primary production (Sandin & Peters, 2018). However, the rate at which used fashion products displace new ones is a contested issue and is highly dependent on the quality of products and the user needs (WRAP, 2011). Some estimates suggest a 65% replacement rate (Farfetch, 2020).

While most of the above noted studies look at fashion in general or fashion textiles, less attention has been paid to the accessories sub-sector. In the case of leather fashion products, alternative materials imitating the look of leather have been developed to respond to animal welfare concerns and toxicity- and water use-related impacts from leather production. Some initial LCA studies comparing the environmental benefits of leather alternatives have been conducted. GFA & BCG (2017) report that synthetic leather made from polyurethane may cause only a third of the impact in global warming and eutrophication compared to conventional leather. A preliminary LCA study found that imitation leather from hemp could have roughly 80% lower acidification and global warming potential than bovine leather (Hultkrantz, 2018). However, no studies have specifically addressed and attempted to quantified environmental benefits of circular economy practices in the leather-accessories market. Some general research has shown that lifetime extension of products could play an important role in lowering impacts (e.g. WRAP (2012) estimated that extending a garment's lifetime by just nine months can lower its water, carbon, and waste footprint by 20-30% respectively), but this and the development of secondary markets specifically for leather fashion products has not been explored.

2.3. Blockchain technology as an enabler for circular fashion

One critical element in the development of circular practices in the fashion sector is enhanced traceability and assured provenance of goods (Schenten et al., 2019; Boiten et al., 2017; Fashion Revolution, 2020; Koksal et al., 2017). In an industry characterised by highly fragmented supply chains (Gereffi & Frederick, 2010), access to accurate data across different processes and stages can be extremely challenging. This limits opportunities to increase efficiency, assess environmental hotspots and organise circular practices which require involvement of the whole supply chain. Blockchain technology has recently received much attention as an enabler of transparency and traceability in global supply chains (Swan, 2015; Deloitte, 2017). Application sectors for the tracing technology have been examined notably in food, pharmaceuticals and luxury sector (Tan et al., 2018; Rotunno et al., 2014; Choi, 2019), where traceability is vital to achieve assurance concerning the chain of custody. Pautasso et al. (2019) examined the application of blockchain to the fashion industry and found that traceability is one of the main opportunities for companies, gaining disclosure of information on the origin of raw materials, processing, and end-of-life routes. When integrated with Internet-of-Things (IoT) technologies, such as RFID sensors for automatic data collection, blockchain technology can track a product and record its "digital footprint" along its entire value chain (Wang et al., 2019). Increasing the entire value chain transparency, may enable brands to introduce evidence-based solutions to address sustainability and circularity concerns, and consumers to make more sustainable purchase choices (Rusinek et al., 2018; Kearins & Wallace, 2020). Rusinek et al. (2018) note that blockchain also empowers consumers to adopt better care and disposal behaviours through blockchain-enabled information. The technology has the potential to facilitate closed-loop systems due to its material traceability function (Rusinek et al., 2018; Rudolphi, 2018). For instance, resale markets can capitalise on product traceability by ensuring the authenticity of the product (Kulkarni, 2018). Recyclers can benefit from increased accurate information about material composition which, coupled with automated sorting processes, can improve materials sorting (Fletcher, 2012). The transparency of information throughout the entire value chain of a product system may also be used to gather accurate data for estimation of environmental impacts, combining LCAs with blockchain and IoT technologies (Zhang et al., 2020). Thus far, however, there is a lack of applied research looking at the potential to connect blockchain and LCA to better assess environmental hotspots and quantify impact reduction potential of CE practices.

The literature has highlighted data gaps for estimation of environmental impacts using LCA. Blockchain technology, as an enabler for transparency and traceability, may enable up-to-date and real time data collection, thereby enabling assessment of circular fashion strategies. So far, though, integrative approaches combining LCA and BC are largely missing. This research aims to fill the gap in the literature by examining the role of LCA and blockchain technology to promote circular fashion, taking a case study approach of leather bags. This also contributes to shed some light on CE potential for the fashion accessories market, which has been overlooked in the literature.

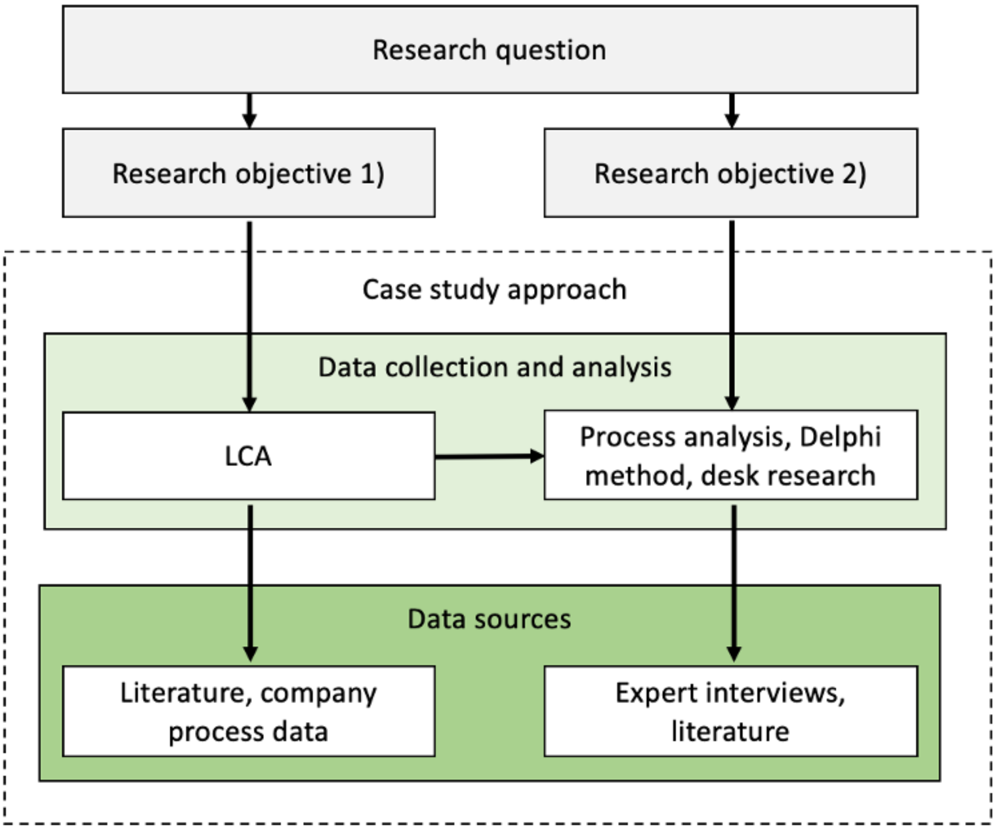
3. Methods, modelling and data

Based on the identified research gaps, this study is driven by the research question of ‘how the integration of blockchain technology and LCA can enable the adoption of circular strategies in the fashion industry’, using leather bags as case study. The specific research objectives include:

1) To understand the strengths and weaknesses of LCA as a tool for assessing circular fashion strategies, using leather bags as a case study.
2) To understand and discuss how the integration of blockchain technology and LCA can enable circular fashion strategies.

Figure 1 illustrates the methodological approach taken. To fulfil the research objectives, leather handbags were used as a case study, as they represent a product category with promising potential for circularity (BCG, 2019). Case studies are intensive studies of single cases for the purpose of drawing conclusions on a larger class of similar cases (Gerring, 2007). Thus, they are suitable for exploratory research, as they are effective for theory-building and generating frameworks (Baskarada, 2014). Within this case study, a mix of quantitative and qualitative methods was used to achieve the research objectives. To realise the first objective, an LCA model was developed to assess and quantify impacts of a standard leather handbag. The LCA model allowed to identify hotspots and develop and evaluate different circular scenarios. The LCA model developed also contributed to identify challenges and opportunities associated to the use of LCA applied to complex fashion value chains. This was then used as the basis for the second main area of enquiry, the assessment of the potential of blockchain to address data limitations and enable circular practices. This part of the research was based on an iterative process of interviews conducted with experts on blockchain technology applied to fashion. Details of the methods are provided in the sections below.

Figure 1. The methodological approach of this study.



Source: authors’ own elaboration.

3.1. LCA model of leather handbags

The LCA method adopted in this study followed the ISO 14040:2006 standard guidelines. This study used the software SimaPro v8 to carry out the impact assessment of all scenarios and EcoInvent database.

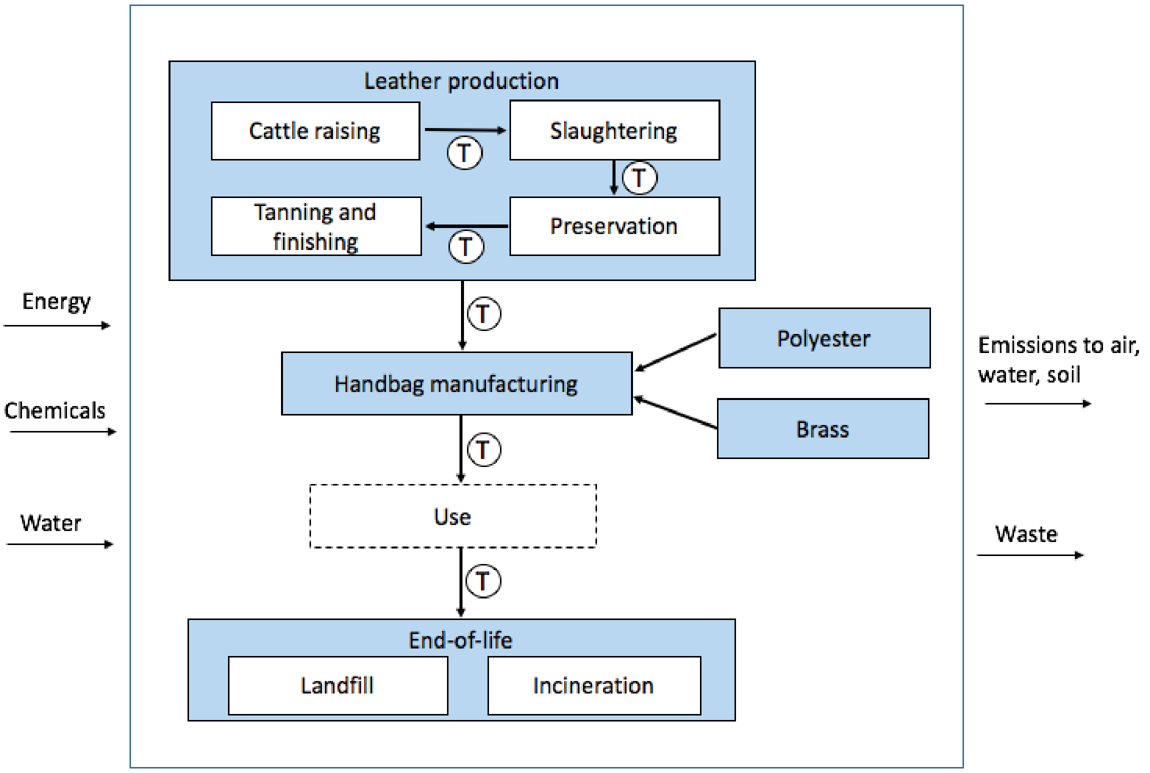
3.1.1. Goal and scope definition

The goal of the LCA study is to assess the lifecycle impacts of a standard bovine leather handbag and compare them with two more circular scenarios, to estimate the potential role of CE practices in lowering the impacts of fashion accessories.

The scope of the study is from cradle to grave, covering production, distribution, and end-of-life disposal of the handbag (Figure 2). The main material for the baseline handbag is leather, for which the European Product Environmental Footprint Category Rule (PEFCR) was followed to assess the impacts of leather production. Leather was assumed to be a by-product from the meat and dairy industry and impacts from cattle farming and slaughter were determined through allocation rules. See SI for more details.

In contrast to apparel, leather handbags are rarely washed during their lifetime. Hence, energy use, water use and microfiber shedding, which normally drive impacts for textiles during this stage (Laitala et al., 2018), were negligible in this study.

Figure 2. System boundary of the leather handbag.



Source: Authors' own elaboration.

The functional unit (FU) chosen for the baseline scenario was one bovine leather handbag (1.6 mm thickness), with the dimensions 41 cm x 28 cm x 12 cm, two carrying handles of 30 cm, polyester lining, and brass trimming from cradle to grave.

3.1.2. Inventory analysis

Inventory data for the baseline handbag was mostly based on secondary data. Data sources include academic studies on leather production (e.g. Notarnicola et al., 2011; Gottfridsson & Zhang, 2015), the European PEFCR for leather, expert inputs, and global databases (EcoInvent v3). Some primary data was collected concerning the composition and weight of the leather handbag components, based on own measurements and information from websites. For the detailed lifecycle inventory, please see S1 in the SI.

Production

The bill of materials is shown in Table 1. Even though the amount of leather of the handbag was calculated to be 0.388 m^2 (including seam allowance), more leather is likely used for the manufacture, due to quality losses and cutting wastage (DeGraeve, n.d., Sterlacci, 2010). Based on this, a total requirement of 0.54 m^2 of 1.6 mm leather was deemed appropriate and was validated by an expert, who recommended a 20-30% cutting waste loss.

Table 1. Bill of Materials of leather handbag.

Materials	Amount
Bovine leather (body, handles, inner trimmings)	0.388 m^2 or 473 g in the final product, but 0.54 m^2 or 660 g required for the production
Polyester (lining)	45 g
Brass (zipper, buckles, buttons)	80 g

Distribution

The distribution includes transportation of the handbag from the Italian manufacturer to the UK-based distribution centre by road freight.

End-of-life

As for most textiles, the majority of leather goods is disposed of through landfill or incineration (Pringle et al., 2016). Recycling of leather, whether through mechanical, chemical or biological processes, remain only at research-scale. No accurate data on end-of-life treatment for leather goods exist, so values from EU clothing disposal rates (JRC, 2014) were taken as an approximation.

3.1.3. Impact assessment

The method for impact assessment adopted was ReCiPe Midpoint (H), consisting of 18 impact indicators, including climate change, ozone depletion, human toxicity, terrestrial acidification, terrestrial ecotoxicity, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, marine eutrophication, photochemical oxidant formation, particulate matter formation, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, fossil depletion.

3.1.4. Scenario development of circular handbags

The two circular scenarios were analysed. The construction of the scenario was based on current practices in the fashion accessories market and compared to the baseline handbag scenario (no circularity assumed). Two scenarios were developed: 1) Scenario 1 depicts CE practices associated to life extension through secondary markets, and 2) Scenario 2 represents circular practice associated with material substitution, testing a leather-alternative handbag. Scenario 1 was constructed based on a 65% displacement rate of second-hand fashion purchases, as suggested by literature (Farfetch, 2020; WRAP, 2011), plus adding additional impacts from transport and end-of-life phases associated with reverse logistics (see SI for detailed inventory and additional information). For constructing scenario 2, primary data from a manufacturer of an alternative leather material made from agricultural waste was used. This plant-based leather has the same thickness as the animal leather used for the baseline handbag, allowing for optimal comparability (see Appendix A.2). Apart from the agricultural residues, the production of the plant-based material requires the inputs of water, energy and chemicals (as described in the inventory provided in the SI). The remaining inventory for the bag production remains the same as for the baseline leather handbag.

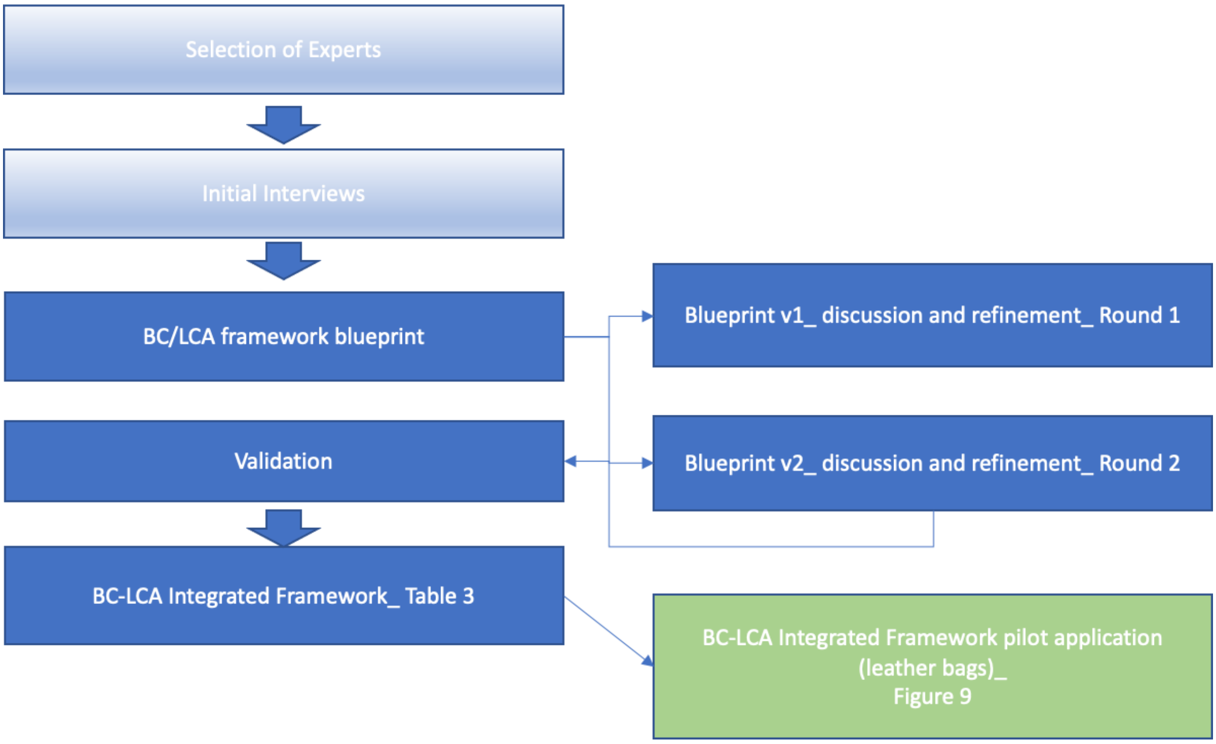
The FU for Scenario 1 is one second-hand leather handbag (1.6 mm thickness), with the dimensions 41 cm x 28 cm x 12 cm, two carrying handles of 30 cm, polyester lining, and brass trimming from cradle to grave. The FU for Scenario 2 is a plant-based leather handbag with the same dimensions and features as Scenario 1 from cradle to grave.

3.2. Blockchain-based LCA Framework

The findings from the LCA model above were used to guide the development of a framework for blockchain-LCA integration for circular fashion. An understanding of leather supply chains, hotspots, and data challenges of LCA served as a basis for developing the framework. Since research in the field of blockchain technology for fashion is scarce, qualitative methods were deemed appropriate to develop understanding of an explorative area (Merriam & Tisdell, 2015) such as the integration of blockchain and LCA. A process analysis, which involves gaining an understanding of business processes, including actors, procedures, technologies, data, and their interactions (ABPMP, 2019), was carried out to understand how blockchain technology can enable more circular practices in fashion. Primary data for the analysis was collected through an iterative Delphi-inspired method and complemented with desk research. The Delphi method is a widely used method for collecting data from participants within their area of expertise, employing several iterations of data gathering (Hsu & Sandford, 2007).

Seven experts were chosen through a targeted sampling method, whose backgrounds complemented each other, as shown in Table S10 in SI. Initial data was collected through two semi-structured interviews, as they allow for certain flexibility for interviewees to express more complex phenomena that would be difficult to capture in fixed questionnaires (Robson, 1993; Merriam & Tisdell, 2015). Based on the interviews with the first two participants, an initial blueprint (blueprint v1) was developed that was later refined through an iterative feedback process conducted via email. Participant 3 provided feedback on the initial blueprint during the interview, and then comments during the iterative process. All seven interviewees participated in an iterative process of refining and validating the original blueprint, into the proposed framework, which is presented in Table 3, section 4.2.3. After two rounds of iterations, the participants did not provide any more feedback other than the approval of the general validity of the framework, reaching saturation point. Figure 3 illustrates the process of development and validation of the proposed framework.

Figure 3. Delphi-inspired method for the development of the BC-LCA framework



Source: authors' own elaboration.

Primary data was then complemented with secondary data included academic and grey literature, company websites and internal presentations, which provided a basis for refining the blueprint and validate data gathered from the interviews.

3.3. Limitations

Leather handbags were chosen as a case study to illustrate the potential for integrating LCA and BC, but since they are one of many fashion product categories, the extent of generalisability of the findings may be restricted to fashion accessories rather than fashion textiles in general (Baskarada, 2014). Handbags differ from other fashion products in their composition, processing/ manufacturing processes, use life (including lifespan) and end-of-life, and, therefore, suitable circular strategies may differ significantly from other fashion goods. Still, complex supply chains typical for fashion products are well-represented by this case study and that illustrates the representation of the role of traceability as a key enabling factor of circular strategies in fashion.

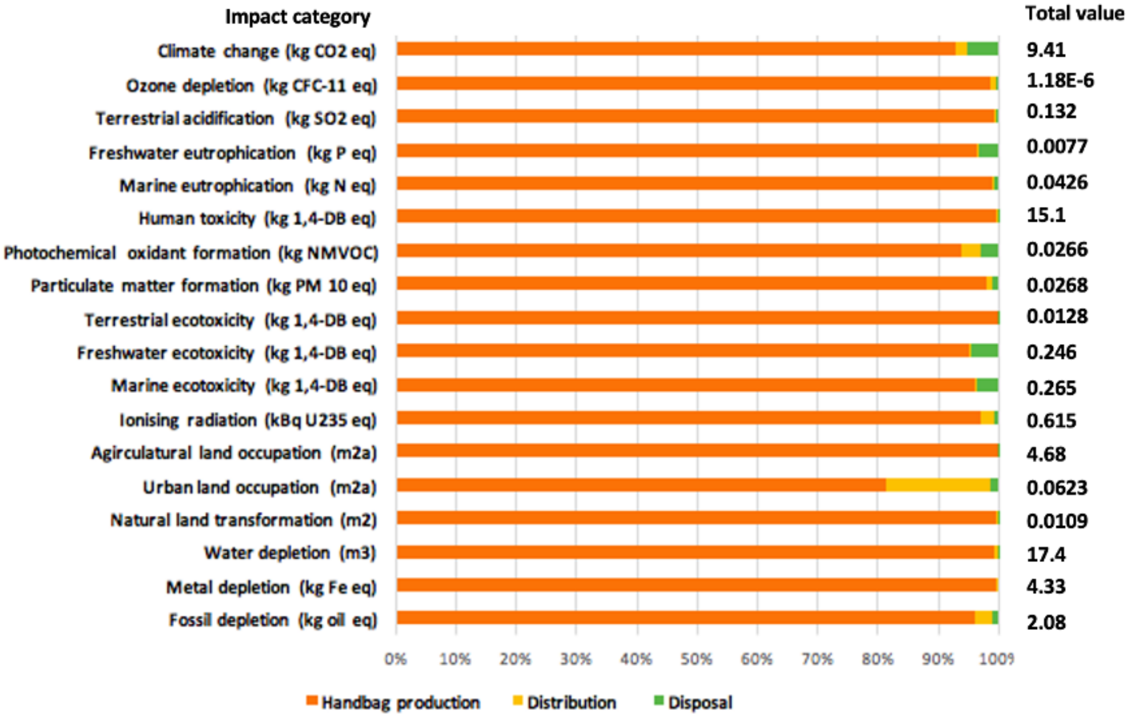
The applicability of framework beyond leather handbags, may work with adaptations, as suggested by contacted experts. The exploration of circular strategies in this research has been limited to two main types of strategies: 1) material substitution and 2) life extension through secondary markets. Other strategies exist, but the purpose of the paper was to illustrate how the integration of LCA and BC could enable better monitoring and quantification of impacts, identification of hotspots and adequate evaluation of circular interventions. The framework acts thus as an enabling tool for circularity rather than a strategy for circularity in itself.

4. Results and discussion

4.1.1. LCA results of the leather handbag

The environmental impacts of a leather handbag are shown in Figure 3. Out of the considered stages manufacturing has the largest contribution across all impact categories (>90% in 17 out of 18 categories, which is agreement with findings from the literature (JRC, 2014; McKinsey & GFA, 2020). Distribution only accounts for less than 5% of impacts in 17 out of 18 categories, and the end-of-life contributes less than 6% in any category.

Figure 4. Impact results of the leather handbag.



Normalised results are used to understand the relative significance of the impacts. Figure 5 shows that key normalised impact categories are natural land transformation, followed by marine ecotoxicity, freshwater ecotoxicity, human toxicity, and freshwater eutrophication. A look at Figure 6 provides insights into the specific drivers behind each impact category. As expected, most impact categories (11 out of 18) are driven by the production of leather, including natural land transformation due to farming and tanning activities.

During the manufacturing stage, the tanning process is especially burdensome due to the use of chemicals such as basic chromium sulphate and the greasing agent, also validated in the literature (Notarnicola et al., 2011). The cattle-raising stage is another of the key processes in terms of environmental impacts (> 65% in 4 out of 18). The impacts attributed to this stage are significant, considering only 0.42% of impacts were allocated to leather production. These findings are in line with research on environmental impacts of beef and livestock reported in the literature (Head et al., 2014; Gerber et al., 2013; Herrero et al., 2009).

Compared to the cattle-raising and tanning stages, slaughtering and preservation exhibit much lower impacts across all categories, which is also in line with previous studies (Notarnicola et al., 2011; Deselnicu et al., 2014). Brass is the other significant contributor, dominating in metal depletion and freshwater eutrophication, human toxicity, freshwater ecotoxicity, and marine ecotoxicity (> 70% of impact). Brass is an alloy of copper and zinc, the productions of which are chemical- and energy-intensive, causing impacts in marine ecotoxicity and freshwater ecotoxicity (Beylot and Villeneuve, 2017; Nuss & Eckelmann, 2014). This illustrates how leaving out any unnecessary brass trimmings or replacing them with recycled metals could significantly improve a handbag's environmental impact.

In contrast, neither the use of polyester nor electricity use during the manufacturing stage has remarkable effects on overall impacts. This suggests that measures to reduce impacts should focus on the production of leather, and more specifically on the tanning and finishing processes as well as the cattle raising stage. Figure S2 in the SI shows the impact results of 1 m^2 leather and table S11 compares the results with results reported in the literature.

Figure 5. Normalised results of the leather handbag.

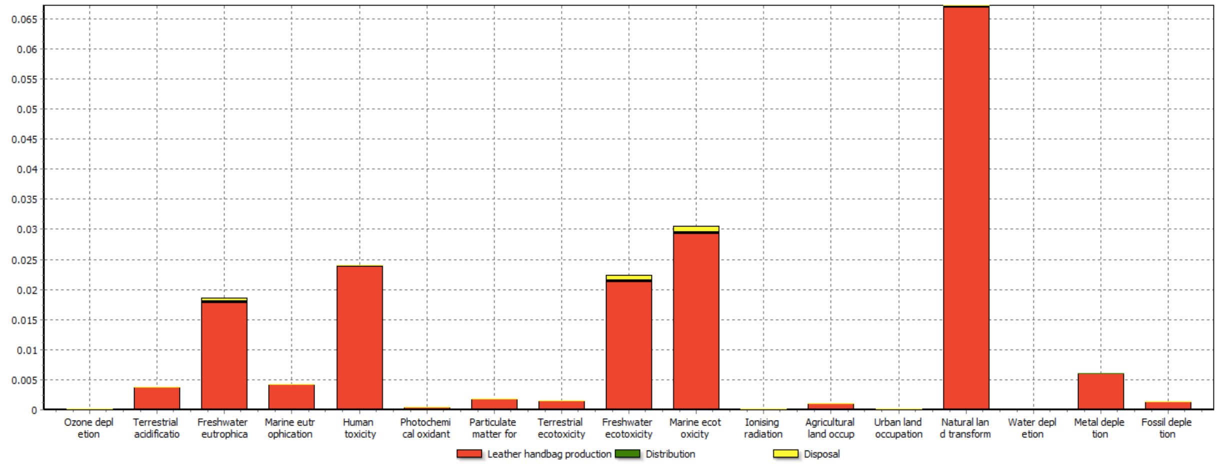
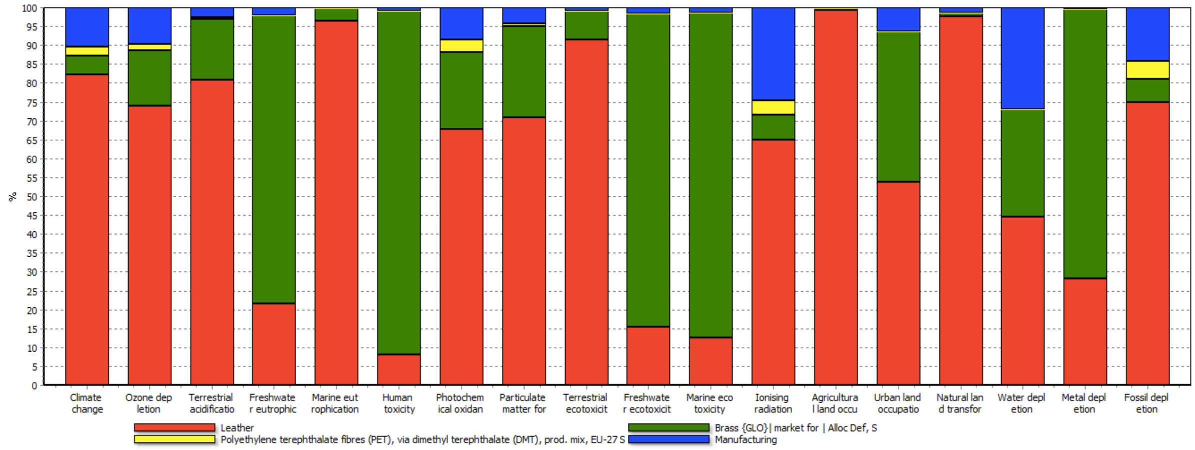


Figure 6. Contribution of materials and processes from leather handbag production to impacts.



4.1.2. Comparison of circular scenarios

The two circular scenarios proposed in this study reduce overall impacts, across all categories. Figure 7 and Table 2 summarise the comparison of the circular scenarios against the baseline scenario. The Scenario 2, second-hand bag, results in impact reduction between 34.8% and 53.8% compared to the leather bag across all impact categories. Similarly, for Scenario 1, the plant-based leather bag, scores are lower in all impact categories except for ionising radiation, due to the higher use of fossil fuel-based electricity during production. In most categories (10 out of 18), the alternative leather bag saves more than 35% of the impacts compared to the leather bag. However, for other set of indicators, such as freshwater ecotoxicity, marine ecotoxicity, human ecotoxicity, freshwater eutrophication, and water depletion, the gains of the plant-based bag compared to the conventional reference leather bag were relatively small (< 13%), as most of these impacts (except for water depletion) were driven by the brass components in the leather bag, which were assumed to be the same in the leather alternative model.

Scenario 1 exhibits even lower impacts compared to scenario 2 in terrestrial acidification, marine eutrophication, terrestrial ecotoxicity, agricultural land occupation, and natural land transformation, because it was assumed that the material feedstock was sourced from agricultural waste, requiring no direct land or agrochemical inputs.

For the complete characterisation results of both circular scenarios, see SI (table S12, S13, S14).

Figure 7. Comparison of the circular scenarios against the baseline leather handbag.

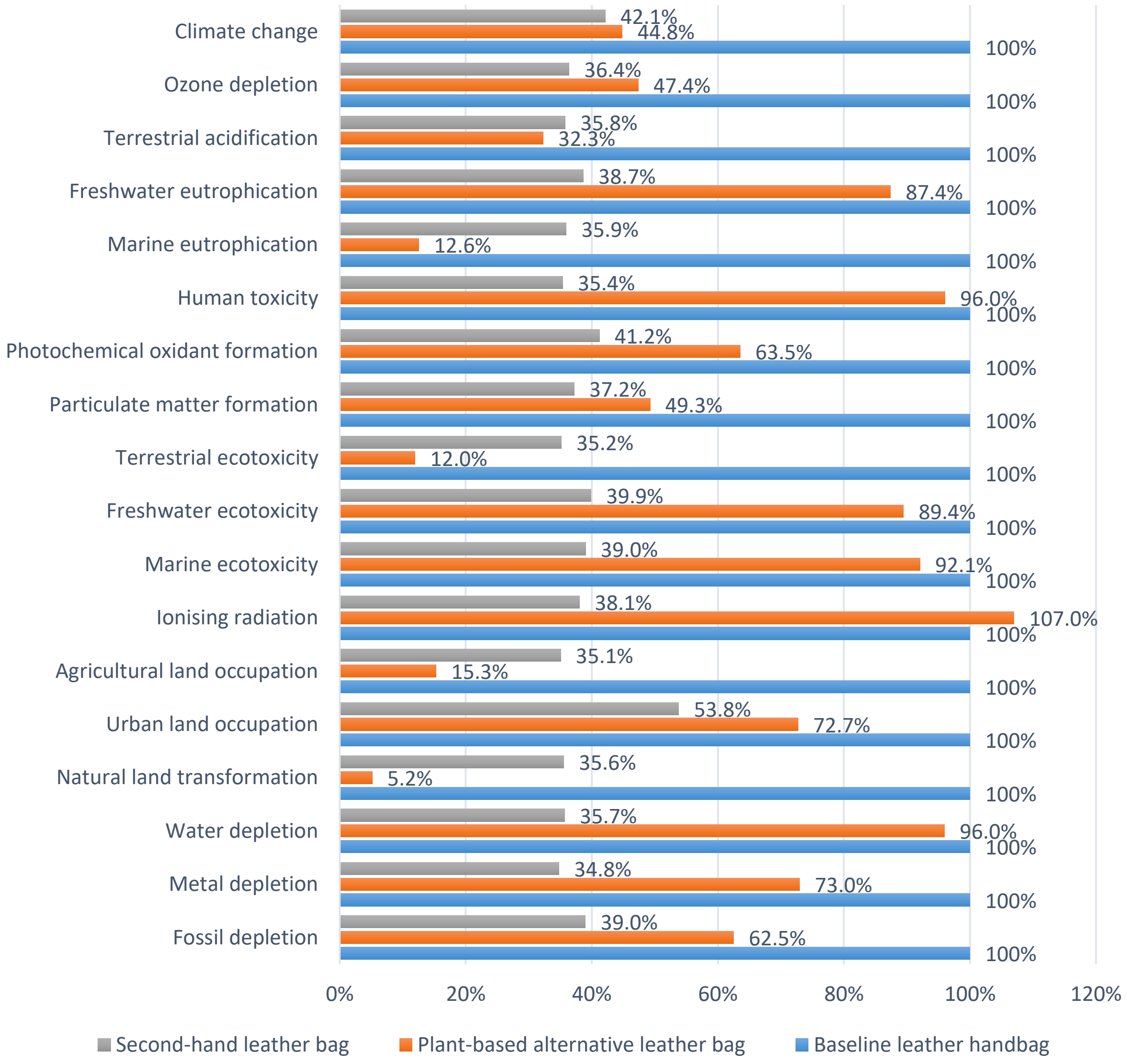


Table 2. Comparison of the handbags in selected impact categories.

	Leather handbag	**Second-hand bag**	**Plant-based handbag**
Climate change (kg CO_2-eq)	9.41	3.96	4.22
Water depletion (m^3)	17.4	6.21	16.7
Human toxicity (kg 1,4-DB eq)	15.1	5.34	14.5
Natural land transformation (m^2)	0.011	0.004	0.0006

4.2. Blockchain-based LCA framework

Based on the results from the LCA study and the limitations, highlighted by this and previous research, to access accurate data, this section reports the blockchain-LCA framework proposed in this study.

4.2.1. Blockchain for circular fashion

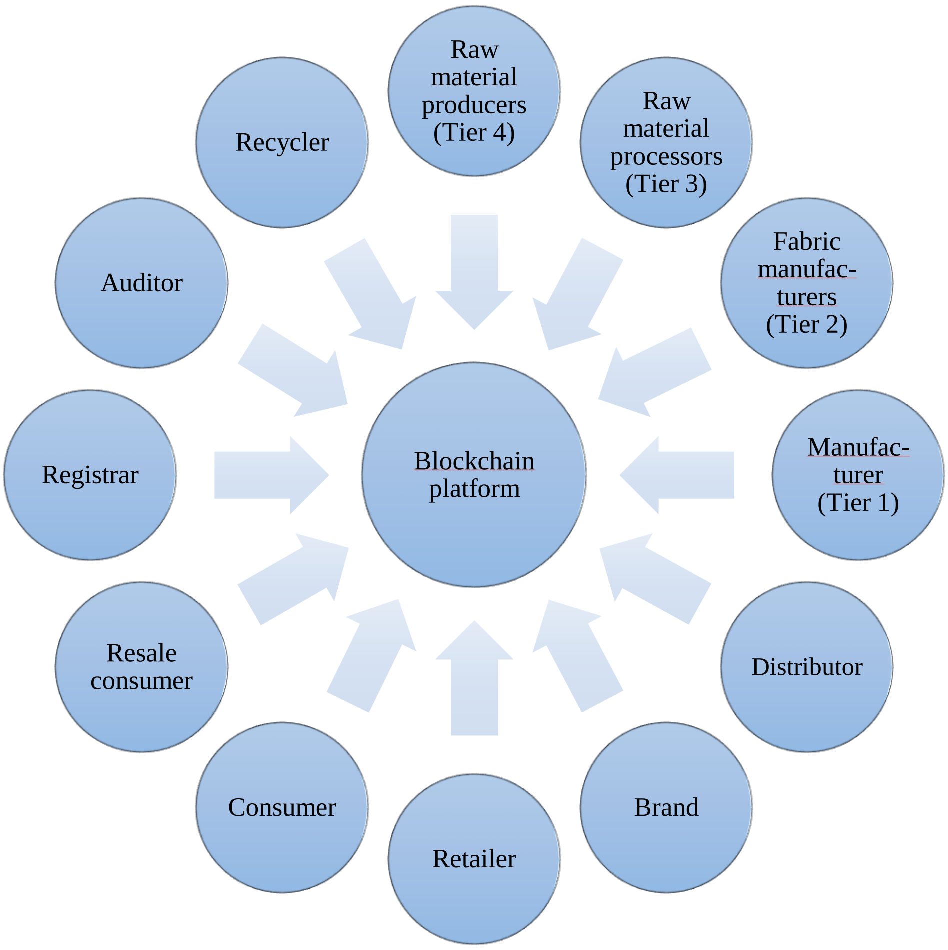
The following protocol describes the stylised process of how blockchain technology works and how it can enable enhanced circularity in fashion value chains, based on results of the Delphi-inspired process.

1. An actor (e.g. slaughterhouse) records their asset (e.g. raw hide) with a unique batch ID on the blockchain. By embedding the batch ID onto smart tags (e.g. RFID, NFC) on the asset, its digital identity is linked with the physical material. The actor initiates a transaction (e.g. selling a batch of raw hide), which must be authenticated by the buyer (e.g. tannery). The buyer authenticates the asset by using sensor technology. Through the transaction, a block is created recording information incl. supplier information, batch ID, location, time, and process data for the LCA.
2. With each further transaction along the supply chain (e.g. selling finished leather to manufacturer), the above process is repeated, and a new block with respective information is added onto the blockchain.
3. The final manufacturer embeds a unique ID on or into the item, enabling traceability and authentication of the item. A digital ownership certificate is created on the blockchain, which includes traceability information (e.g. details on the fabric production).
4. The ownership certificate is transferred along with the physical item through sensor technology with each transaction, such as from manufacturer to distributor, from distributor to brand.
5. The consumer scans the item to view details of the product's provenance and impact.
6. After purchase, the consumer can access their ownership certificate. They can access information on secondary markets for their particular item so that once the item is no longer needed, it can be resold. Upon inputting condition of the used item, price, as well as the re-commerce platform, they receive an offer to sell.
7. New owner receives the item and the ownership certificate. To verify the authenticity of the physical item, the new owner scans the tag embedded on or within the item.
8. When the item becomes irreparably damaged or unfit for further use, the consumer sends it to be recycled (e.g. brand's take-back scheme). The information on the blockchain includes composition and disposal information, which aids the recycler in properly segregating and recovering materials.

4.2.2. Stakeholders of the blockchain network

For the protocol suggested above to be implemented, all key stakeholders involved in the supply chain need to be part of the BC. Figure 8 summarises key groups of stakeholders in the BC for enhanced traceability of the fashion supply chain. Each participant is registered onto the blockchain network and assigned their individual digital signature to sign their transactions. Various versions of blockchain networks with fewer participants than depicted can exist, as some participants are more likely than others to be part of the blockchain platform. This can depend on several factors including technical readiness and willingness to share data. From a blockchain-enabled LCA, some of the depicted stakeholders play a significant role in data collection, such as the Tier 1-4 suppliers, but other actors, such as brands have more capacity to mobilise action across the value chain.

Figure 8. Participants of the blockchain network.



Source: Authors' own elaboration.

4.2.3. Blockchain-based LCA framework

Based on the proposed protocol presented in 4.2.1, an LCA-BC integrated framework is defined in consultation with BC experts and summarised in Table 3. The framework is structured along the main four steps laid down in the ISO 14040:2006 standard guidelines for LCA and cross-linked with the different stages of the BC development. Each step is then described in more detail below. The design options for the BC platform and technical capabilities and technologies for data acquisition and recording were discussed with BC experts and conform to operational parameters of BC platforms.

Table 3. Blockchain-based LCA framework for fashion.

1. Goal and scope definition	**2. Inventory analysis**	**3. Impact assessment**	**4. Interpretation and reporting**
• **FU is the specific item with a unique ID** • **Scope includes production of the item (starting from raw material production) transport, and EoL. Use stage is excluded due to variability of consumer care.** • **Data, and hence LCA results are refreshed on a regular basis (1-4 times a year) in order to have up-to-date results**	• Primary data, collected at facility level through IoT technologies and supplier questionnaires, is allocated to the specific product • Missing data and background data taken from standardised databases	• LCA software module on the blockchain uses data collected to perform impact calculation • Selected impact categories may be GHG emissions, water use, land use, water pollution	• Hot spot analysis to identify most important processes for impact reduction measures • Critical review of data completeness and consistency • Communication of impact results to consumer through various channels (labels, website etc.)

	• Several methods of data validation • Integration of AI and OCR for data processing		

Source: Authors' own elaboration.

Goal and scope definition

The scope of a blockchain-based LCA can be designed as cradle to gate, including all production and transport stages up to retail stage. Aligning stakeholders along the value chain is critical for the successful implementation of the BC system. As noted above, brands' sphere of influence along the value chain is significantly higher than that of other actors and would be in a better position to lead and leverage the system implementation. However, the system could also be designed to adopt a cradle to grave boundary if the end-of-life stage can be registered on to the BC platform. This, however, would imply to extent the BC system to participants that are not conventionally included in the BC protocols, such as consumers and recyclers. Extending the boundary, though, would provide additional information to consumers to avoid impacts through reselling or recycling their items and critical information to recyclers to adequately recover materials. In this case, leverage of the systems' implementation may come from policy/regulatory requirements and would need to consider multiplicity of actors involved and time lags between use and end of life stages.

Inventory analysis

As described in Table 3, Blockchain-based LCA enables the cumbersome process of inventory data collection to be streamlined through automatic and verified data collection. With the implementation of IoT technologies, process data can be collected automatically and transferred directly to the blockchain platform. This requires an IT infrastructure, including smart meters measuring electricity, water, and gas consumption, RFID readers or other applicable tracking devices. An alternative and complementary method of data collection is through supplier questionnaires. This method involves suppliers filling in questionnaires to provide data on metrics, such as energy consumption, and waste generation, supplemented by proof documents. Supplier responses on total production capacity and average production for the specific client allow allocation of inventory data attributed to a certain batch of goods. To validate data provided by the actors, proof documents, such as electricity or water bills are uploaded on the blockchain platform. An optical character recognition (OCR) tool on the platform matches the documents with the responses and extracts the correct information. Another method of data validation that may be performed on the platform is mass balancing. When a tagged material is processed and transformed, mass balancing ensures that outbound quantities of a material (e.g. recycled polyester yarn) do not exceed their inbound quantities (e.g. recycled polyester fibre). This method is also applied by certification organisations, such as Fairtrade (n.d.) to account for transformation processes of materials. While the second method of data collection based on questionnaires requires more human involvement and thus may be more prone to error, the first method with machine-to-machine conversation technically allows for real time validated information transfer. As an additional layer of trust, independent auditors may certify the data input and material flow and record their results on the platform. Existing data gaps due to incomplete information from suppliers, as well as any background data (e.g. for energy, transport or waste processes), can then be added from standardised LCA databases.

Impact assessment

The BC generated inventory is then used to calculate the impact using an integrated impact assessment LCA tool. The categories and number of indicators to report can then be customised according to the needs of different stakeholders, seeking a balance between relevant information and overload for the user.

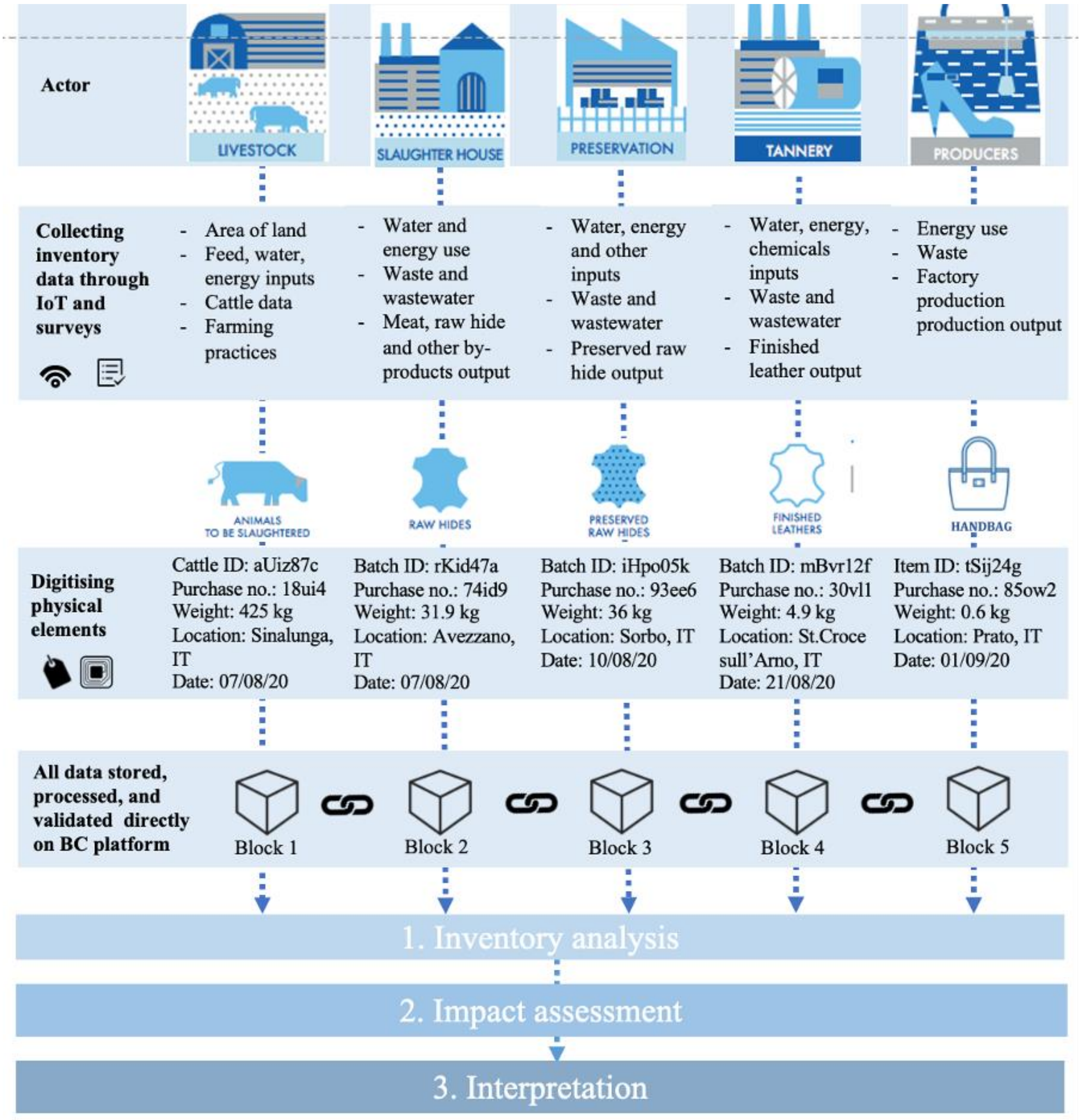
Interpretation and reporting

The indicators can each be contextualised with benchmarks to provide a holistic view of the item's impacts. The different impacts can also be translated into a single score to allow for quicker comparability of different products in addition to individual key indicators. Lastly, the use of data visualisation tools facilitates effective communication of LCA results to the user. Several examples of intuitive visualisation for environmental impact communication exist (e.g. TrusTrace user interface).

4.2.4. Pilot application of the LCA-BC integrated framework to the case study of leather handbags

Building on the framework presented in Table 3, Figure 9 illustrates the blockchain-based data collection for LCA applied to a leather handbag covering all production stages. Transport and end-of-life stages have been left out for two reasons: firstly, impacts from these stages can be estimated using recorded location points, weight, and secondary data, and secondly, impacts during these stages are comparatively lower for a handbag. The depicted actors represent a simplified supply chain of leather products, since some stages, in particular the farming and tanning stages, often contain multiple actors. As data collection starts at the farm, traceability of the animal is ensured through (electronic) ear-tagging of the calf, linking each animal to its virtual passport. Because bovine animals are commonly traded between multiple farms during their lifespans, this traceability practice is already regulated in the EU for food safety and animal health reasons (European Commission, n.d.). At the slaughterhouse, the raw hides can be tagged at unit- or batch-level. Digital tags can be complemented with DNA technology for optimal authentication of the hides (Sander et al., 2018; Applied DNA Sciences, n.d.). The DNA markers can be applied anywhere in the leather supply chain, including farm- or slaughterhouse-level (BLC, 2020). Allocating impacts between farming and slaughtering stages can be done according to existing standards or more precise allocation factors could be calculated if the farmer and slaughterhouse provide additional data. For example, an accurate economic allocation factor of slaughtering can be determined from the actual selling prices of raw hide compared to meat and other co-products.

Figure 9. Blockchain-based data collection for leather handbag LCA.



Source: Authors' own elaboration, with pictograms taken from UNIC, 2017

Proof documents to validate inventory data in this case include water and electricity bills, waste transfer notes, and Manufacturing Restricted Substances Lists (MRSL) regarding chemicals inventory. Farms and tanneries may be able to provide extensive evidence if they already undergo audit processes regularly (e.g. Leather Working Group (LWG) audit protocols for tanneries). As suppliers usually serve multiple customers, their total production capacity along with the average production for the specific customer needs to be recorded, so that the share of inputs and outputs can be attributed to the specific batch at each step. Where data does not exist or cannot be collected, standardised LCA databases can be used as approximations.

Generally, what becomes evident is that the accuracy of a blockchain-based LCA is dependent on the amount and quality of data that each individual participant is able and willing to share. Performing an LCA on the blockchain platform after collecting and processing large amounts of data is technically feasible, but a bigger challenge, according to Participant 2, is "whether the brand is able to push their suppliers to (…) share the data online". In his view, it depends on the supplier’s acceptance and the brand’s relationship with the supplier, which shapes suppliers’ willingness to collect and share primary data. This also holds true for leather supply chains specifically, as Participants 3 and 4 emphasise, in which transnational brands with a lot of influence over the entire value chain can more easily push for transparency and traceability of leather products. Participant 3 notes that some tanneries, such as those working with the LWG, already share large amounts of data with brands, whereas smaller tanneries are often “very reluctant to share this data” or have limited resources and capability to do so.

Another challenge for the implementation emphasised by all experts consulted is that, in practice, mapping suppliers beyond Tier 1 can be extremely difficult. The manufacturer may source leather from several suppliers, whom each may source their inputs from several suppliers. Normally, many more actors than depicted in Figure 8 are involved in the production of leather, such as intermediate traders at raw material or finished leather stages or several tanneries that focus on individual sub-processes of tanning and finishing. The current lack of digitalisation within the industry is another significant barrier, according to Participants 1 and 4. Each facility requires hardware equipment and IT capacity which may be missing.

Lastly, data collection and validation must be designed in a way that minimises errors in inputting information into the system. Blockchain experts consulted agreed that no solution which guarantees 100% accuracy exists, as a residual risk remains that some data inputs could be flawed or manipulated. However, if combined with robust tracing technologies and verification systems, a blockchain-based traceability system can validate the authenticity of a product and provide an accurate overview of its environmental impacts. As Participant 1 sums it up: “There are always going to be bad actors, and blockchain does not prevent them from acting completely, but it makes it much more difficult for them to trick the system”.

4.3. Discussion on the role of LCA and BC to promote circular fashion

Performing an LCA of a standard leather handbag and assessing impact reduction potential of circular alternatives has illustrated the use of LCA as a tool to explore and assess possible circular strategies for fashion by: a) revealing the hotspots of the product lifecycle that should be addressed first, and b) and comparing different interventions to assess impact reduction potential of circular pathways.

In agreement with previous literature (see, for example, van der Vendel et al, 2014, Ross et al. (2015), manufacturing accounts for the most impactful stage across the lifecycle of fashion items. Hence, both circular practices proposed in the explored scenarios led to important impact reduction potential.

The development of well-functioned secondary markets, which allow to extend the lifespan of fashion items by cascading them across users, where it displaces some of the primary production, is an attractive pathway. Secondary markets can be powered by BC, helping to address some of the current barriers to effectively resell second hand fashion items, as demonstrated by the rapid growth of start-ups in this area in the last 5 years (Vogue Business Index, 2021). The study also explored the deployment of less impactful alternative materials, such as plant based leather alternatives, as effective measures to reduce overall lifecycle impacts. The LCA study also pinpointed hotspots from production to disposal, which helped to identify additional impact reduction measures across both scenarios (e.g. use of less or recycled brass components, shift from fossil fuel-based to renewable electricity).

It was out of the scope of this study to assess the impact of resource-efficiency measures during leather production process, such as cleaner technologies and substitution of chemical inputs, as the focus was on circular strategies associated with life extension and alternative materials. Additional future research, backed up by primary data of the manufacturing processes, can help to shed more light on the role of technological and process development to reduce impacts.

Building on Zhang et al.'s (2020) general framework for integrating LCA into blockchain technology, this research examined how BC can be leveraged by the fashion industry for promoting circularity and provided a further specified framework for fashion products. The proposed blockchain-based LCA framework validated by BC experts provides a basis for brands, suppliers and other key decision-makers to acquire data across the supply chain in real-time, as an enabler for accurately assess the impact of circular practices.

The study also examined the role of blockchain technology in facilitating secondary fashion markets, building on Rusinek et al. (2018), further elaborating on the aspect of traceability of second-hand goods, especially in the luxury segment of the market, to foster secondary market development. The findings suggest that by enabling traceability of products and their impacts, platforms for verifying and trading used items can be established, which would enhance functioning of fashion secondary markets and, potentially, displace primary production. These platforms could help to monitor the life extension of goods in secondary markets and calculate associated impact reduction.

The proposed framework supports brands and other key stakeholders in adopting circular fashion practices in several ways. First, it highlights the critical role of supply chain collaboration, which serves as a foundation for introducing circular measures of products. Blockchain technology, which is built on transparency and trust, requires and fosters stakeholder collaboration, leading to more effective identification of circular measures across the value chain. Second, it offers tools to access data in a way that allows for accurate and up-to-date impact information, increasing transparency and trust. This serves as a basis for analysing the main variables across different stages of the product lifecycle, benchmarking them, and identifying possible circular measures to reduce impacts. By integrating BC and LCA brands could also further capitalise on sustainability practices, as materials and impact per garment could be communicated to users and other stakeholders in a more transparent way. Third, by communicating sustainability efforts to consumers and other stakeholders, sustainable consumption choices can be facilitated. Finally, companies may grasp the opportunity to create new revenue streams from secondary markets by building re-commerce solutions that facilitate trading in resale markets and authenticity and provenance of second-hand fashion items.

5. Conclusion

This study aimed to understand how the integration of LCA and blockchain technology can enable the introduction of circular fashion practices. The study used the case study of leather bags to illustrate how LCA can be used to evaluate the environmental impact reduction potential of selected circular fashion strategies. The analysis first highlighted key hotspots of the product life cycle, pointing to production of leather, followed by brass, as two main contributors. Within leather production, this study included allocated impacts from the cattle-raising stage, typically excluded in previous studies. In fact, cattle-raising represented the most impactful process, followed by the tanning process. From the baseline scenario, two circular scenarios were developed. They tried to illustrate different possible pathways to increase circularity. The first circular scenario was based on material substitution and was represented by an alternative leather material made using agricultural waste. Findings suggested that this scenario contributed to savings of more than a third of impacts in most categories. The other circular scenario analysed, a second-hand leather bag, saved between 60 to 65% across most impacts.

Future research is required to re-evaluate assumptions made regarding durability and biodegradability of the different handbag options respectively to refine the findings. The main purpose of the analysis was to illustrate how LCA could be used as a tool to explore and compare different circular fashion strategies. However, one main drawback was the difficulty of obtaining specific process data across multiple tiers, which results in limitations in terms of reliability and accuracy for LCA studies on fashion products.

For these two scenarios, data acquisition represented one major challenge. An integrated LCA-BC framework was proposed as an enabler allowing better traceability and monitoring of impact reduction potential. Thus, the second part of this study examined how blockchain technology can be used by the fashion industry to facilitate reliable LCA-relevant data collection and enable traceability as a key underlying condition for many circular strategies. The framework was developed and then validated in an iterative process of co-creation with experts. The framework illustrates key elements for BC-LCA integration from technology implications, mapping of value chain participants, required tracking methods and data collection and validation protocols. The framework also helped to highlight issues around data traceability which may emerge along the process. The proposed framework was then pilot tested using leather handbags as a case study.

Some barriers and enablers to implementing blockchain technology within fashion value chains and its contribution to circularity have been discussed but further research is needed, especially regarding barriers to implementation and key drivers. Lastly, the application of the framework to other fashion products, such as fashion textiles, and required adaptations should be part of the future research agenda.

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REFERENCES

ABPMP (2019) *Guide to the Business Process Management Body of Knowledge*. 4th ed. Independently published.

Adom, F. and Dunn, J.B. (2015). *Material and Energy Flows in the Production of Macro and Micronutrients, Buffers, and Chemicals Used in Biochemical Processes for the Production of Fuels and Chemicals from Biomass.* Available at: https://greet.es.anl.gov/files/fuel-chemicals-biomass (accessed 7 September 2020)

Applied DNA Sciences (n.d.) *Leather Supply Chain Protection*. Available at: https://adnas.com/leather/ (accessed 7 September 2020)

Baskarada, S. (2014). Qualitative Case Study Guidelines. *The Qualitative Report*. 19 (40): 1–25. Available at: https://nsuworks.nova.edu/cgi/viewcontent.cgi?article=1008&context=tqr (accessed 7 September 2020)

BCG (2019). *True-Luxury Global Consumer Insight Summary of the BCG-Altagamma 2019 Study*. Available at: https://altagamma.it/media/source/Summary%20True-Luxury%20Global%20Consumer%20Insight%202019_vFinal_Sent.pdf (accessed 7 September 2020)

Beylot, A. and Villeneuve, J. (2017). Accounting for the environmental impacts of sulfidic tailings storage in the Life Cycle Assessment of copper production: A case study. *Journal of Cleaner Production*, 153(1), pp.139–145.

BLC (2020). *DNA tracking in leather*. Available at: https://www.blcleathertech.com/what-we-do/research-innovation/dna-tracking-in-leather (accessed 7 September 2020)

Boiten, V. J., Han, S.L.-C., and Tyler, D. (2021). Circular economy stakeholder perspectives: Textile collection strategies to support material circularity. Available at: https://pdf4pro.com/view/circular-economy-stakeholder-perspectives-textile-4e1ce7.html

Brydges, T. (2021). Closing the loop on take, make, waste: Investigating circular economy practices in the Swedish fashion industry, Journal of Cleaner Production, 293, https://doi.org/10.1016/j.jclepro.2021.126245

BSI (2006). BS EN ISO 14040: 2006 Environmental management. Life cycle assessment. Principles and framework.

Bukhari, M., Carrasco-Gallego, R., Ponce-Cueto, E. (2018). Developing a national programme for textiles and clothing recovery.Waste Management & Research 2018, Vol. 36(4) 321–331.

Chen, X., Memon, H.A., Wang, Y. *et al.* (2021). Circular Economy and Sustainability of the Clothing and Textile Industry. *Mater Circ Econ* **3,** 12, https://doi.org/10.1007/s42824-021-00026-2

China, C.R., Maguta, M.M., Nyandoro, S.S., Hilonga, A., Kanth, S.V., and Njau, K.N. (2020). Alternative tanning technologies and their suitability in curbing environmental pollution from the leather industry: A comprehensive review. *Chemosphere*, 254, p.126804.

Choi, T.-M. (2019). Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains. *Transportation Research Part E*, 128, pp.17–29.

Chrobot, P., Faist, M., Gustavus, L., Martin, M., Stamm, A., Zah, R., and Zollinger, M. (2018) *Measuring fashion: Environmental impact of the global apparel and footwear industries study. Full report and methodological considerations.* Available at: https://quantis-intl.com/wp-content/uploads/2018/03/measuringfashion_globalimpactstudy_full-report_quantis_cwf_2018a.pdf (accessed 7 September 2020)

Cognizant (2018). *A blockchain-based framework for apparel & footwear supply chain traceability*. Available at: https://www.cognizant.com/whitepapers/a-blockchain-based-framework-for-apparel-and-footwear-supply-chain-traceability-codex4088.pdf (accessed 7 September 2020)

Deloitte (2017). *When two chains combine. Supply chain meets blockchain*. Available at: https://www2.deloitte.com/content/dam/Deloitte/pt/Documents/blockchainsupplychain/IE_C_TL_Supplychain_meets_blockchain_.pdf (accessed 7 September 2020)

Denzin, N. (2006). *Sociological Methods: Methodological Perspectives*. 1st ed. London: Routledge.

De-Rosa Giglio, P., Fontanella, A., Gonzalez-Quijano, G., Ioannidis, I., Nucci, B., Brugnoli, F (2018). PRODUCT ENVIRONMENTAL FOOTPRINT CATEGORY RULES. Available at: https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_leather.pdf (accessed 7 September 2020)

EEA (2017). *Textiles in Europe's circular economy*. Available at: https://www.eea.europa.eu/themes/waste/resource-efficiency/textiles-in-europe-s-circular-economy (accessed 7 September 2020)

Ellen MacArthur Foundation (2014). *Towards The Circular Economy, Vol. 3: Accelerating The Scale-up Across Global Supply Chains*. Available at: https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-3-accelerating-the-scale-up-across-global-supply-chains (accessed 7 September 2020)

Ellen MacArthur Foundation (2017). *A New Textiles Economy: Redesigning fashion's future.* Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf (accessed 7 September 2020)

European Commission (n.d.). *Identification - Bovine animals*. Available at: https://ec.europa.eu/food/animals/identification/bovine_en (accessed 7 September 2020)

Fairtrade (n.d.) *Are Fairtrade Products Fully Traceable?* Available at: https://www.fairtrade.org.uk/What-is-Fairtrade/FAQs/ (accessed 7 September 2020)

Farfetch (2020). *Understanding the environmental savings of buying pre-owned fashion*. Available at: https://cdn-static.farfetch-contents.com/content/UP/PRODUCTION/LANDING-PAGES/SUSTAINABILITY-CALC/Understanding%20the%20Environmental%20Savings%20of%20Pre-owned_Farfetch%20Report%202020.pdf (accessed 7 September 2020)

Fashion Revolution (2020). *Fashion Transparency Index – 2020 Edition*. Available at: https://issuu.com/fashionrevolution/docs/fr_fashiontransparencyindex2020?fr=sNmI5NzYxMDk0OA (accessed 7 September 2020)

Fletcher, K. (2008). *Sustainable fashion and textiles: design journeys*. 1st ed. London: Earthscan.

Fletcher, K. (2012). *Sustainable Fashion and Textiles: Design Journeys*. 2nd ed. London: Routledge.

Fridrihsone, A., Stirna, U., Misane, M., Lazdina, B., and Deme, L. (2020). Life Cycle Assessment of vegetable oil based polyols for polyurethane production. *Journal of cleaner production*, 266, p.121403.

Geier J. and Lessmann H. (2012). Leather Industry'. In: Rustemeyer T., Elsner P., John SM., Maibach H.I. (eds), *Kanerva's Occupational Dermatology*. Berlin: Springer.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome.

Gereffi, G. and Frederick, S. (2010) *The global apparel value chain, trade and the crisis: Challenges and opportunities for developing countries*. Policy research working paper 5281. World Bank, Washington, DC, USA.

Gerring, J. (2007). *Case Study Research: principles and practices*, New York: Cambridge University Press.

Global Fashion Agenda & Boston Consulting Group (2017). *Pulse of the Fashion Industry*. Available at: https://globalfashionagenda.com/wp-content/uploads/2017/05/Pulse-of-the-Fashion-Industry_2017.pdf (accessed 7 September 2020)

Gottfridsson, M. and Zhang, Y. (2015). Environmental impacts of shoe consumption: Combining product flow analysis with an LCA model for Sweden. *Master's Thesis, Chalmers University of Technology, Sweden*. Available at: http://publications.lib.chalmers.se/records/fulltext/218968/218968.pdf (accessed 7 September 2020)

Grand View Research (2018). *Handbag Market Size & Share, Global Industry Report, 2019-2025*. Available at: https://www.grandviewresearch.com/industry-analysis/handbag-market (accessed 7 September 2020)

Head, M., Sevenster, M., Odegard, I., Krutwagen, B., Croezen, H. and Bergsma, G. (2014). Life cycle impacts of protein-rich foods: creating robust yet extensive life cycle models for use in a consumer app. *Journal of Cleaner Production*, 73, pp.165–174.

Herrero, M., Thornton, P.K., Gerber, P., and Reid, R.S. (2009). Livestock, livelihoods and the environment: understanding the trade-offs. Current opinion in environmental sustainability, 1(2), pp.111–120.

Hsu, C.C. and Sandford, B.A. (2007). The Delphi Technique: Making Sense of Consensus. *Practical assessment, research & evaluation*, 12(10), pp.1–8.

Hultkrantz, M. (2018). An overview on the environmental impacts of synthetic leather made of hemp fiber with preliminary life cycle assessment. *Master's thesis*, Available at: https://pdfs.semanticscholar.org/b122/c9c97c95f8fc3fb322989a56dbf929515d46.pdf (accessed 7 September 2020)

Jönsson, C., Wei, R., Biundo, A., Landberg, J., Schwarz Bour, L., Pezzotti, F., Toca, A., Jacques, L., Bornscheuer, U., Syrén, P. (2021). Biocatalysis in the Recycling Landscape for Synthetic Polymers and Plastics towards Circular Textiles, ChemSusChem, https://doi.org/10.1002/cssc.202002666

Joseph, K. and Nithya, N. (2009). Material flows in the life cycle of leather. *Journal of Cleaner Production*, 17(7), pp.676–682.

JRC (2014). *Environmental Improvement Potential of Textiles*. JRC Scientific and Technical Reports. Seville: European Commission JRC – IPTS. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85895/impro%20textiles_final%20report%20edited_pubsy%20web.pdf (accessed 7 September 2020).

Juanga-Labayen, J.P.; Labayen, I.V.; Yuan, Q. A Review on Textile Recycling Practices and Challenges. Textiles 2022, 2, 174–188. https://doi.org/10.3390/ textiles2010010

Kant, R. (2012). Textile dyeing industry: An environmental hazard, *Natural Science*, 04 (01).

Kearins, J. and Wallace, M (2020). Finding the right fit: Why AI is the solution to the sustainable fashion crisis, *IBM*, 13 February. Available at: https://www.ibm.com/blogs/think/uk-en/finding-the-right-fit-why-ai-is-the-solution-to-the-sustainable-fashion-crisis/ (accessed 7 September 2020)

Koksal, D., Straehle, J., Mueller, M. and Freise, M. (2017). Social Sustainable Supply Chain Management in the Textile and Apparel Industry-A Literature Review. *Sustainability*, 9(1), p.100.

Koszewska, M. (2019). Circular economy in textiles and fashion—the role of a consumer in Muthu (ed.). *Circular economy in textile and apparel*, Processing, Manufacturing, and Design, The Textile Institute Book Series, Pages 183-206

Kulkarni, A. (2018). How Resale Items Can Get A Second Life With Blockchain Verification, *Medium*, 22 March. Available at: https://medium.com/@ajitkulkarni/how-resale-items-can-get-a-second-life-with-blockchain-verification-63748302bf68 (accessed 7 September 2020)

Laitala, K., Klepp, I. and Henry, B. (2018). Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type. *Sustainability* 10, 2524.

Ljungkvist, H., Watson, D., and Elander, M. (2018). *Developments in global markets for used textiles and implications for reuse and recycling*. Mistra Future Fashion report. Available at: http://mistrafuturefashion.com/wp-content/uploads/2018/09/Mistra-Future-Fashion-2018.04-M-Elander-D.3.3.4.1.pdf (accessed 7 September 2020)

Ma, Y., Zeng, B., Wang, X. & Byrne, N. (2019). Circular Textiles: Closed Loop Fiber to Fiber Wet Spun Process for Recycling Cotton from Denim. ACS Sustainable Chem. Eng. 2019, 7, 14, 11937–11943, https://doi.org/10.1021/acssuschemeng.8b06166

McKinsey & GFA (2020). *Fashion on climate*. Available at: https://www.mckinsey.com/~/media/McKinsey/Industries/Retail/Our%20Insights/Fashion%20on%20climate/Fashion-on-climate-Full-report.pdf (accessed 7 September 2020)

Merriam, S.B. and Tisdell, E. J. (2016). *Qualitative research: a guide to design and implementation*. 4th ed. San Francisco: John Wiley & Sons.

Middlemas, S., Fang, Z.Z. and Fan, P. (2015). Life cycle assessment comparison of emerging and traditional Titanium dioxide manufacturing processes. *Journal of Cleaner Production*, 89(C), pp.137–147.

Moorhouse, D. & Moorhouse, D. (2017) Sustainable Design: Circular Economy in Fashion and Textiles, The Design Journal, 20:sup1, S1948-S1959, DOI: 10.1080/14606925.2017.1352713

Notarnicola, B., Puig, R., Raggi, A., Fullana, P., Tassielli, G., De Camillis, C., Rius, A. (2011). Life cycle assessment of Italian and Spanish bovine leather production systems. Afinidad. Revista de química teórica y aplicada, 68(553), pp.167–180.

Nuss, P. and Eckelman, M.J. (2014). Life Cycle Assessment of Metals: A Scientific Synthesis. *PloS one*, 9(7), p.e101298.

Padilla-Rizo, B. et al. (2018). Studying type wet blue tannery process for estimating environmental performance using the Life Cycle Analysis methodology: A Case Study in Mexico. *International Journal of Scientific and Research Publications*, 8(6), p.7855.

Pautasso, E., Ferro, E., and Osella, M. (2019). Blockchain in the Fashion Industry: Opportunities and Challenges. Annex 1, TCBL Deliverable 2.10. Available at: https://issuu.com/tcbl/docs/blockchain_in_the_fashion_industry (accessed 7 September 2020)

Payne, A. (2015). ‘6 - Open- and closed-loop recycling of textile and apparel products’, in *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*. Elsevier Ltd, pp. 103–123.

Pithers, E. (2019). The Leather Debate: Is Vegan Leather a Sustainable Alternative to the Real Thing?, *VOGUE*, 24 April. Available at: https://www.vogue.co.uk/article/vegan-leather-sustainability-debate-2019 (accessed 7 September 2020)

Robson, C. (1993). *Real World Research*. 1st ed. Oxford: Blackwell Publishing.

Roos, S., Sandin, G., Zamani, B. and Peters, G. (2015) *Environmental assessment of Swedish fashion consumption: Five garments – sustainable futures*. Mistra Future Fashion report, deliverable number D2.6. Available at: http://mistrafuturefashion.com/wp-content/uploads/2015/06/Environmental-assessment-of-Swedish-fashion-consumption-LCA.pdf (accessed 7 September 2020)

Rotunno, R., V. Cesarotti, A. Bellman, V. Introna, and M. Benedetti. (2014). Impact of Track and Trace Integration on Pharmaceutical Production Systems. *International Journal of Engineering Business Management*, 6: 25.

Rudolphi, J.T. (2018). Blockchain for a circular economy. *Master’s thesis*. Available at: https://pure.tue.nl/ws/portalfiles/portal/97558362/Rudolphi_0913284.pdf (accessed 7 September 2020)

Rusinek, M., Zhang, H., and Radziwill, N. (2018). Blockchain for a Traceable, Circular Textile Supply Chain: A Requirements Approach. *Software Quality Professional*, 21(1), pp.4–24.

Sander, F., Semeijn, J., and Mahr, D. (2018). The acceptance of blockchain technology in meat traceability and transparency. *British food journal* (1966), 120(9), pp.2066–2079.

Sandin, G. and Peters, G.M. (2018). Environmental impact of textile reuse and recycling – A review. *Journal of Cleaner Production*, 184, pp.353–365.

Shenten, J., Führ, M., Kleinhauer, S., Schönborn, J. (2019). Traceability as driver for more sustainable chemistry in the global textile supply chains, Current Opinion in Green and Sustainable Chemistry, Volume 19: 87-93.

Smith, P., Baille, J. & McHattie, L. (2017) Sustainable Design Futures: An open design vision for the circular economy in fashion and textiles, The Design Journal, 20:sup1, S1938-S1947, DOI: 10.1080/14606925.2017.1352712

Sterlacci, F. (2010). *Leather Fashion Design*, London: Laurence King Publishing Ltd.

Swan, M. (2015). *Blockchain: Blueprint for a New Economy*. 1st ed. Sebastopol: O’Reilly Media, Incorporated.

Sweet, S. and Wu, A. (2019). *Second-hand and leasing of clothing to facilitate textile reuse*. Mistra Future Fashion Report. Available at: http://mistrafuturefashion.com/wp-content/uploads/2019/10/S.Sweet_.-second-hand-and-leasing-clothing-textile-reuse.-mistra-Future-fashion-2019.13.pdf (accessed 7 September 2020)

Tan, B., Yan, J., Chen, S. and Liu, X. (2018) The impact of blockchain on food supply chain: The case of Walmart, 11373, pp.167–177.

Tasca, A.L. and Puccini, M. (2019). Leather tanning: Life cycle assessment of retanning, fatliquoring and dyeing. *Journal of Cleaner Production*, 226, pp.720–729.

TrusTrace (2020). *Integrated Traceability Solution for fashion*. Available at: https://trustrace.com/integrated-traceability-solution-for-the-fashion-industry/ (accessed 7 September 2020)

UNIC (2017). *Sustainability Report 2017*. Available at: http://s.unic.it/5/files/assets/common/downloads/publication.pdf (accessed 7 September 2020)

Van der Velden, N. M., Patel, M. K. and Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, 19(2), 331–356.

Van Rensburg, M.L., Nkomo, S.L. and Mkhize, N.M. (2020). Life cycle and End-of-Life management options in the footwear industry: A review. *Waste Management & Research*, 38(6), pp.599–613.

Vogue Business (2021). Vogue Business Index, accessible online at: https://www.voguebusiness.com/companies/resale-rental-nft-vogue-business-index-trends-innovation [accessed 13 may 2022]

Wagner, M.M.; Heinzel, T. (2020). Human Perceptions of Recycled Textiles and Circular Fashion: A Systematic Literature Review. *Sustainability*, *12*, 10599. https://doi.org/10.3390/su122410599

Wang, Y., Singgih, M., Wang, J. and Rit, M. (2019). Making sense of blockchain technology: How will it transform supply chains? *International Journal of Production Economics*, 211, pp.221–236.

WRAP (2011). *Benefits of reuse – case study: clothing*. Available at: https://www.wrap.org.uk/sites/files/wrap/Clothing%20reuse_final.pdf (accessed 7 September 2020)

WRAP (2012). *Valuing our clothes: the True Cost of How we Design, Use and Dispose of our Clothing in the UK*. Available at: http://www.wrap.org.uk/sites/files/wrap/VoC%20FINAL%20online%202012%2007%2011.pdf (accessed 7 September 2020)

WRAP (2017). *Mapping clothing impacts in Europe: the environmental cost*. Available at: http://www.ecap.eu.com/wp-content/uploads/2018/07/Mapping-clothing-impacts-in-Europe.pdf (accessed 7 September 2020)

Zhang, Y., Liu, X., Xiao, R. and Yuan, Z. (2015). Life cycle assessment of cotton T-shirts in China. *The International Journal of Life Cycle Assessment*, 1-11.

Zhang, A., Zhong, R.Y., Farooque, M., Kang, K. and Venkatesh, V.G. (2020). Blockchain-based life cycle assessment: An implementation framework and system architecture. *Resources, Conservation & Recycling*, 152, 2020.

List of acronyms and abbreviations

AI	artificial intelligence
BC	blockchain technology
BCG	Boston Consulting Group
CE	circular economy
CO2	carbon emissions
Cr(III)	chromium (III)
DB	dichlorobenzene
EMF	Ellen MacArthur Foundation
EOL	end of life
EU	European Union
FU	functional unit
GFA	Global Fashion Agenda
GHG	greenhouse gases
GWP	global warming potential
IOT	Internet-of-things
ISO	International Organisation of Standardisation
IT	information technology
JRC	Joint Research Center
LCA	lifecycle assessment
LWG	Leather Working Group
MRSL	Manufacturing Restricted Substances Lists
OCR	optical character recognition
PEFCR	Product Environmental Footprint Category Rule
PM	particulate matter
RFID	radio frequency identification
SI	supplementary identification
UK	United Kingdom
USD	United States Dollar
VOC	volatile organic compounds