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Traceability as a means to investigate supply chain sustainability: the real case of a leather shoe supply chain

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In recent years, the growing attention to environmental challenges has shown that these issues are becoming of more and more interest to both research and industry. Companies are expected to ensure their products are fully traceable and more sustainable, which requires the involvement of all of the actors in the production network. According to this aim, this study proposes a structured approach that uses the traditional traceability concept as a means to identify the main information needed to assess environmental impacts along the whole supply chain (SC). The proposed approach is composed of four main steps: (i) SC modelling to identify all stakeholders and their inter-relations, (ii) data sharing to collect all relevant data, (iii) data elaboration to calculate performance at different levels of detail and (iv) result interpretation to optimise the SC. The distributed implementation of the approach at different SC steps represents a useful means to practically realise a sustainable SC management. A case study involving a leather shoe SC is used to demonstrate the effectiveness of the approach in identifying criticalities, supporting the selection of the most appropriate suppliers and correctly setting a management strategy towards the optimisation of internal and external traceability and environmental sustainability performances.

Keywords: sustainable supply chain management; environmental sustainability; traceability; sustainable supply chain; collaborative network

1. Introduction

In recent years, the preservation of the environment has become one of the most critical problems facing humanity. Thus, the concept of sustainable development, which refers to the ability to produce goods or services without compromising the ability of future generations to produce and manufacture the same products and services (WCED 1987), is currently a key aspect to take into account at different levels. This situation has forced European and international governments to issue legislation and develop long-term programmes, such as the 7th Environment Action Plan (European Parliament and Council 2013), with the final aim to provide strategic vision to drastically reduce the impacts caused by human activities on the environment.

Given the increasing pressure from government regulators, community activists and non-governmental organisations, and owing the global competition, sustainability practices and their applications are gaining attention, from both academia and industry. Manufacturing companies significantly impact the global environment with their high energy and resource consumption and greenhouse gas emissions. Therefore, companies not only need to think about economic benefits, but also must promote 'green' products and processes to reach their sustainability aims and potentially acquire additional market segments.

In general, a product is the result of several production steps performed by different participants that interact together to exchange materials, semi-finished goods and information. Thus, product sustainability is strictly correlated to the performance of the entire supply chain (SC). Indeed, to fruitfully pursue sustainability, it is not sufficient to have a view limited to the company boundaries: all the actors that contribute to manufacturing the final products and semi-finished goods have to be considered and traced. Unfortunately, this idea is very difficult to put into practice, because of the lack of dedicated methods and tools.

This study aims to overcome this challenge by proposing an approach for tracing, modelling and measuring the environmental performance of complex SCs. The main novelty of the proposed approach is the possibility of using traceability as a means to investigate and collect most of the data needed to quantitatively assess the environmental sustainability of an SC. Its application allows the identification of the current main production flows (i.e. traceability), from

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raw materials extraction to semi-finished parts realisation and ultimately to final product manufacturing, as well as the characterisation of each node in the network in terms of resource and energy consumption. The final objective is to provide a means to guarantee a high product quality standard, monitoring the environmental performance and discovering possible issues on which to focus attention, such as the use of toxic substances along the production chain.

The distributed implementation of the method represents a useful means to practically realise the concept of sustainable supply chain management (SSCM). However, this implementation requires the active collaboration of partners involved in the same production network, which have to be willing to share internal information with the other SC actors. This issue can be viewed as the main limitation of the proposed approach, because only if data are available can they be used to pursue a global optimisation of the SC. Using this approach, each actor can include in its network the most appropriate and sustainable partners, which can adopt the same method for the selection of their own suppliers. The main benefit for the entire SC, as well as for each involved stakeholder, is the possibility of optimising internal and external traceability and the environmental sustainability performances, in order to be compliant with regulations and increase competitiveness in the market.

The remainder of this paper is structured as follows. The Research Background section presents a review of the most relevant research in the fields of SSCM, SC traceability and environmental sustainability assessment. The Method section describes the details of the four steps, together with a step-by-step procedure to explain how the method can be implemented in real industrial contexts. The Method Implementation section presents an application of the proposed approach in the context of a complex leather shoe SC. Finally, the Conclusions section discusses the main advantages and drawbacks of the proposed approach and the directions for future research on this topic.

2. Research background

Usually, industries are committed to pursuing optimisation using different points of view on both on internal and external processes in order to achieve, for example, cost reduction, profit maximisation or product quality improvement (European Commission 2001). In addition to tackling these issues, companies have been implementing sustainable practices in their industrial processes in order to improve both the product and process environmental performance (Ahi and Searcy 2013; Germani et al. 2016; Kamalahmadi and Mellat-Parast 2016). This industrial trend also involves changes in the supply chain management (SCM) (Chardine-Baumann and Botta-Genoulaz 2014), which is responsible for material flows within human society as well as the exchange of materials and energy with the environment (Cooper, Lambert, and Pagh 1997). Over the last decade, the sustainability concept applied to SCM (i.e. SSCM) has received considerable attention in the scientific literature (Pagell and Shevchenko 2014), becoming the subject of numerous studies (Linton, Klassen, and Jayaraman 2007; Seuring and Müller 2008; Seuring and Gold 2013; Beske, Land, and Seuring 2014; Govindan et al. 2014). Kuik, Nagalingam, and Amer (2010) demonstrate that traditional SCs should adopt SSCM when they face social, economic and environmental issues and should define the relative benefits at the same time. According to this definition, SSCM is seen as an extension of the traditional concept of SCM where the aim is to maximise value creation through the management of relationships among key partners in the same network, adding environmental and ethical aspects (Wittstruck and Teuteberg 2013). The maximisation of product profitability while both minimising the environmental impacts along the entire SC and respecting the social well-being of each supplier involved is also a purpose of SSCM (Hassini, Surti, and Searcy 2012).

Several research studies address SCM from different points of view. The main such studies of the last decade are limited to quality, delivery, risk and leadership issues. For example, quality management offers an opportunity for improving SCM performance (Flynn and Flynn 2005; Vanichchinchai and Igel 2010; Foster, Wallin, and Ogden 2011; Xu 2011), whereas risk management influences the SCM performance through information sharing (Wakolbinger and Cruz 2011; Ho et al. 2015) as well as the SC leadership (Melnyk et al. 2009; Huang, Ho, and Fang 2015). Other authors support the incoming application of SSCM; the majority use analytic methods, such as fuzzy decision-making (Erol, Sencer, and Sari 2011), simulation (van der Vorst, Tromp, and van der Zee 2009) and life cycle assessment (LCA) (Matos and Hall 2007). Such examples remain too theoretical, defining in detail only the framework or the conceptual model proposed, but without providing quantitative values and measures of environmental sustainability along the SC. Although Boukherroub et al. (2015) propose a first integrated approach to select the partners to include in the SC, their work measures a supplier's sustainability only through the assignment of qualitative weights according to three main sustainability dimensions. Another example is Validi, Bhattacharya, and Byrne (2015), who propose a decision-making tool able to identify a realistic network. However, they only consider alternative transport scenarios.

According to this literature review, this study addresses SCM from the point of view of sustainability, proposing an approach to assess the environmental impacts of each partner involved in the SC as well as that of the SC as a whole.

Moreover, a key aspect of SCM is traceability, which allows the connection and coordination between producers and firms, as well as those between firms and retailers to be highlighted (Alfaro and Rábade 2009). Indeed, traceability systems are used to collect in a rigorous way all of the information related to different products along the SC (Dabbene and Gay 2011). Therefore, an optimised and sustainable SC necessarily requires taking the traceability concept into account (Dabbene, Gay, and Tortia 2014). In the literature, there are many studies about this topic. Most of them refer to traceability systems applied to the food sector, where consumers require high-quality products (Aung and Chang 2014). Others are used to recognise unsafe products and minimise scandals and recalls, which are very dangerous for the company image (Kang and Lee 2013). The most used technologies are Radio Frequency IDentification (RFID) and the 2D barcode (Qian et al. 2012), as several studies demonstrate (Gaci and Mathieu 2011; Kang and Lee 2013; Musa, Gunasekaran, and Yusuf 2014).

The interest in product and process traceability should support companies to retracing all of the main impact factors along their SCs (e.g. carbon footprint, product composition and product disposal), and replying to tightening government regulations (e.g. the European WEEE directive and carbon tax). To meet these requirements, companies have begun to incorporate sustainability principles in the management of their operations and processes, applying the traceability perspective to SSCM principles. Although numerous studies are related to traceability, few of them also consider the integration of sustainability aspects (Björk et al. 2011). This study tries to close this gap by answering the following research questions: (i) 'How is it possible to link environmental impacts to traceability?' (ii) 'How should traceability be conducted in order to recognise data involved in the environmental assessment?' and (iii) 'How can reliable data from each partner involved along the chain be collected, shared, and elaborated?'

Answering these questions, this study aims to apply the traceability concept to the SC of shoe production, where the added value for customers is the quality of each shoe's component. Therefore, traceability focuses on a product's lifecycle visibility along the entire SC. Indeed, this study proposes a method able to define the environmental sustainability of each partner involved in the SC, considering not only transportation, but also all of the production processes, the related air and water emissions, and all of the factors that have a potential impact on the environment. The final aim is to assess each partner from an environmental point of view in order to choose the SC with the lowest impact, integrating the traceability concept into the thinking on sustainability.

The novelty of this proposed approach is owing to three different aspects:

- the implementation of traceability as a means to assess the environmental sustainability of the SC;
- the proposal of a detailed step-by-step workflow that becomes a decision-making tool for industrial companies in the SSCM; and
- the actual applicability of the method in real industrial contexts, as proved by the case study results.

3. Method

The proposed method (Figure 1) is an extension of the traditional traceability concept in which only the material flows between partners are monitored to retrace the product history. By collecting and elaborating on additional data, such as data on energy and resource consumption, the environmental sustainability of the entire production chain can be assessed in order to optimise the overall performance. The following sections describe in detail each step in the method as well as the activities involved.

3.1. *Supply chain modelling*

In general, an SC is a company's network that obtains raw materials, transforms them into semi-finished goods and, finally, distributes goods to final users. This network generates value by means of coordinated and accurate management of materials and information flows. Each actor in the SC actively contributes to value generation and influences the sustainability of the network. For this reason, the identification of all of the steps, along with the related links, and the building of an SC map are essential tasks to retrace the network and pinpoint the most critical aspects.

For SC mapping, the Integrated DEFinition method (IDEF0) should be adopted (NIST 1993). As shown in Figure 2, this method allows the representation of the main flow of materials and the main aspects that characterise a single step. In particular, these aspects include the following:

- inputs in terms of raw materials, semi-finished products, etc.;
- outputs in terms of products (semi-finished products, final products, by-products and co-products) and waste (solid waste and emissions); and
- resources required for the process (energy, water, etc.).

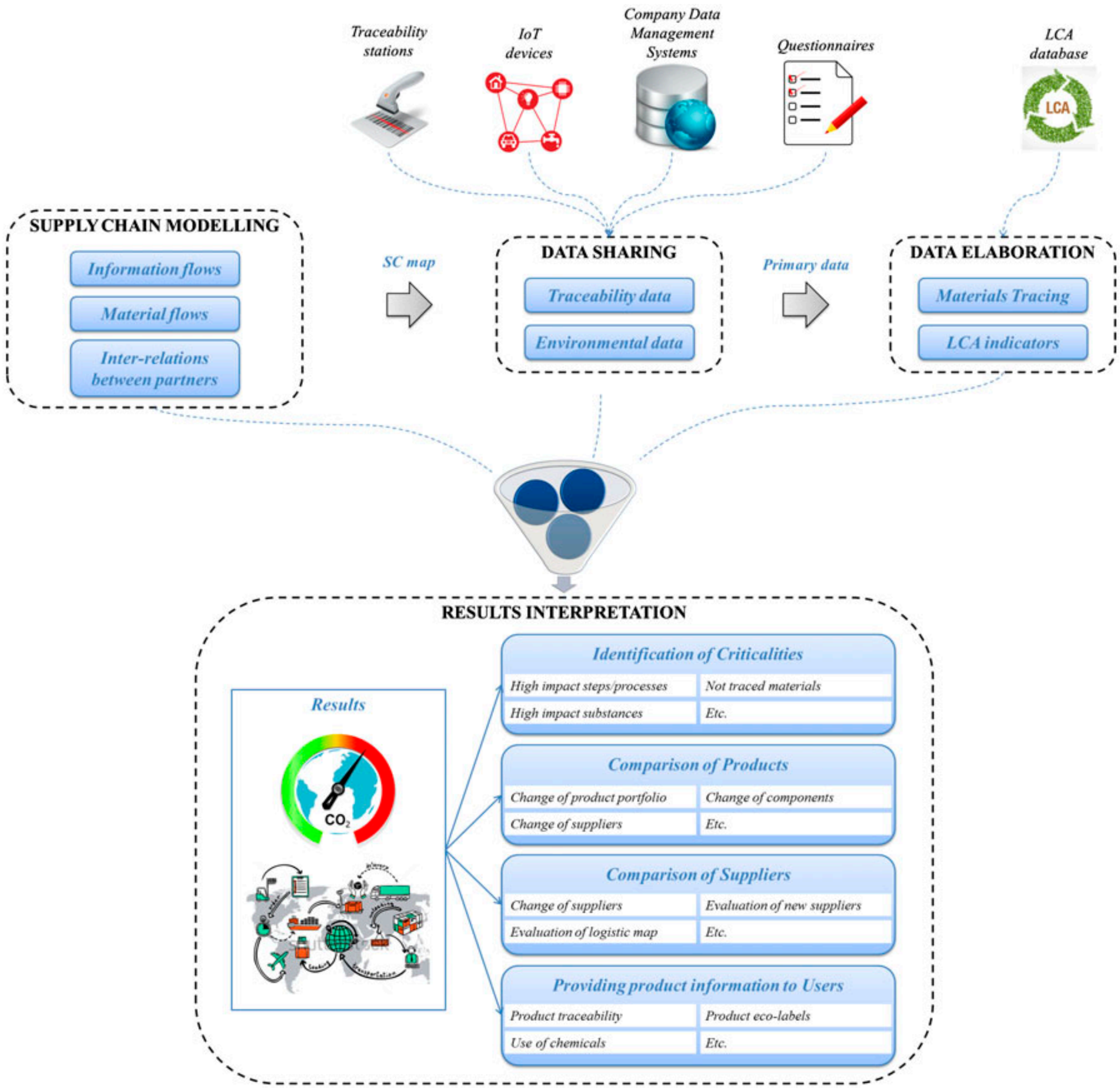

Figure 1. Proposed method.

3.2. *Data sharing*

Data sharing represents a crucial step towards the concurrent assessment of traceability and sustainability. It has to be performed continuously by each stakeholder involved in the SC in order to always have updated data for the analyses. However, before effective data sharing, it is essential to define which aspects have to be investigated and, consequently, which data are significant and how they can be retrieved in an effective and reliable way.

3.2.1. *Data classification*

According to the main goal of the proposed method, this study focuses on two information classes: traceability and environmental sustainability. As shown in Table 1, the most important data for both categories have been identified and grouped in several classes according to their nature (e.g. input, output and processes) (Germani et al. 2014; Favi et al. 2016).

The *Traceability* category includes all of the data related to (i) materials and semi-finished goods received as inputs from suppliers, (ii) products provided as outputs to customers, (iii) other components coming from external subjects and (iv) manufacturing processes (internal and external). With these data, it is possible to better manage the production

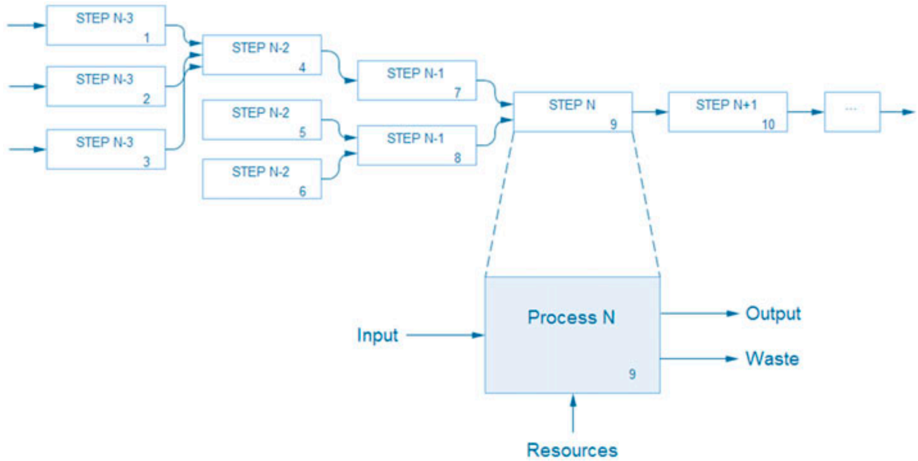

Figure 2. Supply chain network.

phases and completely map the flows for the most important parts or components of a product's bill of material (BoM), linking the different SC steps.

The *Environmental Sustainability* category comprises all of the data required to carry out an LCA and to characterise and evaluate each actor in the SC from an environmental point of view. The data mainly consist of (i) materials related to main flows (e.g. inputs and outputs), secondary flows (e.g. by-products and co-products) and scraps, (ii) resource consumption, (iii) emissions and (iv) transportation.

In addition to quantitative data, qualitative information has to be considered for both categories in order to characterise the context of the analysis and to better interpret the shared data. This information is used to understand the approach toward environmental issues (e.g. environmental risk management, certifications and awareness of proper impacts) and the process features (e.g. quality control, automation level and standards) for each actor in the SC network.

3.2.2. *Data collection*

The availability and reliability of primary data are some of the most important requirements to make the proposed method effective and scalable. For this reason, the last column of Table 1 (Collection methods) depicts how these data can be collected in real industrial contexts. There are several different solutions to efficiently retrieve data from partners involved in the production chain.

- *Internet of Things (IoT) devices*. These are the most efficient solutions because they guarantee the availability of data in real time. The use of a network of sensors to monitor the significant parameters of a production step allows reliable data to come directly from the factory environment. Some examples are smart metres to monitor electricity and gas consumption; traceability stations to monitor the flows of materials in input, output or within a production plant, etc. These kinds of devices do not add complexity in the operations of a company and completely solve the problem of the availability and reliability of the needed information. However, these solutions are probably the most expensive, since they require the installation of hard devices.
- *Company Data Management Systems (Product Lifecycle Management – PLM, Enterprise Resource Planning – ERP, Manufacturing Execution System – MES, Product Data Management – PDM, etc.)*. Some data can also be retrieved from the internal repositories of each company on a daily basis, as in the cases of BoMs; production lots; details on internal processes, such as the use of chemicals, scraps, input materials and suppliers. Since some of the data cannot be easily retrieved from IoT devices installed in the factory environment, interfacing with company databases (DBs) is usually needed to complete the set of information.
- *Dedicated questionnaires*. The last solution to collect data is the use of questionnaires for each involved company to manually fill in. In the context of this study, the questionnaire has been structured in four main sections: (i) Basic, which allows the tracing and quantifying of input/output materials flows, by-products, scraps, external treatments and the related information about transportation; (ii) Flows, which includes all of the data required to carry out the LCA, such as resource consumption (electricity, water, heat), use of chemicals, waste produced, packaging and emissions into air and water; (iii) Process Quality, which aims to understand the company approach

Table 1. Classification of data.

Data categories	Data classes	Description	Data types	Collection methods
Traceability	Input	Materials and semi-finished products received as inputs from other companies in the traced SC network	Quantity	Traceability stations
			Origin	Company DB
	Output	Output products sent to other companies in the traced SC network	Quantity	Traceability stations
		Bills of materials		Company DB
		Production lots		
	Processes	Details of internal and external processes	Quantity Transports	Company DB
	Inputs	Materials and semi-finished products received as inputs from other companies in the traced SC network	Quantity	Traceability stations
			Transports Origin	Company DB
Environmental sustainability	Other Inputs	Secondary input materials and semi-finished products received from companies not traced in the SC network	Quantity	Traceability stations
		Packaging materials	Transports	IoT devices Company DB
		Chemicals		
	Outputs	Output products sent to other companies in the traced SC network	Quantity	Traceability stations Company DB
	By-products Co-products	Secondary outputs which generate revenue or are reused to manufacture other products	Quantity	Traceability stations Company DB
	Processes	Internal and external processes	Quantity Transports	Company DB
	Wastes	Scraps from manufacturing processes Other waste from companies Wastewater	Quantity	IoT devices Company DB
	Emissions	Emissions to air Emissions to water	Quantity	IoT devices
	Energy	Electricity consumption Heat consumption Electricity generation	Quantity	IoT devices Company DB
	Water	Water consumption	Quantity	IoT devices Company DB

towards environmental issues, environmental risk management, certifications, etc; and (iv) Product Quality, which focuses on the typologies of the produced items. Since questionnaires hardly guarantee an acceptable level of data reliability, this collection method has to be used only in cases where the other solutions cannot be applied (e.g. if parameters are difficult to automatically monitor, during the first phase of the method implementation). Data collected by questionnaires have to be accurately checked in order to avoid significant errors in the successive assessments.

The collection of traceability data essentially consists of the mapping of all of the flows of materials. In the check-in phase, input materials, components or semi-finished products coming from a supplier have to be identified. In the check-out phase, the identification of goods sent to other partners involved in the same SC is necessary instead. Traceability data can refer to single products or groups of products, such as production lots, boxes and pallets. This choice depends on the basic unit that each company decides to univocally identify and, thus, to monitor along the SC. For the correct implementation of the method, these activities have to be performed each time a company exchanges goods with other partners. The adoption of traceability stations and tags (e.g. barcodes and RFID tags) allows the collection of these data in an automatic and rapid way.

The collection of environmental data, on the other hand, can be performed through one of the three methods described above. This phase can be synchronous with respect to the sharing of traceability data if the environmental data are automatically monitored together with data related to material flows, or the phases can be asynchronous if environmental data are collected at a lower frequency (e.g. after a predefined time span, when significant modifications to the production conditions occur).

3.3. *Data elaboration*

The data elaboration phase is performed by using the primary data collected from the production environment and linking them with secondary data coming from a commercial LCA DB. Through the traceability assessment, all of the materials, components and products within the SC can be monitored, building a complex map of all of the flows of materials. Furthermore, the collection of all of the data described above allows the classical traceability analyses to be extended and an LCA-compliant sustainability assessment to be performed to quantify the environmental impacts of the entire SC, the single actors involved, single products or even single activities.

The degree of detail of these analyses strictly depends on the granularity of data collected during the data-sharing phase. If the data are general and refer to the whole company, the basic unit will be the single company, and only the entire SC or its sub-segments can be analysed. However, if the data are related to single processes and activities, an assessment 'within the gates' of each company will be possible.

3.4. *Results interpretation*

After the assessment, the last phase is the interpretation of the results obtained to discover weaknesses and successively set corrective actions.

The first output of the method implementation is the univocal *Identification of Criticalities* within the SC. These weak points can be related to (i) traceability issues, such as non-traced materials or components, complex logistic maps and suppliers located in high-risk geographical areas or (ii) sustainability issues, such as stakeholders responsible for high environmental impacts, processes with high emissions and chemical substances with high potential risks to human health. All of these evaluations contribute to taking a clear picture of the entire SC, sub-segments or single activities, and they represent the starting point for the successive optimisation phase, aimed at mitigating the identified traceability and sustainability issues (e.g. choosing partners that guarantee full traceability, choosing suppliers located in the same production district, improving of the overall efficiency of internal processes and choosing suppliers that guarantee the minimum impact on the environment).

The method can be also used by each company as a means to quantitatively assess its operations from different points of view by considering both internal and external activities. The *Comparison of Products* allows the verification of which products or product families are the most critical (e.g. products manufactured by the use of non-traced components, those realised through high energy consumption processes and those treated with unhealthy or toxic substances). In this way, if a company decides to undertake specific strategies for the optimisation of its products in order to guarantee to its customers fully traced or green products, the method becomes a valid tool for product portfolio management. Changing critical materials or components or changing suppliers could be corrective actions to implement after the interpretation of the results with the aim to optimise the overall performance of the company.

A *Comparison of Suppliers* is possible through the method implementation, since it allows the comparison of different companies which supply materials or components of comparable quality in order to better balance the flows for a general SC optimisation. One such example is a company that wants to optimise the logistics and transportation routes within its SC with the aim to minimise the distances travelled and, thus, to reduce delivery times and environmental impacts. Furthermore, the method is also suitable for evaluating new suppliers that want to collaborate. In this case, a company can compare the performance of new actors with that of other comparable partners (e.g. products of the same quality and comparable company dimensions), and the method represents a useful tool to guide the decision-making process.

The method is also a useful tool for companies to *Provide Product Information to Users*. Following the method steps and collecting the described data, each company is able to provide to its customers accurate information about the origins and environmental loads of its goods. This step is essential for the detailed eco-labelling of products considering the entire production network.

3.5. *Use in real industrial cases*

The proposed methodological approach can be applied in any SC, where each actor has to perform the following workflow based on the main steps described above:

(1) *Checking available data*. According to data belonging to the information classes described in the *Data Classification* section (i.e. traceability and environmental sustainability), the company identifies which data are available through the use of current company data management systems (e.g. PLM and MES) and IoT devices (e.g. sensors).
(2) *Benchmarking the main tools to collect missing data*. For those data not available through the current tools and devices, the company has to identify the best data gathering strategy, selecting and installing the most appropriate solution according to its needs. For example, to collect information about the energy consumption of a production line, it is possible to install dedicated electricity metres (for each line or machine) or analyse the electricity bills. The adopted strategy depends on the desired level of detail, costs, production flow characteristics, technical feasibility, etc.
(3) *Manual data filling*. For those data not available through the implementation of IoT devices or the use of the company tools, it is necessary to collect data manually by filling in the dedicated questionnaire described in the *Data collection* section.
(4) *Data monitoring*. After identifying a tailored strategy to collect the required data (i.e. current company tools and devices or new tools and devices), all of the data gathered by the adoption of IoT devices need to be monitored over time in order to have updated values.
(5) *Data sharing into the SC database*. All of the data collected by the company are stored in a shared database (see *Data elaboration* section).
(6) *Data analysis*. At this stage, it is possible to conduct several environmental assessments from different points of view (e.g. at company level or at SC level) in order to identify any possible optimisation to maximise environmental sustainability.
(7) *Updating the current scenario*. Data collected by the company need to be updated according to any improvement or change implemented or if any new actors are involved. For example, a new supplier interested in joining the SC needs to put its industrial process under control in order to assess the related environmental impact.

The main difficulty in the implementation of this approach is in *Data sharing*, because companies are generally unwilling to share their information and data externally, primarily for security reasons. For this reason, the full collaboration of all of the involved stakeholders is essential to obtain reliable data.

Another technical challenge that is certainly easier to manage and that could emerge during the implementation of the method is that of data with non-homogenous units of measurement (e.g. kilograms vs. square metres in the case of skins). In this case, it is necessary to foresee specific conversion factors to manage any exchanges among different suppliers in the SC.

4. Method implementation

This section illustrates the real application of the method in a leather shoe SC, which is important to the Marche region in Italy. Such an industrial chain is characterised by significant environmental impacts and provides products for a very wide market. Moreover, since the final products belong to the fashion industry, customers' environmental awareness is very high.

The scope of the case study is to make the shoe producer and its upstream SC traceable and sustainable. This case study aims to demonstrate that the use of traceability principles, with the support of other information collected inside each SC actor, leads to detailed knowledge of the environmental sustainability of the whole SC. The analysis conducted includes all of the elaboration and transportation processes and the related resource flows, from the supply of raw materials (animal skins) to the manufacturing of the final product (shoes).

4.1. *Case study description*

At first, the method envisages the identification of all of the shoe SC actors, by means of expert interviews and a literature review. As shown in Figure 3, the shoe network starts with the farming process, which is mainly related to bovine, ovine, caprine and swine livestock, and proceeds to the slaughterhouse, where the animals are slaughtered and their skins are salted and/or dried to prevent the degradation process. However, in this case study, the leather is assumed to be a by-product of the meat industry, and, therefore, the farming and slaughter stages have been omitted (Djekic and Tomasevic 2016).

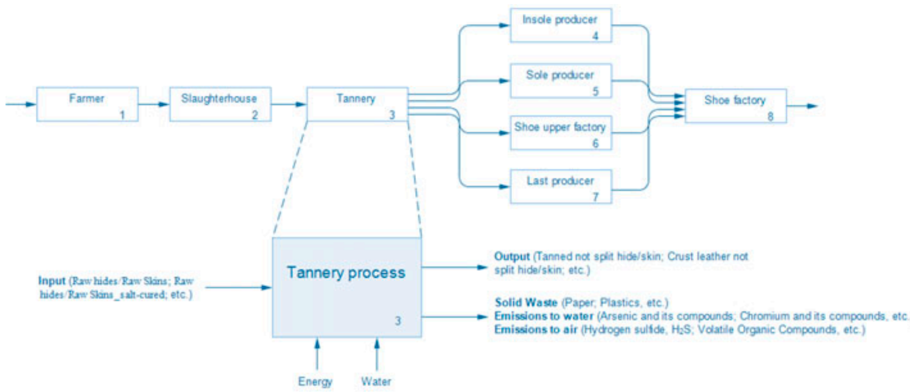

Figure 3. Shoe supply chain and tannery process details.

Continuing along the shoe SC map, tanneries recover the hides and skins from slaughterhouses and treat them to make the leather, a more stable and durable product. This step is the most important in leather production, and different methods can be applied. The most common methods are vegetable tanning and chrome tanning, depending on the final leather usage. These three stages are common to all of the main components of the shoe (i.e. the shoe upper, sole and insole) because the input for each is the same: tanned leather. Hereafter, these components undergo different processes by different manufacturers, which are, respectively, the shoe upper factory (which executes the cutting and linking processes), the sole producer and the insole producer. Another component in shoe production is the last, which is a mechanical form that allows the simulation of the human foot. In this case, only the step related to the last producer has been considered because the last is characterised by raw materials that are not leather (e.g. plastics and wood). Finally, all of these components are provided to the shoe factory, where the assembling and finishing processes take place in order to obtain the final products, the shoes.

As anticipated above, the downstream SC is out of the scope of the analysis, so the steps related to the distribution and the user have not been considered. However, the shoe is not an energy-consuming product, so the environmental impact related to its use can be neglected without compromising the reliability of the results. In addition, the distribution network of the SC under consideration is very fragmented, manages other products in addition to shoes (e.g. bags, wallets and belts) and provides the final product to multi-brand stores. These characteristics do not favour the implementation of the proposed system.

In addition to the main flow, each step of the SC has been investigated in order to identify other necessary data (e.g. tannery process details in Figure 3).

As far as the data collection is concerned, several methods and tools are used to collect real and reliable data from each actor involved in the leather shoe SC. According to the supply network shown in Figure 3, different actors are involved, with at least one actor for each production step. In more detail, this case study shows the involvement of three tanneries, one using vegetable tanning and the others using chrome tanning; one sole producer; one insole producer; one last producer; two shoe upper factories; and one shoe factory where the shoe is assembled and finished.

Once the data already available in the company have been checked (step 1 of the above workflow), each actor in the network identifies the most appropriate solution to install in order to gather the missing data (Step 2 of the above workflow). To this end, Table 2 shows the data collected by the different actors and what means or tools they used for data collection. As shown, the primary data are mainly collected through the company PLM systems, the computers on board along the production processes, and the implementation of IoT devices in production plants with the aim to monitor several process parameters. It is worth specifying that for some data it was not possible to collect the values directly through one of these tools because the installation of hard devices was considered too expensive for this preliminary experiment. Therefore, in these cases, a tailored questionnaire was created on the basis of the structure previously described (Step 3 of the above workflow). The quantity and quality of the collected data made the information sample complete and significant for modelling the leather shoe SC. This information has been monitored at each company involved in the SC (Step 4 of the above workflow) and shared in a common database where all of the data from each actor are collected (Step 5 of the above workflow).

To guarantee the accuracy and reliability of these data, they have been checked and compared with the reference data of this sector. For each step in the SC or company typology (e.g. vegetable tanneries rather than chrome tanneries),

Table 2. Primary data provided by the nine actors involved in the shoe supply chain.

	Tannery A	Tannery B	Tannery C	Sole producer	Insole producer	Last producer	Shoe upper factory A	Shoe upper factory B	Shoe producer
Input	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM
Output	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM
By-products	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.
Scraps	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM	PLM
External/internal process info	PLM	PLM	Quest.	PLM	Quest.	Quest.	Quest.	Quest.	PLM
Electricity consumption	IoT	IoT	IoT	Quest.	Quest.	Quest.	Quest.	Quest.	IoT
Heat consumption	IoT	IoT	IoT	Quest.	Quest.	Quest.	Quest.	Quest.	IoT
Water consumption	IoT	IoT	IoT	Quest.	Quest.	Quest.	Quest.	Quest.	IoT
Chemicals	PLM	PLM	PLM	Quest.	Quest.	Quest.	Quest.	Quest.	PLM
Waste	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.
Accessories	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	PLM
Packaging	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	Quest.	PLM
Emissions to air	IoT	IoT	IoT	Quest.	Quest.	Quest.	Quest.	Quest.	IoT
Emission to water	IoT	IoT	IoT	Quest.	Quest.	Quest.	Quest.	Quest.	IoT

data from the literature have been collected in order to verify that the data provided through the questionnaires do not deviate too much from the average values. For example, a set of thresholds (percentage ranges) for the main data classes (e.g. emissions to air, water consumption and energy consumption) has been defined on the basis of Best Available Techniques Reference documents (BREFs) (European Commission – Joint Research Centre 2013), which give information on the techniques and processes used in the specific sector and the related current emission and consumption levels. It is worth specifying that once the number of traced actors is significant (i.e. when the shared database is populated with a relevant amount of data), a reliability check can be performed by considering the collected data.

Regarding secondary data on input materials, which come from other suppliers not belonging to the traced SC network (e.g. heel and laces), the Ecoinvent v3 commercial database has been used for the analyses.

In order to properly elaborate on the collected data, a set of rules and algorithms has been defined to ensure the proper workflow and avoid inconsistencies. In particular, a list of materials that each SC step could use as an input or output to its production has been created in order to minimise non-uniform answers. In order to better model the company reality, several criteria for the allocation of resource consumption, emissions, etc. are proposed (e.g. quantities and output turnovers). To solve the issue related to non-homogenous units of measure and reproduce the correct materials flows, the questionnaire requires the specification of the conversion factor to express the input/output quantity in a standard unit (e.g. the insole producer declared that the kg/piece conversion factor related to the *finished leather split for footbed* is 0.015). To simplify the traceability of all materials, chemicals, accessories, etc. and calculate the environmental impacts related to their movements, several transportation scenarios (starting point, arrival point and means of transport) have been created as follows:

(1) the world map has been divided into 30 areas;
(2) for each area, the most representative airports and harbours have been identified; and
(3) a set of default routes has been defined and the relative kilometres have been calculated.

Finally, to support the data elaboration phase, a specification document has been created to link each questionnaire answer to an Ecoinvent data-set. In this way, primary and secondary data have been used to estimate the environmental impacts of the entire SC and to identify the main hot spots where it would be useful to define potential improvement actions (Step 6 of the above workflow).

5. Results and discussion

The traceability of the network allows the mapping of all flows along the SC. In particular, for each company, it is possible to localise on a map the suppliers of input materials, chemicals, packaging and accessories. For example, in Figure 4, the map related to tannery C is shown. On the one hand, a wider dispersion of leather suppliers emerges, mainly owing to the high number of leather requirements (related to factors such as thickness, quality and type of

Figure 4. Traceability of tannery C suppliers.
Source: Authors.

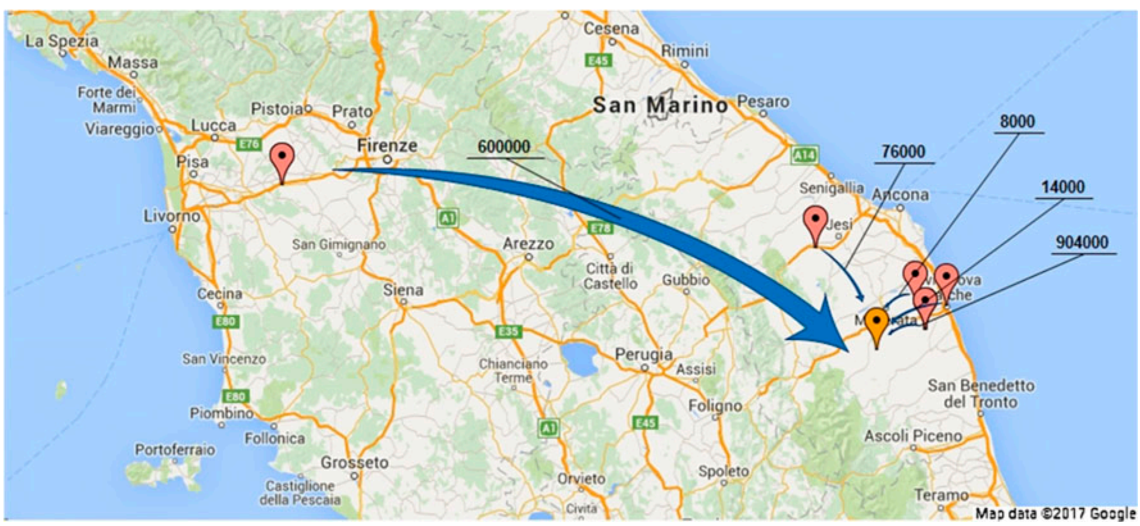

Figure 5. Traceability of sole producer inputs with details of transported pieces.
Source: Authors.

animal skin). On the other hand, the main suppliers of chemicals and packaging are usually located in circumscribed areas. Going into more detail, it is also possible to analyse the flows related to the input materials in order to have an overall view of their quantities and origins and to preliminarily evaluate the transportation impacts and/or logistic criticalities. As an example, in Figure 5, a partial representation of the input flows of the sole producer is shown.

The collected data allow the environmental impacts of the traced SC to be quantified and alternative scenarios to be simulated. The 'ILCD 2011 Midpoint' method (European Commission – Joint Research Centre 2012) has been used for this scope, and 15 indicators have been selected.

Taking into account the climate change indicator, the results of the analysis show that the majority of the environmental impact originates from the inputs of the shoe factory and the related upstream SCs (left graph of Figure 6). It is worth specifying that the results do not refer to a single pair of shoes but to the overall output of the considered shoe factory over one year. Going into more detail, the most critical inputs are the upper and the sole, owing to the tannery process (right graph of Figure 6). In particular, the latter is responsible for about 47% and 87% of the impact of the shoe upper considering the climate change and human toxicity indicators, respectively.

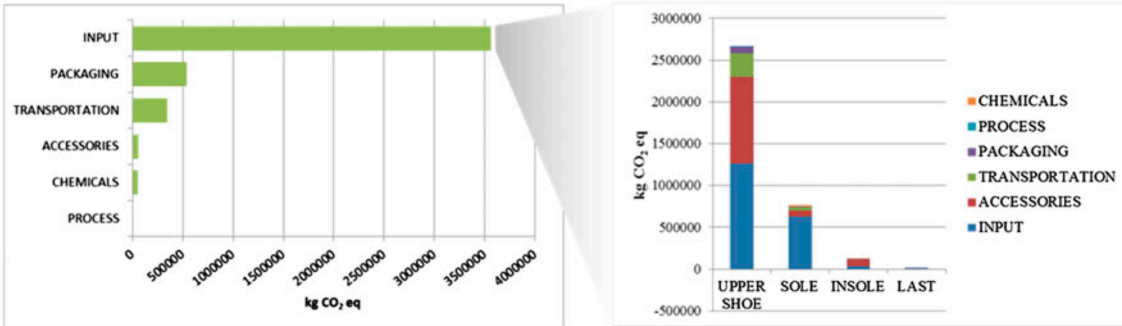

Figure 6. Shoe supply chain environmental impact and details of shoe factory inputs.

		Climate change [kg CO2 eq]	Freshwater ecotoxicity [CTUe]	Human toxicity [CTUh]
TANNERY A	*Chemicals*	413944,8497	402670,9903	0,04432735
	Transportation	241084,8401	104946,0471	0,01618899
	Packaging	4075,5070	6442,2800	0,00068997
	Process	0,1101	0,4004	0,00000024
TANNERY B	*Chemicals*	490941,7333	3043147,9957	0,31967901
	Transportation	50631,0075	24115,7140	0,00392653
	Packaging	17143,8937	6684,5314	0,00033863
	Process	0,1065	0,8088	0,00000054
TANNERY C	*Chemicals*	490632,8056	7241593,0213	0,73231184
	Transportation	212584,3390	92539,5643	0,01427517
	Packaging	7011,1797	7337,3584	0,00143640
	Process	0,9618	6,2256	0,00000402

Figure 7. Environmental impact comparison among the three involved tanneries.

For this reason, an in-depth analysis has been carried out considering three different tanneries. The results (Figure 7) show that chemicals are the main cause of the environmental impact in all three cases. The significant impact on freshwater and the human toxicity of tanneries B and C is because of the use of chrome salts. Tannery A, however, uses vegetable tanning, which is more environmental friendly. The comparison of the three tanneries provides important feedback about the environmental sustainability of different typologies of leather.

From Figure 6, it also emerges that a significant contribution is related to the packaging used in the different steps of the SC. The packaging represents a rather surprising hot spot that is usually missed, but in this case study, it has been identified through the sustainability analysis realised by applying the proposed method. In particular, a relevant portion of the impact is owing to the shoe factory because of the heavy use of cotton and corrugated board boxes for each pair of shoes (Figure 8).

Another important consideration derives from the analysis of the environmental impacts of the accessories used for shoe upper production (Figure 8). In fact, the heavy use of nylon and cotton makes this stage not sufficiently sustainable.

As shown by these results, the method implementation allows the mapping of the component flows along the entire SC, identifying its most critical stages. At the same time, this method allows the analysis of the most important environmental hot spots of each company. These are essential outputs to guide the decision-making process to correctly focus the management strategy towards an optimisation of the overall SC.

First, a critical aspect of the considered case study is certainly the complexity of the upstream SC related to raw materials (i.e. skin). The three involved tanneries receive skins from all over the world (e.g. from Northern Europe and Central and South America). The analysis performed through the application of the proposed method suggests that

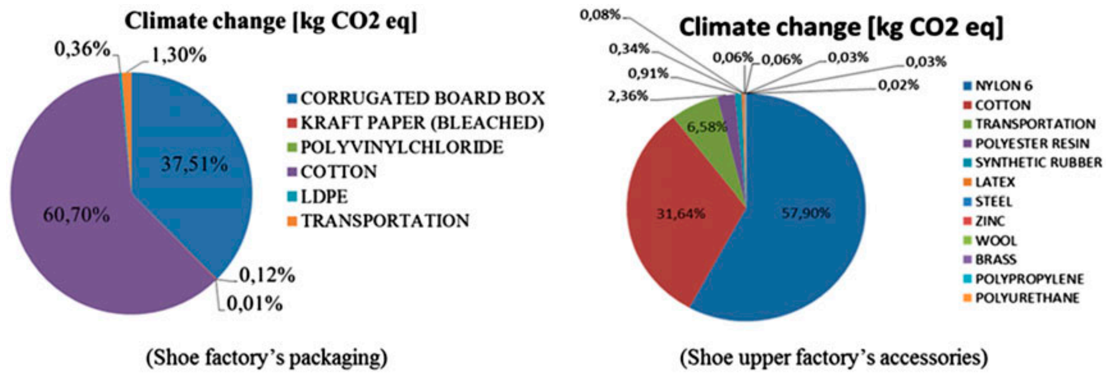

Figure 8. Details of two hot spots (packaging for the shoe factory and accessories for the shoe upper factory).

a collaboration between the three tanneries could potentially lead to a reduction of the number of skin suppliers, with sensible benefits in terms of the complexity of the network, transportation, environmental impacts and also costs.

Another important outcome is the possibility for the involved companies to optimise the environmental performance of their products by choosing the most sustainable raw materials and components to use and partners to involve. For example, the comparison between the three involved tanneries suggests to the shoe upper factories the convenience in changing the current supplier (i.e. tannery B) of specific components (e.g. linings, shoe uppers), since components of comparable quality can be supplied by more environmentally friendly partners (i.e. tannery A).

Finally, concerning the internal optimisation, the detailed analysis of the environmental impacts related to the shoe allowed for the discovery of the relevant influence of packaging and accessories. This result suggests the need to properly redesign shoe bags and boxes to minimise the use of impactful materials (e.g. cotton) or to select reinforcing tape, interlining and lining made from 'green' materials.

6. Conclusions

This study proposes a method able to extend the classical concept of SC traceability, where only flows of materials are monitored, by including additional data on energy and resource consumption, which are useful to realise a detailed environmental sustainability assessment. The SC considered in this study is a leather shoe SC, because it is complex (different partners collaborate to realise the shoe components) and environmentally impactful.

The method allows discovering potential problems (e.g. quality and toxicity) and hot spots, as well as communicating to each actor and to consumers the exact origin of each raw material, semi-finished part or final product. This tool is useful for practically implementing SSCM for a multi-objective optimisation of SC performance (e.g. logistics, transportation and environmental sustainability).

Furthermore, this approach overcomes the common LCA boundaries (gate-to-gate activities) by considering the whole SC as an integrated collaborative system. In this sense, the proposed case study about the leather shoe SC highlights the need to focus the attention on tanneries, because they have a relevant role. The final shoe package (e.g. boxes and cotton bags) also has a high impact, and this finding suggests the design should be optimised in order to minimise the usage of materials.

Future work will be focused, at first, on considering other aspects out of the scope of the present work. For example, a method including the social aspects should be investigated in order to have a more comprehensive overview of SC sustainability performance. Moreover, the implementation in the industrial context should be deepened in order to recognise other impacts, such as costs and time of implementation, which affect each company. In this sense, the development of a software application for the automatic traceability of material flows, the collection of needed data and the realisation of the assessments would certainly contribute to improve the usability of the proposed approach.

Disclosure statement

No potential conflict of interest was reported by the authors.

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