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INVESTIGATING THE SUSTAINABILITY OF PRODUCT SUPPLY CHAINS

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Abstract

According to the growing pressure on Sustainability issues from governances, manufacturing industries must pay their attention to optimize their processes. Anyway, it is necessary go behind this preliminary approach, extending the boundaries from the single company to the other actors that operate in the same supply chain.

In this context, the paper proposes a methodology to increase the sustainability and to guarantee the traceability along the whole product supply chain. The methodology allows to model any supply chain, through the data collection from all the actors involved, and to measure the environmental sustainability, through the implementation of a distributed software system.

The experimental case study, which involved a leather shoe supply chain, allowed to demonstrate the effectiveness of the approach in the selection of suppliers and in the optimization of the supply chain, taking into account the environmental aspects together with the other constraints such as design, costs and quality.

Keywords: Design for X (DfX), Sustainability, Supply chain modelling, Traceability

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1 INTRODUCTION

The Sustainability concept refers to the ability to produce goods or deliver services without compromising the aptitude of new generations to produce and manufacture the same products and services in the future (WCED, 1987). According to the incoming pressure from government regulators, community activists, non-governmental organizations, and due to the global competition proper of the current industrial world, the Sustainability practices and their application are growing attention, both in academia and industrial companies. Following this trend, European and International governments issued legislations and programmes, such as the 7th Environment Action Plan (European Parliament and Council, 2013), aiming to provide a strategic vision and new guidelines in the environment topic, in order to reach a global sustainability.

By the Industry point of view, manufacturing companies are increasingly involved to pay attention to such issues seeing one the most actor to the global environmental impact, due to its very high energy and resource consumptions and greenhouse gases emissions. For this reason, companies has to operate not only to obtain economic benefits through their activities, but they must promote “green” products and processes, to reach the sustainability aim.

Since a product can be viewed as the final result of different productive steps performed by several actors which use different processes, its environmental sustainability strictly depends on the performances of the supply chain. Nevertheless, companies usually have a view limited within their boundaries, tending to assess and optimize only the internal activities and processes, omitting the other productive steps which could be the most critical ones. This is due to the difficulty to model a complex network of suppliers and to obtain the necessary data without dedicated tools and methods.

In order to prompt manufacturing companies to go behind their boundaries, this paper presents a methodology and a system to model, measure and, as a consequence, optimize the environmental performances of a generic supply chain, from the raw materials retrieval to the assembly of the final product. It takes into account all the materials and semi-finished parts that flow between the different actors of the network and their related industrial processes in order to guarantee the complete traceability of the final product. Therefore, the implementation of the proposed methodology allows modelling a supply chain with all the productive steps and characterizing each node of the network in terms of resource and energy consumptions. The methodology implementation represents an effective mean for companies to certify their products in terms of environmental sustainability, as well as to guarantee the traceability. This latter is strictly related to product quality and, in particular, it is essential to discover possible problems of suppliers in terms of toxic substances, a theme very deeply felt by final consumers.

2 LITERATURE REVIEW

In the last decades, researchers have paid their attention to extend the Sustainability concept at Supply Chain level, going behind the common boundaries of a company dedicated to the goods production (i.e. Product Sustainability), and considering not only the manufacturing process needed to realize a product, but also the entire network of stakeholders and suppliers involved in its production, from actors deal with raw materials procurement, to other ones dedicated to the final product delivery and disposal. The Sustainability concept is the pillar of Eco-design approach, indeed Eco-design has arguably been developing since the first wave of sustainability during the 1960’s (Bhamra and Lofthouse, 2007), when designers such as Victor Papanek began to link the environmental concerns of scientists with the art of production (Papanek, 1977). Within the literature surrounding this research area there is a range of terms all of which loosely refer to the “integration of environmental aspects into product design and development”(ISO, 2002; Bhamra 1999).

In literature, lots of papers face the Sustainability theme along the industrial Supply Chain, but especially as review works. They investigate the three sustainability dimensions, identifying the main affected assets for each one. For instance, according to Hassini et al. (2012), the main objective of a Sustainable Supply Chain is maximize the product profitability, both minimizing the environmental impacts along the entire Supply Chain, and respecting the social well-being of each supplier’s company involved. Other researchers (Wittstruck and Teuteberg, 2011) defines Sustainable Supply Chain as an extension of the traditional concept of Supply Chain Management, where the aim was to maximize the value creation through the management of relationship among key partners of the network, adding environmental and ethical aspects.

Besides them, several research methodologies support the incoming problems about Supply Chain Sustainability; the majority uses analytic methods as Fuzzy decision making (Erol et al., 2011), simulation (Van Der Vorst et al., 2009) and Life Cycle Assessment (Fiksel et al., 1996; Matos and Hall, 2007). Anyway such examples remain too theoretical, defining in detail the framework or the conceptual model proposed, but without providing quantitative values and measures of Sustainability along the Supply Chain (Gosling et al., 2014; Grimm et al., 2014). Despite Boukherroub et al. (2014) proposed a first integrated approach to select the partners to involve in the Supply Chain network, its work measures the supplier's sustainability only through the assignment of qualitative weights, according to the three main sustainability dimensions. Another example of method application has been defined by Validi et al. (2014) that proposed a decision-making tool able to identify a realistic network, according to alternative transporting scenarios. Our work is inspired by such approaches but proposes a method able to define the sustainability of each partner involved into an industrial supply chain, not only considering the transportation but also identifying each production process, the main emissions and several other factors.

An optimized and sustainable supply chain necessarily requires to take into account the traceability (Dabbene et al., 2014). According to ISO 9000, traceability is defined as "the ability to trace the history, application or location of that which is under consideration". It is also specified that traceability should consider the origin of raw materials and parts, the processes, the distribution and the final location of the product. In literature there are many studies about this topic. Kang and Lee (2013) presented a generic traceability service, based on RFID (Radio Frequency Identification) and on the EPCglobal Architecture Framework. Another interesting example regards the use of the RFID technology in the chemical sector, to facilitate the procedures to comply with the requirements of the European REACH regulation (Gaci and Mathieu, 2011). The most of the works about traceability systems regards the food sector, in which the final consumers require high quality products (Aung and Chang, 2014). Although traceability requires a rethinking and a reorganization of the food supply chain, it is recognized as an essential way to prevent unsafe products and minimize scandals and recalls, which are very dangerous for the company image (Kang and Lee, 2013). In the meat sector it is possible to find different examples of systems to guarantee the traceability and to optimize the supply chain organization, through the sharing of the generated information (Fenu and Garau, 2009).

In spite of the very high number of research works related to traceability, only few of them consider the sustainability aspects (Bjork et al., 2011). This because the sustainability assessment linked to traceability requires to obtain a huge amount of data and in literature there is a lack of dedicated tools and methods, able to support companies in these complex analyses. In this context, the present paper aims to go beyond, proposing a well-defined methodology to support companies which want to start a path toward sustainability and traceability.

3 METHODOLOGY FOR SUPPLY CHAIN TRACEABILITY AND SUSTAINABILITY ASSESSMENT

An essential pre-requisite to guarantee traceability of materials and semi-finished products and to assess the environmental load of a product is the deep knowledge of the company supply chain. Only knowing all the involved subjects, together with the relative inter-relations and exchange of data and materials, a product can be traced and all the environmental impacts can be estimated, avoiding to neglect important data and contributions. First of all, the different steps have to be identified and linked together with their input/output flows, in order to build a detailed supply chain map, considering all the most important involved subjects. Then, for each step, all the necessary information to calculate the environmental impact and to guarantee the traceability have to be gathered, retrieving it from the supply chain actors. At the end, the productive history of each bill of materials or production lot can be rebuilt and, at the same time, the relative environmental impact can be quantitatively measured with a very high accuracy.

The next sections explain the methodology steps to model a supply chain together with the data to gather, and how it is possible to implement the proposed methodology in a real context.

3.1 Methodology description

Almost all the complex products are manufactured through several productive steps performed by different subjects, which together contribute to reach the final solution. This is possible thanks to a

supply chain network which includes many subjects, several flows of materials and semi-finished goods and different data exchanged by the supply chain actors. In order to reconstruct the history of a product, to trace their materials and components and to assess the sustainability, a deepen knowledge of all the above items is required. In Figure 1 the different steps to guarantee the product traceability and assess the environmental sustainability, considering the whole supply chain, are showed.
The first step is relative to the supply chain modelling. Following the links between the different actors it is possible to build a detailed "supply chain map", which is essential to trace the product history, from raw materials, to the final manufacturing processes.
This graph (Supply chain modelling in Figure 1) allows to identify all the direct and indirect relations between the involved participants, and, as a consequence, the real "path" for each product part.

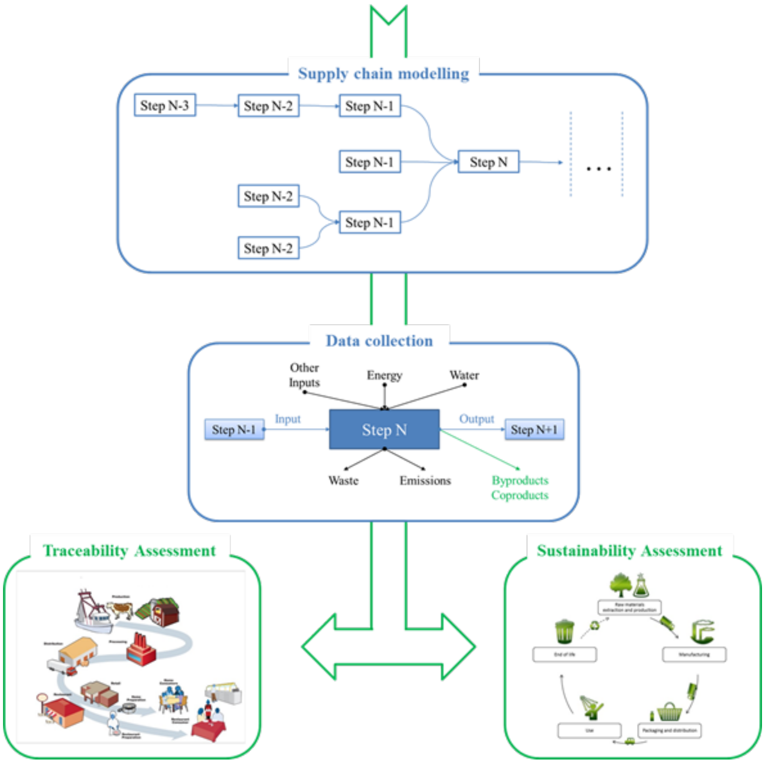

Figure 1. Methodology steps

Once the supply chain map has been built, each productive step has to be characterized not only in terms of inputs and outputs of materials and semi-finished products, but also in terms of flows of energy, wastes and emissions (Data collection in Figure 1). Only in this way a supply chain can be, at the same time, completely traced and assessed in terms of environmental sustainability.
According to Table 1, the necessary data to share between the different supply chain actors belong to two main categories: traceability and sustainability. Concerning the first category, the data required are essentially the quantities and typologies of materials and semi-finished products received in input from other supply chain actors, the quantities and typologies of outputs provided to other steps, the details about the manufacturing processes to know the productive history of each final or semi-finished product, and, finally, information relative to bill of materials/production lots. For what regard the environmental sustainability, the necessary data to consider has been subdivided in four sections, in which the first two (Basic and Flows) include the "classical" data to realize a LCA (Life Cycle Assessment), such as energy consumed, water used, by-products or co-products (avoided wastes), scraps and other wastes (solid, wastewater, etc.), emissions to air and the necessary transportation stages to move materials and products from a productive step to another one. Product Quality and Process Quality sections, instead, include more qualitative information used to measure the approach of a company about environmental and sustainability issues (e.g. environmental risks management, certifications, etc.) and the process features (e.g. quality control, etc.).

Table 1. Classification of data used by the methodology

Data Categories	Section	Data classes	Description	Data considered
Sustainability info	A. Basic	Inputs	Traced materials and semi-finished products	Quantity Transports Origin
		Other Inputs	Not traced secondary input materials or semi-finished products Packaging materials Chemicals	Quantity Transports
		Outputs	Traced output products	Quantity
		By-products Co-products	Not traced secondary outputs	Quantity
		Processes (internal/external)	Internal and external processes	Quantity Transports
	B. Flows	Wastes	Scraps Other wastes Wastewater	Quantity
		Emissions	Emissions to air Emissions to water	Quantity
		Energy	Electricity consumption Heat consumption Electricity generation	Quantity
		Water	Water consumption	Quantity
	C. Process Quality	-	Process Certifications Sustainability awareness Energy efficiency …	-
	D. Product Quality	-	Product Quality Contested goods motivations Quality tests …	-
Traceability info	Input		Input materials and semi-finished products	Quantity Origin
	Output		Bills of materials Production lots …	Quantity Destination
	Processes		Data about internal processes	-

The gathering of all the data described above, allows to realize a Traceability Assessment for the entire product, as well as, for each component or semi-finished part traced in the supply chain map, built during the first step of the methodology. This is essential in order to deeply know the "history" of a product and to communicate to final consumers an accurate traceability.
Conveniently combining the gathered sustainability primary data with secondary data coming from a commercial LCA DB, it is possible to realize an environmental Sustainability Assessment of the final product and of each actor involved in the traced supply chain.

3.2 Methodology implementation

Since the data necessary for the implementation of the proposed methodology partially come from several actors of the supply chain, a distributed collaborative system is needed to assess the whole traceability and environmental sustainability. Figure 2 describes how it is possible to practically implement the methodology steps in a real context, with the workflow for each involved subject.
Starting from a generic supplier, at the input phase it has to identify the input materials or semi-finished products. These ones could derive from another traced supplier, and in this case the data will be automatically read from the traceability support, or could derive from "external" suppliers, and in

this second case the identification phase is manually performed. At the output phase, instead, each supplier has to create an identifier for the outputs, creating a sort of Bill of Materials, using the information gathered at the input and adding those ones relative to their own processes. It is also possible to insert intermediate stations, between input and output, in order to guarantee an internal detailed traceability. The system is suitable both for the identification of single products or groups of products, such as production lots, pallets, etc. It is important to highlight that the proposed methodology and workflow is completely independent from the chosen traceability support (RFID, bar code, mix of both technologies, other supports, etc.) and the only required change is relative to readers for the automatic identification of goods in input and in output: this is a key aspect to guarantee a large replicability in many different industrial contexts. To perform all these activities a Trace Application dedicated to suppliers and linked to a shared Trace DB, which stores the traceability data of each supplier belonging to the traced supply chain network, is required (for additional details about the traceability data see Table 1 and the description in the previous section). Also for this database a distributed structure could be applied, so that each supplier maintains its own data which are synchronized with a supply chain central database. Moreover, each supplier has to fill a sustainability questionnaire, through the use of a dedicated LCA Supplier Portal web application, in order to share the sustainability information, described in the previous Table 1, which will be stored in a LCA DB.
A Supply Chain Trace Application allows to monitor all the flows of materials and semi-finished goods and to simulate different supply chain configuration to the aim of optimizing it. An LCA Calculator, instead, is needed to assess the environmental load of the whole supply chain, as well as of each single involved actor, using the primary data stored in the dedicated supply chain LCA DB, together with secondary data coming from a commercial LCA DB.
The proposed infrastructure should be implemented not only at the manufacturer of the final product, but should be replicated at the different supply chain steps, in order to allow each company to trace and assess the sustainability of its own supply chain. This certainly favours the availability of necessary data and helps to have more detailed and accurate traceability and sustainability information. In this way, each actor can involve the most sustainable partners, interested to collaborate to the final aim of optimizing traceability and sustainability performances, thus the whole supply chain will become a sustainable and collaborative network and the final products and semi-finished parts will have less environmental load.

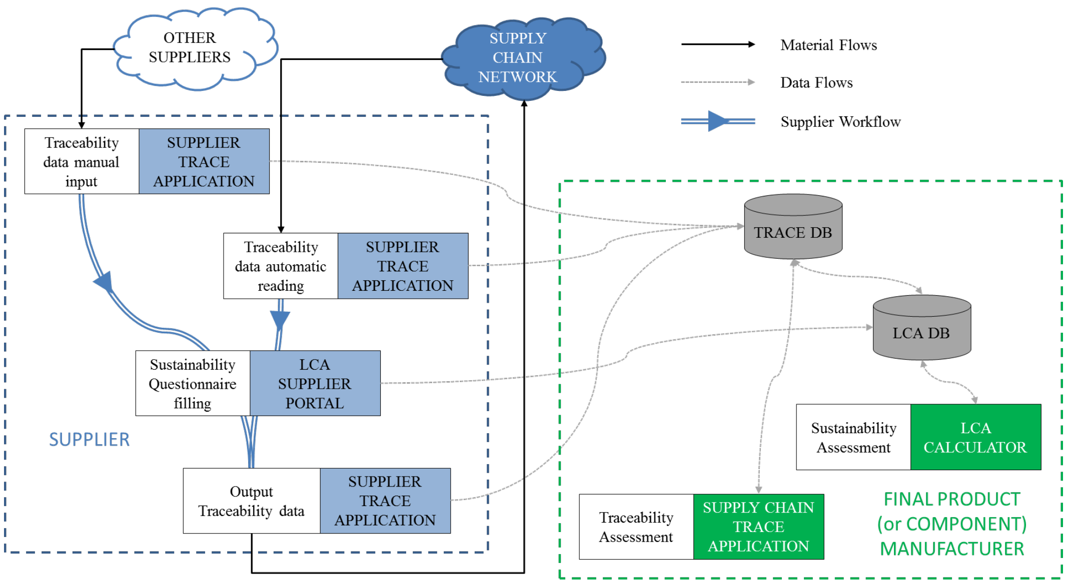

Figure 2. Implementation of the proposed methodology in a distributed system

4 EXPERIMENTAL RESULTS

This section describes how the proposed methodology can be applied and illustrates the results of the sustainability assessment obtained in terms of environmental impact. On the other hand, the traceability assessment has not been implemented in this case study.

In particular, it focuses on a shoe-leather supply chain, which represents an important reality of the Marche Region in Italy. Such industrial chain is characterized by a significant environmental impact and provides products for a very wide market. The analysed supply chain includes all the elaboration and transportation processes and the relative resources flows from raw materials (animals' skin) to the final product (shoe), omitting the distribution and product end of life phases.

4.1 Case study

In order to evaluate the sustainability of the shoe-leather supply chain, each step of the network has been identified and investigated by means of experts interviews and literature review. In this way, the input/output flows between the actors have been mapped (Figure 3). Such map allows tracing all the leather transformation processes along the network. In addition, the single steps have been characterized in order to trace the flows related to secondary inputs/outputs, resources, emissions, etc. (tannery's detail in Figure 3). This in-depth investigation has been carried out only for the most significant components in the shoe manufacturing process: upper, sole, insole and last.
In particular, the analysed supply chain consists in eight main stages:

- *Farmer*, mainly related to bovine, ovine, caprine and suine livestock;
- *Slaughterhouse*, where the animals are slaughtered and their skin is salty and/or dried in order to prevent the degradation process and conserve it;
- *Tannery*, which recovers the hides and skins from slaughterhouses and treats them with several chemicals in order to transform them into a more stable and durable product, the leather. Tanning is the most important step of the leather production chain and it is mainly performed through the use of vegetable or mineral agents;
- *Last producer*, which realize a mechanical form that allows simulating the human foot and properly modelling the upper;
- *Shoe upper factory* that executes the cutting and linking process in order to realize the upper;
- *Sole producer*, which supply the lower part of the shoe that has to get in contact with the ground and may consist of different layers;
- *Insole producer* that realize the part of the shoe – located between the sole and the footbed – on which the upper is attached;
- *Shoe factory*, where the assembling and finishing processes take place to obtain the final product.

In Figure 3, it is possible to observe that the first three steps are similar for the upper, the sole and the insole since they exploit the same raw material (i.e., the leather). Concerning the shoe last, only a single step of its supply chain has been investigated since it is usually made of plastics, wood, etc.. and its productive process is very simple.
However, in this case study, the leather it is assumed as a by-product of the meat industry then livestock and slaughter stages have been neglected in the calculation of the environmental impact.

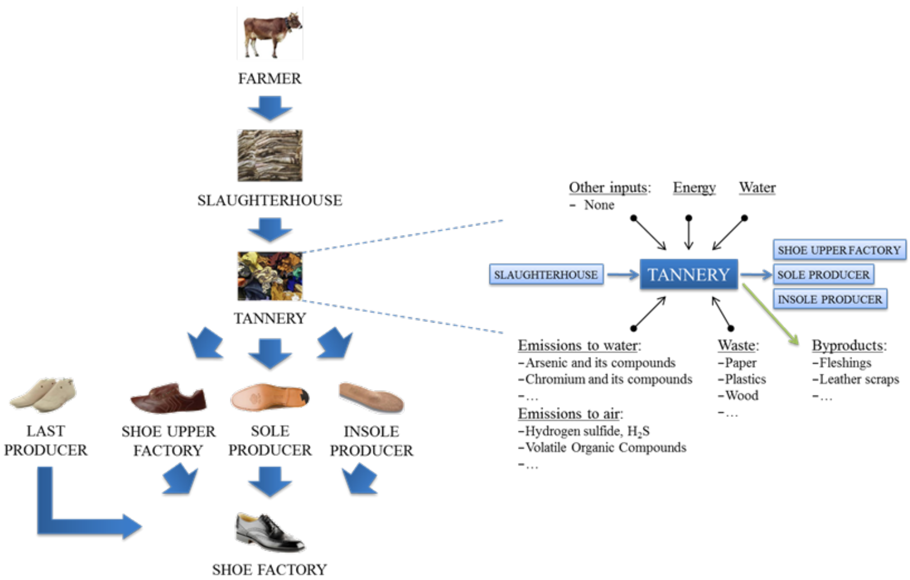

Figure 3. Shoe supply chain and tannery's detail

As far as the data collection is concerned, a questionnaire has been filled by each actor of the shoe supply chain, through the LCA Supplier Portal in order to populate a database with primary data.
It is worth to specify that for the shoe's components not traced by means of the proposed system (e.g., heel, laces, etc.), secondary data concerning input materials, energy and resources from the commercial Ecoinvent v3 database have been used for the analyses.

4.2 Results discussion

The "ILCD 2011 Midpoint" method (European Commission – Joint Research Centre, 2012) has been used for the LCA analysis and the following three indicators have been selected:

- Human Toxicity [CTUh, comparative toxic unit for human toxicity impacts], which is calculated as a sum of cancer and non-cancer effects, based on the UseTox model (USEtox, 2013) and strictly correlated to the use of chemicals;
- Freshwater Toxicity [CTUe, comparative toxic unit for aquatic ecotoxicity impacts] that is based on the UseTox model and it mainly depends on the emissions to water and on chemicals use;
- Climate Change [kg CO2eq, kg of equivalent CO2].

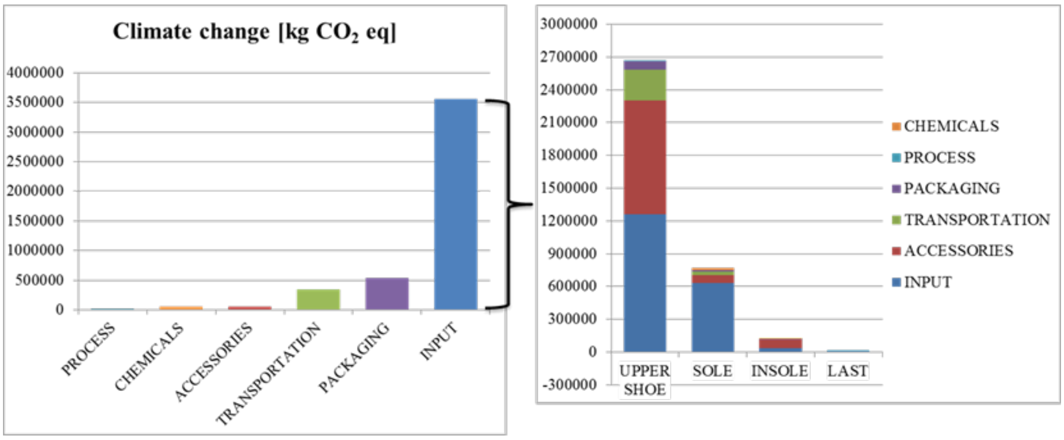

Figure 4. Shoe supply chain environmental impact

		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 5. Environmental impact comparison between three tanneries

Analysing the left graph of Figure 4, it emerges that the main hot spot, according to the climate change indicator, is represented by the inputs of the shoe factory and the relative upstream supply chains. It is worth to specify that the results are not referred to a single pair of shoes but to the overall output of the considered shoe factory. Going into more detail, upper and sole are the most critical inputs from an environmental point of view, as shown by the right graph of Figure 4. This is mainly due to the inputs supply chains and in particular to the tannery process. Indeed, it is responsible for about 47% and 87% of the upper shoe impact respectively considering the climate change and human toxicity indicators.
For this reason, an in-depth analysis has been carried out considering three different tanneries. The results (Figure 5) show that the majority of the environmental impact originates from the use of chemicals in all three cases. The significant impact in freshwater and human toxicity of the tanneries B

and C is due to the use of chrome. On the other side, tannery A realizes a vegetable tanning, which is more environmental friendly. Furthermore, these results highlight how the adoption of an integrated system for the traceability and sustainability assessment of the whole supply chain allows selecting the best suppliers from an environmental point of view, making the network more sustainable.
From Figure 4 it also emerges that a significant contribute is relative to the packaging used in the last step of the supply chain. It represents a quite surprising hot spot, which is usually missed, while in this case study has been identified through the sustainability analysis realized thanks to the proposed methodology implementation. In particular, a relevant portion of the impact is due to the shoe factory because of the large use of cotton and corrugated board boxes (left graph of Figure 6), used for each shoe pair. In a future optimization the packaging will certainly have to be considered, trying to minimize the use of materials or substituting the most critical ones, for example the cotton.
Another important consideration derives from the analysis of the environmental impact of the accessories used for the upper production (right graph of Figure 6). In fact, the large use of nylon and cotton makes this stage not sustainable. However, this may be overcome selecting reinforcing tape, interlining and lining made of “green” materials.

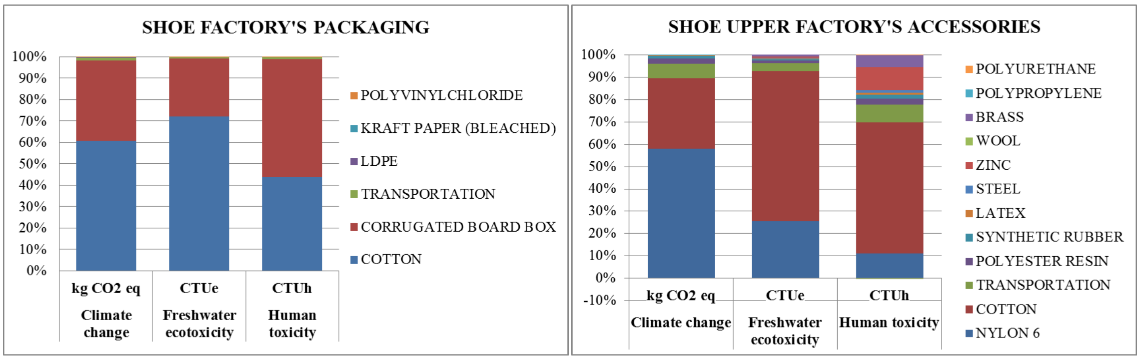

Figure 6. Environmental impact of shoe factory packaging and upper factory accessories

5 CONCLUSIONS

The present paper proposes a methodology which allows to assess a generic supply chain, measuring the sustainability of each actor or supplier involved, and using the traceability as a mean to retrace each production step, from the final product assembly to the raw materials procurement.
The key asset for the effective implementation of this methodology is a detailed model of the supply chain, considering its subjects, each input needed and output created, and every single flow (i.e. energy, resource consumptions, materials). All this data can be properly managed by a distributed software system to calculate the environmental sustainability performances, as well as to trace all the materials and semi-finished goods.
The methodology described in this paper was implemented into a complex supply chain, as the shoes production and assembly can be, in order to guarantee the traceability of all the product components: this is essential to easily discover possible problems (quality, toxicity, etc.), as well as to communicate to final users the exact origin of each raw material or semi-finished part. Furthermore, such system is able to quantitatively assess the environmental sustainability of shoe products, considering the whole supply chain. This allows to highlight the main sustainability “hot spots” to optimize.
In such context, the proposed case study about leather shoe supply chain identifies the tannery like the main impactful supplier along the supply chain, seeing that its industrial process has a relevant role, in particular related to the toxicity indices. Anyway, this is not the only result coming from the sustainability assessment of shoe supply chain. In fact, while the involvement of tannery in the shoe impacts is quite predictable, it is not the same for shoe’s package and accessories, that result high impactful due to the use of boxes, papers, cotton bags, etc.. This suggests not only to operate in the tannery production process optimization, but also in the shoe design phase.
Future works will be focused on the implementation of the proposed framework in different supply chains in order to investigate the applicability in heterogeneous industrial context. Also other aspects of the sustainability, as economic or social issues, could be considered to have a more complete view. Finally, a wider environment could be considered, including not only the network of suppliers but also the distribution phase and subjects involved in the management of the end of life.

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