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Research article

Web-based platform for eco-sustainable supply chain management

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A B S T R A C T

The increasing focus on environmental practices has led academia and industry to address eco-sustainability in different ways. Recent improvements to supply chain management (SCM) have also included environmental sustainability as a key factor, in addition to common drivers such as risk, supply quality, and cost. Although several eco-sustainable SCM approaches have been proposed, often those solutions remain too theoretical and difficult to implement. This paper contributes to this research topic by proposing a web-based platform capable of tracing suppliers and related processes along the entire product supply chain (SC). This platform is a powerful decision-making tool for improving overall SC environmental sustainability. A structured methodology is defined and implemented that can efficiently model complex SCs, share data between actors, and measure its environmental sustainability. To demonstrate the platform applicability and validate its effectiveness in industrial settings, a case study of industrial partners involved in the production of leather shoes is provided.

1. Introduction

Environmental sustainability is becoming a key competitive factor between manufacturing companies owing to pressures from economic markets and international legislation (Knight and Jenkins, 2008; Styles et al., 2012). In recent years, consumer awareness of environmental issues has increased, suggesting that companies offer products that are environmentally tracked and certified (Kikuchi-Uehara et al., 2017). However, the environmental life-cycle management of a product is generally a responsibility shared between different stakeholders: raw material and component suppliers, contractors, distributors, retailers, service providers, and end-of-life stakeholders (Agi and Nishant, 2017; Mengarelli et al., 2016). During the manufacturing phase, distributed networks of actors collaborate to contribute their competencies and experiences to products' realisation (Lanza and Moser, 2014). To efficiently monitor environmental sustainability, each company must broadly consider not only internal activities but also attempt to monitor and optimise the entire supply chain (SC) (Ghadimi et al., 2017). The traceability of components and sub-assemblies must be robustly managed. An effective approach for pursuing eco-sustainability and traceability simultaneously consists of implementing eco-sustainable supply chain management (ESSCM) practices for reliably and flexibly managing material and information flows. Specific rules, ontologies, and systems are needed to guarantee effective data sharing and collaboration between partners in the production network (Palmer et al., 2016). However, such concepts often remain theoretical and lack specific information and communications technology (ICT) tools to support companies in managing the data generated from the entire SC and during the decision-making processes centred on ESSCM.

In this context, the paper wants to address the following research questions: How is it possible to support the information sharing and collaboration within a real production chain? How is it possible to jointly monitor the traceability and environmental sustainability of a SC?

The main objective of this work is to propose an innovative web-based platform capable of simultaneously assessing the environmental impacts of production while effectively tracking products through their SC. The proposed platform is based on a methodology, previously proposed in literature, for tracing and measuring the environmental performance of a SC (Marconi et al., 2017). A 'traditional' traceability infrastructure similar to that largely adopted in industry is used to map and trace the flows of components, unfinished parts, sub-assemblies and data, and to monitor environmental sustainability. The distributed architecture of the proposed platform allows it to be used by different partners that may be directly or indirectly involved in product realisation. The architecture models the entire production chain effectively by building the complete manufacturing flow and characterising each node of the production network in terms of resource consumption, emissions, and waste. By using the platform, all the stakeholders involved may benefit by improving the production traceability and

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environmental sustainability performance of their own contributions, thus increasing their competitiveness in the market. As a case study, the SC for manufacturing leather shoes is used to verify the approach and demonstrate its software implementation. This sector is characterised by the complexity of the supply network and relevance to environmental issues.

After this introduction (Section 1), a review is provided of previous research on tools for managing eco-sustainable SCs (Section 2). The proposed platform is then described with a detailed explanation of its architecture and modules, main functionalities, and workflow scenarios (Section 3). In Section 4, the case study is presented and its results are discussed. Finally, Section 5 reports conclusions and some proposals for future works.

2. Research background

In the last 20 years, market competitiveness has forced companies to broaden their perspective to the entire SC. A key success factor is the creation of a flexible and efficient network of partners whose skilled growth positively influences the entire network. Improving the SC often requires the development and application of methods to efficiently, quickly, and reliably manage data and information flows. The growing relevance of industrial eco-sustainability further implies that such information exchange is no longer limited to traditional aspects such as quality, risk, and cost, but also must include environmental issues (Fernández et al., 2016; Siew, 2015; Zhang et al., 2014).

Eco-sustainability along the SC has been discussed in depth (Dües et al., 2013; Garza-Reyes, 2015) and it is well-known that SC decisions can have significant, and often unforeseen, sustainability related impacts (Carter and Easton, 2011; Murphy and Poist, 2003). From the concept of Green Supply Chain Management (GrSCM) that implies the evaluation of environmental impacts on SC operations (Srivastava, 2007), the rapid progression in this field led toward the Sustainable Supply Chain Management (SSCM). It concerned the integration of environmental, social and economic goals across SC processes (Carter and Rogers, 2008; Seuring and Müller, 2008) in order to address the multifaced nature of decision in SCs. Several robust reviews of the academic literature on this issue have been realised during recent years (Ashby et al., 2012; Carter and Easton, 2011; Koberg and Longoni, 2018; Winter and Knemeyer, 2013) with various objectives: to understanding the evolution of concepts, and classifying/clustering the proposed methods, frameworks and case studies. Their analysis allows understanding the most interesting directions of research the criticalities and limitations, as well as the related areas for future researches. In particular, it is worth to notice that green/environmental issues dominate the research context, in respect to economic and social ones, and qualitative methods prevail on quantitative ones (Rajeev et al., 2017).

Many authors have created SC management models with respect to sustainable indicators engaging with empirical methods (Chin and Tat, 2015; Dam and Petkova, 2014; Ding et al., 2016). Esfahbodi et al. (2016) proposed a theoretical model that includes sustainable procurement, distribution, design and investment recovery. Dubey et al. (2016) used a total interpretive structural modelling to extrapolate drivers of SSCM and their relationships. Reefke and Sundaram (2017) proposed a qualitative approach to identify the planning, execution, coordination and collaboration of key themes for a SSCM. Other interesting studies proposed strategies, frameworks, and conceptual models (Boukherroub et al., 2015; Chardine-Baumann and Botta-Genoulaz, 2014; Grimm et al., 2014; Li et al., 2015; Patala et al., 2014; Schöggl et al., 2016), while few papers reported real use cases that validate the proposed methods (Fritz et al., 2017; Rueda et al., 2017; Uwizeye et al., 2016; Van Der Vorst et al., 2009; Wittstruck and Teuteberg, 2013). Even if numerous, the currently available SSCM theories, frameworks and models fail to provide an effective support to guide real SC decisions on how to operate according to environmental sustainability principles (Reefke and Sundaram, 2018).

Most importantly, it emerges that the collection in a structured and organised way of a wide-range of SC data could support companies in the quantification and improvement of SCs' environmental performances (Acquaye et al., 2017; Pagell and Shevchenko, 2014). The collaboration and communication among the different actors of the SC assumes a primary role (Handson et al., 2015; Jadhav et al., 2018).

In this context, a dual intervention strategy should be implemented: (i) to support companies in automatically acquiring and storing environmental information along the entire SC, favouring and facilitating products and processes traceability (Dabbene et al., 2014), and (ii) to provide solution to quantify environmental performances, understand criticalities and evaluate possible action strategies (Rajeev et al., 2017).

Traceability, which aims to monitor end-to-end industrial processes, from the origin of raw materials and parts to the production and distribution of the final product (ISO, 2015), can answer to this need. However, the existing studies are dedicated to specific sectors, particularly the agri-food sector, where several authors proposed methods, ontologies, frameworks and technologies to monitor and trace product and process flows (Gautam et al., 2017; Dabbene et al., 2016; Pizzuti et al., 2017; Storøy et al., 2013; Thakur et al., 2011). In this specific sector, in fact, final consumers require high-quality products and a clear view of all the steps involved in the product life cycle (Aung and Chang, 2014).

A primary issue for SC traceability is the need for an efficient data sharing among all actors involved (Bjork et al., 2011). Recent developments in Internet of Things (IoT) technologies offer companies effective solutions for monitoring their processes and sharing data (Chen, 2017; Qiu et al., 2015; Wiesner et al., 2017). This condition, i.e. the need to trace, collect and share data, is similar to what is required to carry out an effective environmental impact analysis (Germani et al., 2015a). The availability of specific data in real time, from many different sources, enables product and process analyses to determine environmental impacts and take decisions which can positively affect product environmental performances (Addo-Tenkorang and Helo, 2016). However, the link between the traceability and environmental sustainability assessment of SC has not yet been developed. On one side, the existing platforms for monitoring environmental sustainability of products exist, usually do not provide support to capture SC data, but focus on the manufacturer point of view (Favi, 2013; Germani et al., 2015b). On the other side, available platforms for improving the sustainability performances along the entire SC are specifically developed for particular sectors. Among them, the most interesting are the SustainHub platform (Sustainhub, 2015), which focus on the automotive and electronic sector, SENSE project, for the environmental impact assessment of food and drink products (Keller and Jungbluth, 2014), and SheepToShip Project (2017), which proposed strategies and solutions for a low emission sheep SC.

The analysis of the current state of the art on SSCM topic allows deriving several considerations. At first, among economic, social and environmental aspects, the latter one prevails on the others in terms of number of methods, ontologies or frameworks proposed, thus confirming a particular attention on the matter and the need to support companies in performing this kind of analyses. Data collection and sharing appears as a first step toward the implementation of environmental sustainability strategies inside industrial contexts. Secondly, due to the lack of quantitative tools, the proposal of quantification strategies is recognised as an effective support for companies in monitoring and improving the

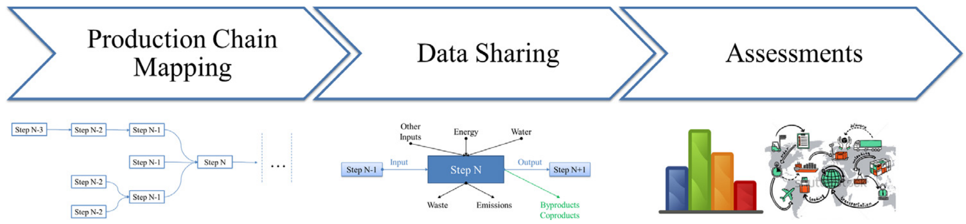

Fig. 1. Three-step methodology (based on Marconi et al., 2017).

environmental impact of each stage of the production chain. Starting from these observations, the present paper proposes a practical decision-making tool, able to support industrial companies in the:

- implementation of the traceability as the tool to assess SC environmental sustainability;
- quantification of environmental impacts of the SC network, allowing to identify the hot spots and to evaluate the effects of possible improvement strategies.

The approach has been implemented as a platform that uses IoT technologies to enable traceability along the SC. With such data gathered into a specific database, the actors involved in the SC can analyse scenarios and adopt the most suitable corrective actions to improve the SC environmental sustainability. Thus, collaborative relationships among SC actors can be fostered, to improve global environmental eco-performance. The experimentation of the tool in a real case study, i.e. leather-shoe production chain, allows verifying the approach and demonstrating its software implementation.

3. Traceability and eco-sustainability assessment software platform

3.1. Methodology

The proposed platform is based on a three-step methodology, as depicted in Fig. 1. The approach enables monitoring of traceability and environmental sustainability in all stages of the SC and product life cycle, from the supply and transformation of raw materials and components to the end of life of finished products. Since the present paper focuses on the web-based platform for ESSCM and its implementation in real industrial contexts, only a summary of the methodology is reported here. The complete description can be found in a previous literature study (Marconi et al., 2017).

The first step (*Production Chain Mapping*) consists of mapping the phases of the production chain using known mapping approaches, such as Integrated DEFinition Methods (IDEF) (NIST, 1993) or Business Process Model and Notation (BPMN) (OMG, 2013). By identifying the actors involved, together with the exchange of data and materials, a product can be traced and its environmental impacts estimated. The output is a production chain map that clarifies the direct and indirect relationships among involved participants and the real path followed by each raw material, component, unfinished part, and final product.

After drawing the SC map, the second step (*Data Sharing*) collects the data required for the next assessment phase. Every stage of production must be characterised by quantitative information related to both traceability and eco-sustainability. The traceability and corresponding infrastructure (e.g. traceability stations) can then be used to monitor the environmental load of each internal or external (but related to the SC) activity. For traceability, required data include the flows of materials between two or more actors involved in the mapped SC. Quantities and typologies of materials, components, and products exchanged between different partners, as well as information about the manufacturing processes used in each step, are essential for understanding the product history in detail.

The data used in assessing eco-sustainability are those that support an LCA analysis, and in addition to material-related data that have been previously stored for process traceability, the following data are needed:

- Energy consumed (e.g. electricity and heat);
- Water used;
- By-products/co-products (secondary outputs);
- Production scraps;
- Solid or liquid waste (e.g. wastewater);
- Airborne emissions;
- Transportation used (e.g. to move goods from one company to another).

Once all the data have been acquired, the third step (*Assessment*) of the approach analyses SC environmental sustainability.

An important aspect of the data elaboration step is correlated to both granularity of data and their allocation to single products or lots. If the objective of the analysis is to measure the environmental sustainability of single products and the available data are relative to single products or production steps (e.g. electricity consumption collected by IoT systems, material quantity needed to manufacture a single product, scrap generated in single processes), material and energy flows can be fully allocated to the product, as direct contributions. Indirect contributions (e.g. energy needed to power the infrastructure, air emissions of the entire production plant) need to be split between products or production lots by following the most suitable allocation procedure (e.g. allocation by quantity, allocation based on the economic value), and then considered as "overhead" contributions for the calculation of impacts. Generally, timely and primary data allow estimation of individual contributions to global environmental impact, as well as analysis of individual lots or potentially a specific product. If, instead, only aggregated data are available (e.g. yearly energy consumption of a production plant, yearly consumption of materials/semi-finished products, total quantity of solid waste generated in a year), the calculation of impacts related to single products necessarily passes through the allocation of all flows, while the exact impacts could be only calculated for the overall company.

Therefore, the degree of detail of the results obtained through an assessment directly depends on the granularity of the data that were gathered. Moreover, each approximation made both during the mapping phase (e.g. simplifications of the SC network) and the data sharing (e.g. lack of data for some partners, estimated data instead of measured one, neglection of production steps) is a potential source of errors in the assessment. A high accuracy and granularity of collected data is an essential prerequisite to obtain reliable results for both general (i.e. regarding an entire company) and specific (i.e. regarding a single product) analyses.

The web-based platform described in the following sections supports the efficient use of the three-step methodology just described.

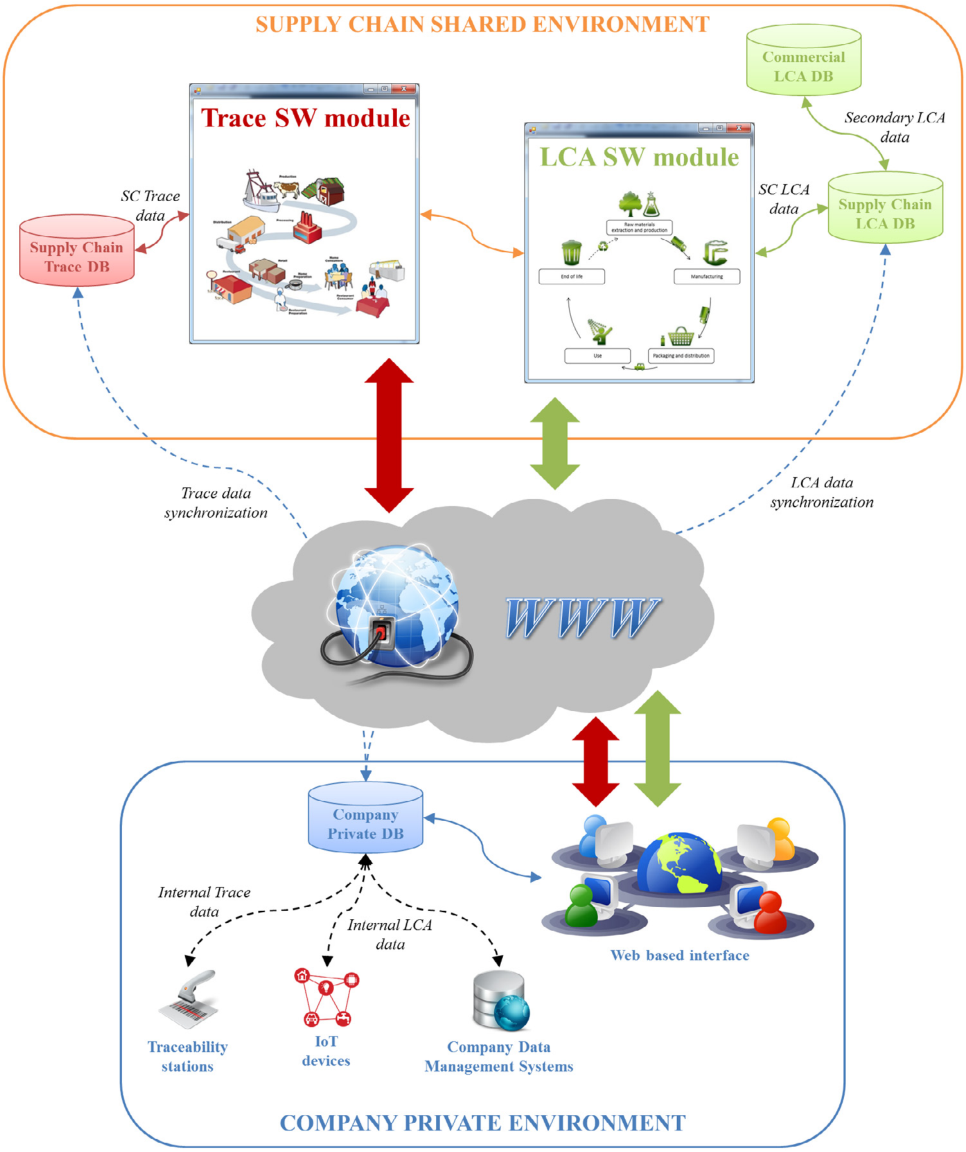

Fig. 2. Distributed platform along SC.

3.2. Platform architecture and features

The traceability and eco-sustainability assessment system is comprised of two interconnected main software modules, *Trace* and *LCA*. They communicate with private and shared databases to provide and retrieve the data necessary for SC assessment. A general architecture of the web-based distributed platform is shown in Fig. 2. Only authenticated users may access the platform, allowing for restriction of resource access (such as database or functionality) provided to each user class. Some platform resources are located within each *Company Private Environment*, because they maintain specific private data about traceability and eco-sustainability. Others are shared between the actors involved in the *SC Shared Environment* because they store aggregated data that are necessary to assess the whole network. In particular, the *Trace SW module* and the *LCA SW module* are used in the *SC Shared Environment*, and are able to communicate both with internal and shared resources and databases, allowing companies to have a global view of the SC.

The next sub-sections describe the functionalities and main features of each module and database.

3.2.1. Databases

Because some data are private while others are shared, a distributed 'master–slave' architecture is required for the repositories. In particular, the web-based platform needs four different databases for storing data:

- *Company Private DB*: This is a 'slave' database containing the data related to a single partner. This repository is physically located at each company and stores the traceability and eco-sustainability data arising from applications and interconnected devices such as *Traceability stations*, *IoT devices*, and *Company Data Management Systems*. This database allows companies to work 'offline', because it collects internal information that is kept synchronised with data arriving from other SC partners. Data synchronisation, for instance from the *Trace* and *LCA* modules, should be transparent to the end users, and each company shares only the data necessary to perform the traceability and sustainability assessments of its own products, production lots, or segments of SC;
- *SC Trace DB*: This is the first 'master' database of the platform, and it is needed to support analysis of the whole SC. In particular, this database stores the information related to

flows of materials, unfinished goods, and products from different *Company Private DBs*. These data are then made available to the *Trace SW module* in order to allow each SC partner to perform a traceability assessment in an automatic way;
- *SC LCA DB*: This second 'master' database is needed to collect data useful for LCA analyses. These primary data are used by companies via the *LCA SW module* in order to assess the environmental sustainability of a particular product or production lot, including the contribution of all stakeholders involved in their production;
- *Commercial LCA DB* (e.g. EcoInvent®, GaBi®, ELCD): This provides secondary LCA data, and is continuously synchronised with the *SC LCA DB*.

3.2.2. Software modules and tools for data collection

Two software modules are included in the web-based platform, one dedicated to traceability and one dedicated to environmental sustainability (see Fig. 2).

In general, the *Trace SW module* allows management of both input and output data related to the traceability of materials, unfinished parts, and products. This module can communicate with *Traceability stations*, which are checkpoints installed within each company to monitor and record the input/output flow of goods. The *Trace SW module* is completely independent of the adopted traceability station technologies such as RFID or bar codes. Only the hardware interfaces must to be customised for the technology used, such as optical readers or electromagnetic gates.

The *Trace SW module* includes five main functions:

- *Setting the Traceability Stations* allows definition of the input and output of each station and configuration of the different bills of materials. This function must be used during the preliminary phase to initialise each station and the SW module for standard operation, such as automatic data acquisition;
- *Audit of the Input* materials or unfinished goods to read and store data relative to input flows. The application manages automatic inputs, reads the information acquired by the traceability technology or by manual input, and is inserted by operators;
- *Output Declaration* registers the output flows. When an internal traceability system is implemented, this phase is completely automatic, but the *Trace SW module* also supports manually checking goods in order to store needed traceability data in the *Company Private DB*;
- *Data Synchronisation* updates data from the *SC Trace DB*. Generally, synchronisation is completely transparent to the end user, and occurs at regular intervals. Data synchronisation functionality is provided to support forcing database synchronisation in particular cases, which is needed owing to errors arising during automatic synchronisation, when updated data must be immediately used, or the arrival of new production lots or new codes from suppliers;
- *Supply-Chain Traceability Evaluation* assesses a particular production lot or bill of materials, and includes the whole network of involved partners.

The *LCA SW module* calculates the environmental impact of the SC. It can interact with local (*Private Company DB*, *IoT devices*, *Company Data Management Systems*) and shared (*SC LCA DB*) resources. The main functions provided by this module include the following:

- *Audit of the Sustainability Data* that reads and records primary LCA data. The software application communicates with internal devices to automatically retrieve data without end-user intervention. The most efficient solution is to connect IoT devices and CPSs to provide real-time monitoring of the key metrics of a production phase; an example is the use of smart metres to monitor electricity consumption of single processes, lines, or plants. These devices address the challenges related to the availability and reliability of LCA data. Another possible solution is to automatically acquire data from *Company Data Management Systems* (e.g. use of chemicals, materials, and suppliers). These solutions are complementary and allow the definition of a complete inventory for LCA analyses;
- *Sustainability Questionnaire* that supports sharing sustainability data about energy and resource and material consumption. This functionality is essential for covering cases where the automatic acquisition of primary LCA data is not yet implemented;
- *Environmental Impact Assessment* that quantifies the sustainability of a SC. Two different scenarios are possible: (i) assessment of a real, traced SC or (ii) simulation of a potential SC. In the former, the assessment is completely automatic because all necessary information can be retrieved from traced production lots or bills of materials. In the latter, simulating the performance of a theoretical SC requires manually building the SC network, and inputting missing information about flows of materials and unfinished goods between involved partners;
- *Result Visualisation* allows end-user consumption of the results obtained with the LCA analyses of the different scenarios. These results can be visualised as tabular data, with details for the different impact categories and for different contributions (materials, energy, etc.), or in a simplified graphical way, as aggregated values for each SC step. This capability to visualise the SC transport network is provided to monitor the flows of goods between involved partners.

Through the above-mentioned functions, each company involved in the network can share useful data, trace their own production, and assess the environmental sustainability of their products or production lots. The developed functions are accessible through a *web-based interface* available to users of different companies located in different geographical areas.

3.3. Platform use: workflow scenarios

In order to clarify how the proposed platform can be practically used in different real industrial contexts, a general workflow is presented in Fig. 3. The flow chart illustrates the main activities with the relative flows of data and materials, as well as the resources of the platform (databases, applications, etc.) used during each step of the workflow.

The platform workflow comprised two primary phases: *Data Acquisition and Sharing* and *Assessment*. While the former is a 'standard' function of the platform with activities that must be continuously performed, the latter is generally asynchronous and must be performed when a company needs to verify traceability and/or environmental sustainability of its products or production lots.

For a generic company involved in the traced SC network, the first step of *Data Measuring and Sharing* is the identification of the input materials or unfinished products. These may be derived from other traced suppliers, involved in the same network (*SC Network* 'cloud' in Fig. 3), or from external untraced suppliers (*Other Suppliers* 'cloud' in Fig. 3). The first case is the more favourable, because all necessary traceability data can be automatically read from the traceability support function. The platform communicates with the *Traceability Stations* to recover data from the different supports such as RFID tags or bar codes. In the second scenario, instead, input identification must be manually performed using the *Trace SW module*. In this case, the input goods do not

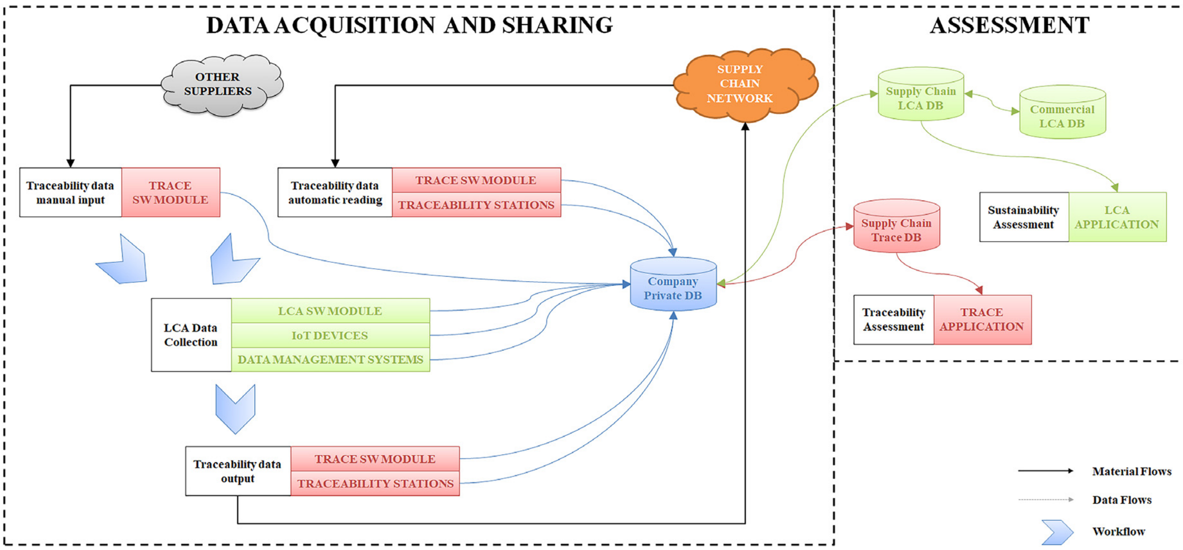

Fig. 3. Generalised platform workflow.

include known traceability as they derive from other suppliers not within the traced SC network. This twofold operation guarantees high platform flexibility, allowing correct operation even during initial implementation or in mixed situations where some partners have already implemented the resources for automatic collection of data, but others have not.

During the output phase, the company must unambiguously declare its outputs, creating a type of bill of materials, using the information gathered at the input and adding those from its internal processes. In this step, the data gathered from the *Trace SW module* and the *Traceability Stations* are used to produce unique identifiers for single products, production lots, or pallets. The choice of the 'traceability unit' depends on the minimum entity that the company decides to monitor along the entire production chain and thus to label with a traceability support. In certain cases (e.g. highly complex processes, many internal activities), the implementation of intermediate traceability stations may be justified, between input and output, in order to monitor internal traceability in detail.

Data Measuring and Sharing also includes the LCA data collection step, needed to share data about company eco-sustainability. As noted in the previous section, the collection methods may be automatic (through *IoT devices* and *Company Data Management Systems*) or manual (through dedicated *Questionnaires*). In both cases, the platform provides the needed functions to each company to collect, share, and reuse relevant LCA data. This step can include synchronous reading and writing of the input and output traceability data, in cases where data are automatically collected and shared. If, instead, LCA data are collected manually with specific questionnaires, this step must be asynchronous because data updates are required at a lower frequency, i.e. during initial system implementation, or to update data after a predefined time span when significant modifications in production conditions occur.

The *Assessment* phase verifies the traceability of a particular production lot or product, using the *Trace SW module*, or quantifies their environmental impacts, using the *LCA SW module*. These activities are completely asynchronous to *Data Sharing* but can be performed only when the databases (i.e. *Company Private DB*, *SC Trace DB*, *SC LCA DB*) are sufficiently populated with primary data arriving from involved partners.

The results obtained during the *Assessment* can be used for different purposes, including

- Identification of SC criticalities, such as untraced materials, materials coming from high-risk regions, problems related to toxic substances, or complex transport networks;
- Comparison of different products or production lots to successively select the best product portfolio of fully traced and green products;
- Comparison of different suppliers able to supply materials or unfinished products of comparable quality to involve the partners most able to support environmental goals;
- Communication of relevant product information to end users to increase transparency and improve the company brand.

3.4. Platform implementation

As mentioned above, the database management system is designed as a master–slave architecture, with two master databases accessible from the web application according to restrictive and targeted policies, and several 'slave' repositories physically located at each company. In particular, Microsoft SQL Server, which is a relational database management system (RDBMS), was used in the implementation here.

The *Trace* and *LCA SW* modules are standalone and multiplatform (Windows, Mac OS, iOS, Android) applications, developed using Visual Studio and Silverlight which provide rich, interactive applications for the Web. In addition, the Google Maps APIs were used to display the SC transport map. Fig. 4 shows the main user interface with a SC map of a specific production lot ('L150').

In order to enable data sharing between the application and common *Company Data Management Systems* (MES, PLM, and ERP), a specific interface and communication protocol has been defined.

In the *Traceability Stations*, two types of distributed resources are provided: mobile and fixed. The former includes a palmtop computer, integrating multiple readers and connected to the wireless company network. The latter consists of a desktop workstation with a barcode laser reader, a decoder, and an RFID antenna, as well as industrial printers for barcode labels and RFID tags. Both types of stations allow the simultaneous use of barcodes and RFIDs for traceability to ensure maximum operational flexibility. In particular, barcodes are easy to use, inexpensive, and are a mature, highly reliable technology in common use, but can only be used within the scanner line of sight. The use of RFIDs is more complex as they are not a plug-and-play technology and cannot be applied in all operational (i.e. wet or acidic) environments, yet provide better

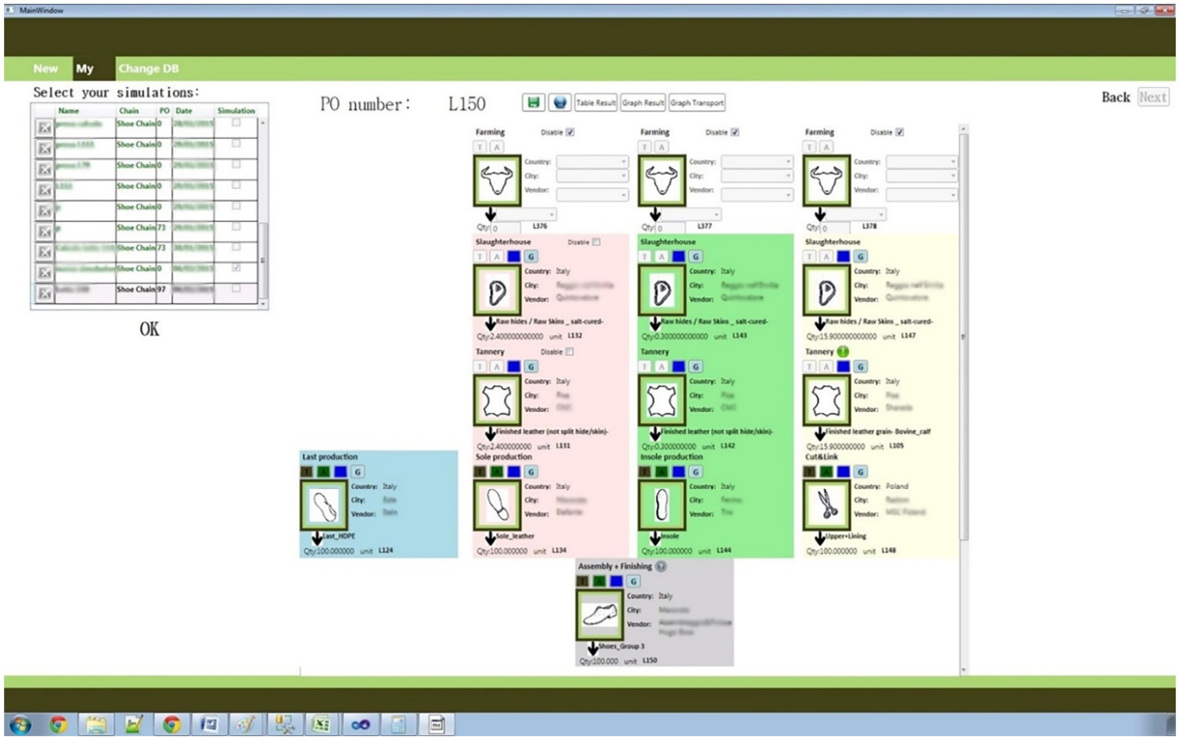

Fig. 4. User interface of the web-based platform.

performance in terms of efficiency, memory, duration, flexibility, speed, and automation. Moreover, depending on company needs, different RFID technologies can be implemented, including passive, semi-passive, and active. The latter two use internal batteries to power their circuits and are recommended for high-value products.

Finally, a wireless sensor network (WSN) is used to automatically transmit the data collected from the production equipment. It includes many sensor nodes able to detect relevant traceability and sustainability parameters, such as energy consumption (e.g. electricity, water, and gas), air quality, and process parameters (e.g. pressure, temperature). The communication between the WSN and the other resources of the SC platform occurs transparently via a dedicated protocol.

4. Case study

The web-based platform described here was applied to a real industrial context to evaluate its applicability, advantages, and drawbacks.

A leather shoe SC in Italy was chosen because fashion is one of the most polluting industries in the world and many stakeholders, including governments and customers, pay close attention to the eco-sustainability of products. Moreover, the traceability of raw materials and unfinished parts is a key issue challenging this sector.

4.1. Leather shoe SC mapping and data sharing

The leather shoe production chain was analysed to map the interrelationships of involved partners, the exchange of data, and the flow of materials. The analysis focused on all activities involved in the transformation of raw materials (animal skins) into finished products (shoes). Expertise and data from the literature were used. The SC was modelled with the IDEF0 approach (NIST, 1993) to clearly represent the inputs, outputs, and resources of each step. The SC starts with the farming of bovine, ovine, caprine, and swine livestock, and then proceeds to the slaughterhouse, where animals are slaughtered for preparation of food for humans, and the skins are salted and/or dried for preservation. Although skin is one of the most profitable parts of an animal, representing approximately 10% of its total value, and its treatment is responsible of significant emissions, in this case study, it has been considered a by-product of the food industry coherently with other literature studies (Djekic and Tomasevic, 2016; Huerta et al., 2016; Noya et al., 2017; Roma et al., 2015). Hence, impacts related to these first two steps are supposed null for the considered SC. The SC map continues to the tanneries that recover the hides and skins from slaughterhouses and treat them in order to produce a stable and durable product, leather. This is the most important step of leather shoe production and different methods can be applied, including chrome and vegetable tanning. Thus, different solutions were considered here. Tanned leather is the primary input to several partners of the network that transform it into the main components of shoes: the shoe upper, sole, and insole. Another key component is the last, which is usually made of plastic or wood. These components are provided to the shoe factory, where assembly and finishing occur to produce shoes. Although the proposed approach can be implemented to all the SC steps, this case study focuses on the evaluation of the shoe SC from tanneries to the shoe factory, not considering the last part of the SC. After all the shoe is not an energy-consuming product, which allows neglecting use phase impact without compromising the results reliability. The sale and post-sale phases are neglected in this work because of their different drivers (e.g. product performance, maintenance, disassembly strategies) and barriers (e.g. privacy issues, user awareness, costs). Moreover, downstream SC is very fragmented due to the simultaneous management of different fashion products by distributors, multi-brand stores, recycling facilities, etc., which makes their traceability more arduous. The SC structure is illustrated in Fig. 5.

In order to collect the data necessary for *Assessment*, different solutions were adopted according to the companies' needs and peculiarities. As specified in Table 1, primary data were collected

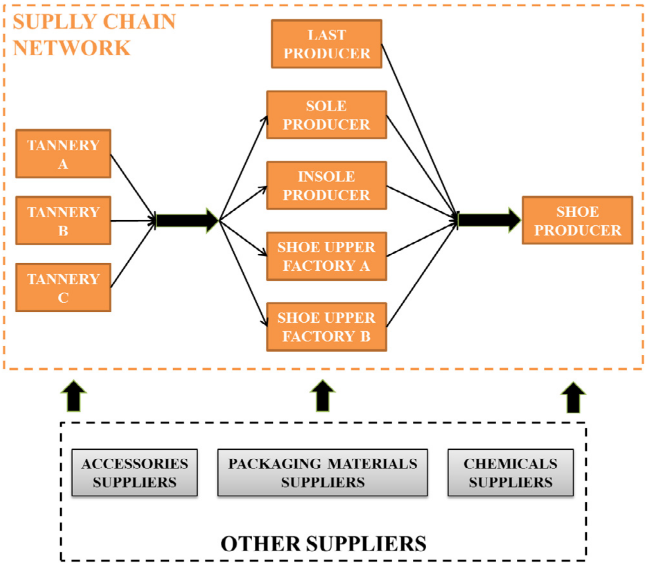

Fig. 5. The shoe SC involved in the case study.

Table 1
SC actors and relative data sources.

Actor	SC network	Traceability data	Sustainability data
Tannery A	Yes	Manual	Primary data (PLM, IoT, Quest.)
Tannery B	Yes	Manual	Primary data (PLM, IoT, Quest.)
Tannery C	Yes	Manual	Primary data (PLM, IoT, Quest.)
Sole producer	Yes	Traceability stations	Primary data (ERP, Quest.)
Insole producer	Yes	Traceability stations	Primary data (ERP, Quest.)
Last producer	Yes	Traceability stations	Primary data (ERP, Quest.)
Shoe upper factory A	Yes	Traceability stations	Primary data (MES, Quest.)
Shoe upper factory B	Yes	Traceability stations	Primary data (PLM, Quest.)
Shoe producer	Yes	Traceability stations	Primary data (PLM, IoT, Quest.)
Accessories' suppliers	No	No	Secondary data
Chemicals' suppliers	No	No	Secondary data
Packaging materials' suppliers	No	No	Secondary data

from the main actors of the leather shoe SC and secondary data were used to account for the environmental impact of accessories, packaging materials, and chemicals. Six companies chose to install *Traceability Stations* for automatic collection of traceability data. In particular, the shoe upper factory B and the shoe producer adopted both barcodes and RFIDs. Other companies only used barcode readers, which require a smaller investment. For tanneries, the intrinsic characteristics of the tanning process (e.g. mechanical operations, different chemical treatments) are not amenable to automatically recording the traceability of hides; therefore, check-in and check-out were performed manually with the *Trace SW* module. The different traceability stations have been implemented by using the following equipment:

- Passive RFID tags operating in the UHF (Ultra High Frequency) band. This solution was chosen as a trade-off among the quantity of data to store in each memory support (some bytes), the required reading/writing distance (less than one metre) and the cost of each tag (to be minimised);
- Barcodes compliant with the UPC (Universal Product Code) standard;
- RFIDs/Barcodes encoders/printers by *Zebra*©;
- Fixed RFIDs/Barcodes reader realised by using a desktop PC, equipped with an RFID antenna and a barcode reader with USB interface;
- Mobile RFIDs/Barcodes reader realised by using a Wi-Fi PDA (Personal Digital Assistant) by *Motorola*©.

As an example, Fig. 6 shows a screenshot of the *Trace SW* module of the shoe producer. It refers to a *Warehouse* that declares inputs according to three scenarios:

- The input does not come from network actors, as is the case with accessories; therefore, the user can declare only their quantities;
- The input comes from a traced network actor, and therefore, the user must read the barcode or RFID associated to the production lot;
- The input comes from an untraced network actor; therefore, the user must register the lot and the related bill of materials.

For data entered with the *LCA SW* module, the companies' data management systems (MES, PLM, and ERP) were leveraged to gather information related to materials, quantities, chemicals, and suppliers. The largest and more-structured companies (tanneries A, B, and C, and the shoe producer) had adopted IoT devices to monitor parameters such as energy consumption and emissions. In addition, structured questionnaires were filled out by each partner to collect other data necessary to perform the LCA analyses (Table 1). In contrast, data coming from questionnaires were checked to ensure their reliability. They were compared with the references from the specific sector (Best Available Techniques Reference documents, BREFs) to determine if they deviated too far from an average (European Commission, 2013). Moreover, a set of rules and constraints supported the compilation:

- For each step of the SC, all possible inputs and outputs were mapped and correctly matched;
- A conversion factor to express quantities in standard units of measurement was required to avoid inconsistencies (e.g. kilogrammes per square metre of tanned leather);
- Different transportation scenarios were created by dividing a world map into thirty regions, mapping representative airports and harbours, defining a set of standard routes according to the specific means of transport, and finally, calculating the corresponding transport distances.

Collected data refer to one year of production of each involved company, including multiple output categories (e.g. classic, casual, sport and prototypes shoes; leather, rubber and leather+rubber soles). They include both direct and indirect contributions. Chemicals, accessories, packaging, emissions, material losses, and transports are strictly related to the entire production process, while electricity, water, heat, solid waste and wastewater refer to the entire production plant. Maintenance of equipment and production facilities have not been considered, and no impacts have been allocated to by-products. The granularity of the data (i.e. yearly consumptions by flow of the entire production process/plant) required their allocation, which has been executed according to the production volume of each product category. Moreover, when the output of a SC actor was partially destined to the considered SC, the related impacts have been opportunely scaled according to the ratio between the quantity of a specific semi-finished product

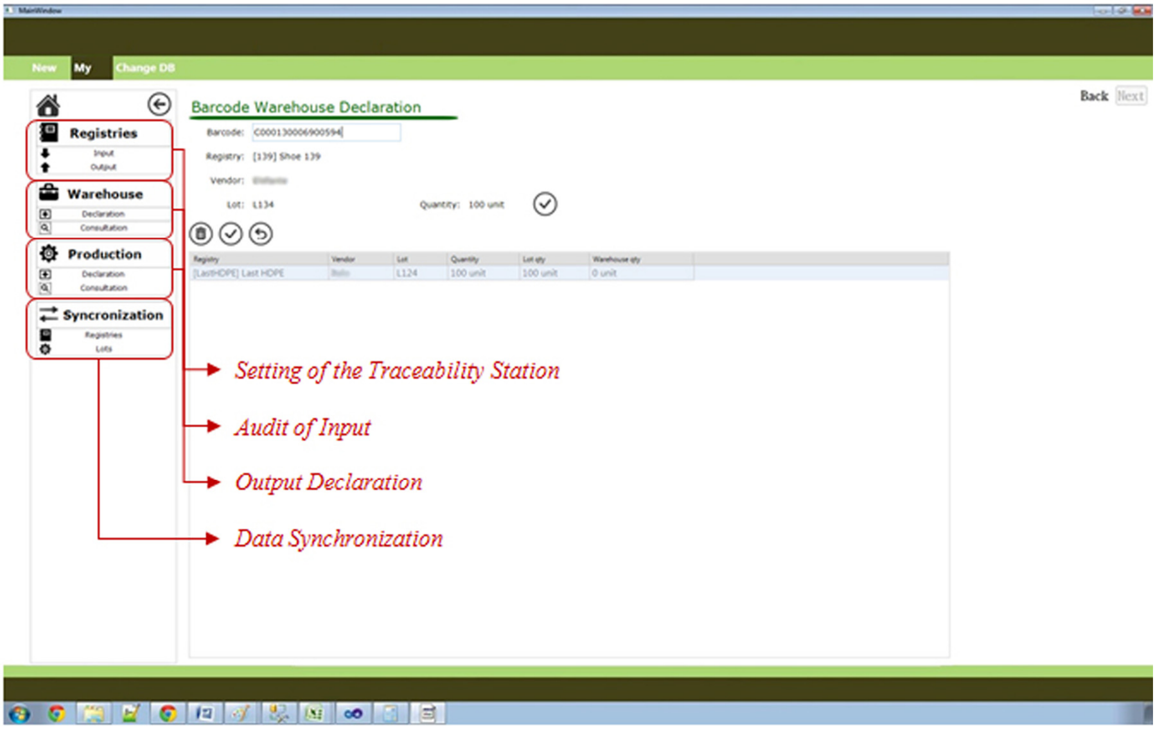

Fig. 6. Screenshot of the *Trace SW* module related to input identification by barcode.

category needed by the company user and the total quantity of that semi-finished product category produced by the supplier.

4.2. *Assessment of the leather shoe SC traceability and environmental sustainability*

Once data collection was completed, both traceability and environmental sustainability of the SC were evaluated and visualised with tables, graphs, and maps. The *Trace SW* module allows being aware of all flows related to a particular production lot within the whole network of involved partners. At the same time, the connection between *Trace SW* module and *LCA SW* module allows assessing the impact related to the abovementioned flows. Fig. 7 shows the results related to the SC transport network for a specific production lot:

- The map shows a partial representation of input flows;
- The histogram summarises the environmental impacts related to the flows of goods between the involved actors, measured using the *Climate Change* indicator. The acquisition of raw hides (tanneries' input) was the least sustainable step in this perspective, and is due to the strong dispersion of leather suppliers worldwide with respect to downstream suppliers.

An in-depth analysis also revealed that suppliers of accessories, chemicals, and packaging are typically located in circumscribed areas; thus, their flows impact the environment less.

With the *LCA SW* module, an overall assessment of the SC environmental impact was also performed. Fig. 8 shows data from modules installed at shoe upper factory B. They do not refer to a single pair of shoes but to the overall shoe factory output in one year. The selected indicator was *Climate Change*, as it is one of the most understandable by industries. Analysing the entire SC (upper graph of Fig. 8), the least sustainable step was tanning, responsible of 47% of the environmental impacts, due mainly to the use of chemicals.

Within company boundaries (graph in bottom left of Fig. 8), the accessories represent the primary environmental 'hot spot', responsible for ∼85% of the total impact. In more detail, among all materials used for accessories, cotton was the main source of impact as shown by the graph at bottom right of Fig. 8.

Other significant findings derived from the results calculated by the platform modules include the following:

- The shoe upper was the most critical component of the shoe, responsible for ∼75% of the total impact;
- Shoe packaging was a surprising 'hot spot' owing to the significant use of cotton (61% of the packaging impact) and corrugated cardboard boxes (38%), and thus requires more careful material selection;
- The 'hottest spot' of a sole producer was tanned leather received as input, causing 94% of company impact;
- For the insole producer, the impact of accessories exceeded the impact of leather because of the use of aluminium shanks and paperboard components;
- For the entire SC, the environmental impact of the last producer can be considered negligible, because it is reused over multiple production cycles.

As stated in Section 3, *Assessment* was also used to compare and simulate different scenarios to select the most sustainable. In this case, the focus was on the most critical step: tanning. First, the environmental impacts of the three tanneries involved were compared. In addition to *Climate Change*, the *Human Toxicity* indicator was selected as significant for this specific context. As shown in Fig. 9, the majority of the impact originated from the use of chemicals in all three cases. However, the impact on human toxicity highlights how the vegetable tanning (tannery A) was more environment-friendly to chrome tanning (tanneries B and C), which makes significant use of chrome salts.

By comparing different companies that supply materials and components of comparable quality, environmental considerations in supplier selection can be accounted for making the SC more

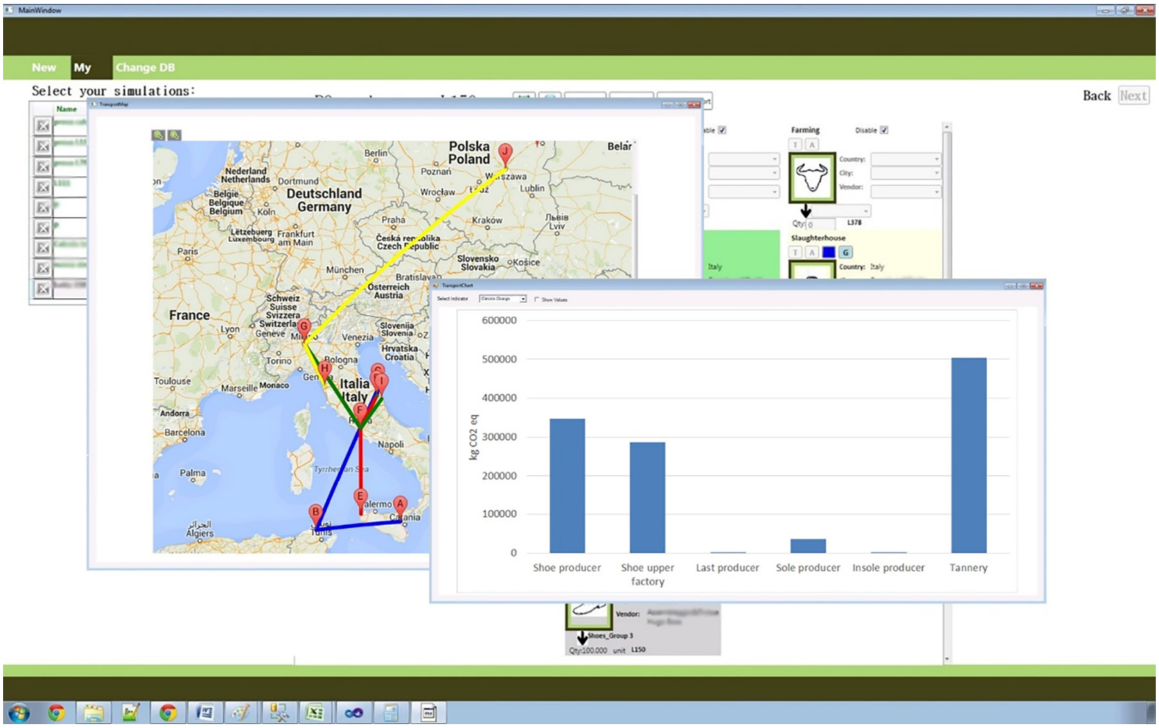

Fig. 7. Map and environmental impact chart related to the goods movement within the shoe SC.

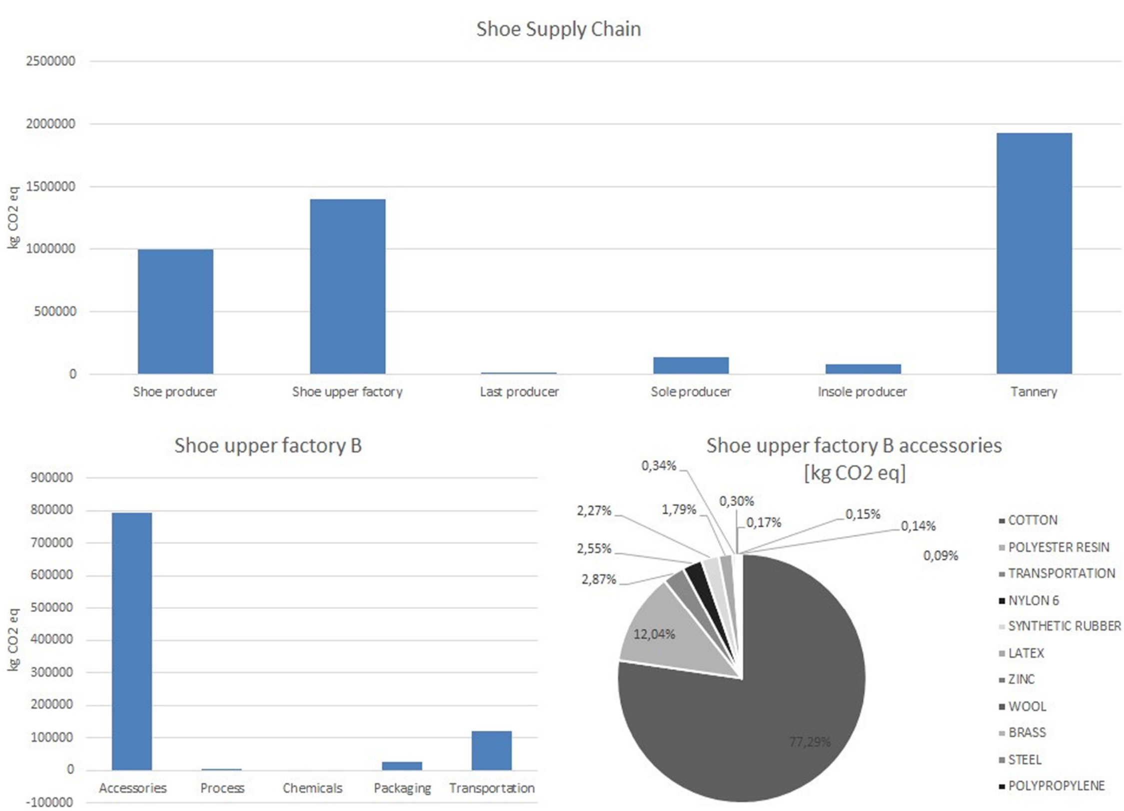

Fig. 8. Environmental impact according to the *Climate Change* indicator and different levels of detail: shoe SC, single company (i.e. shoe upper factory), hot spot category (i.e. accessories).

sustainable. For instance, shoe upper factory B used the proposed platform to perform an in-depth analysis of its suppliers, in order to reduce the environmental impact of its input materials. In particular, shoe upper factory B compared the impact of 1 kg of each tanneries output and simulated two scenarios with different mixes of inputs supplied by them, respecting constraints related to final product requirements and the characteristics of suppliers' products (e.g. unsplit finished leather, finished leather grain, calfskin,

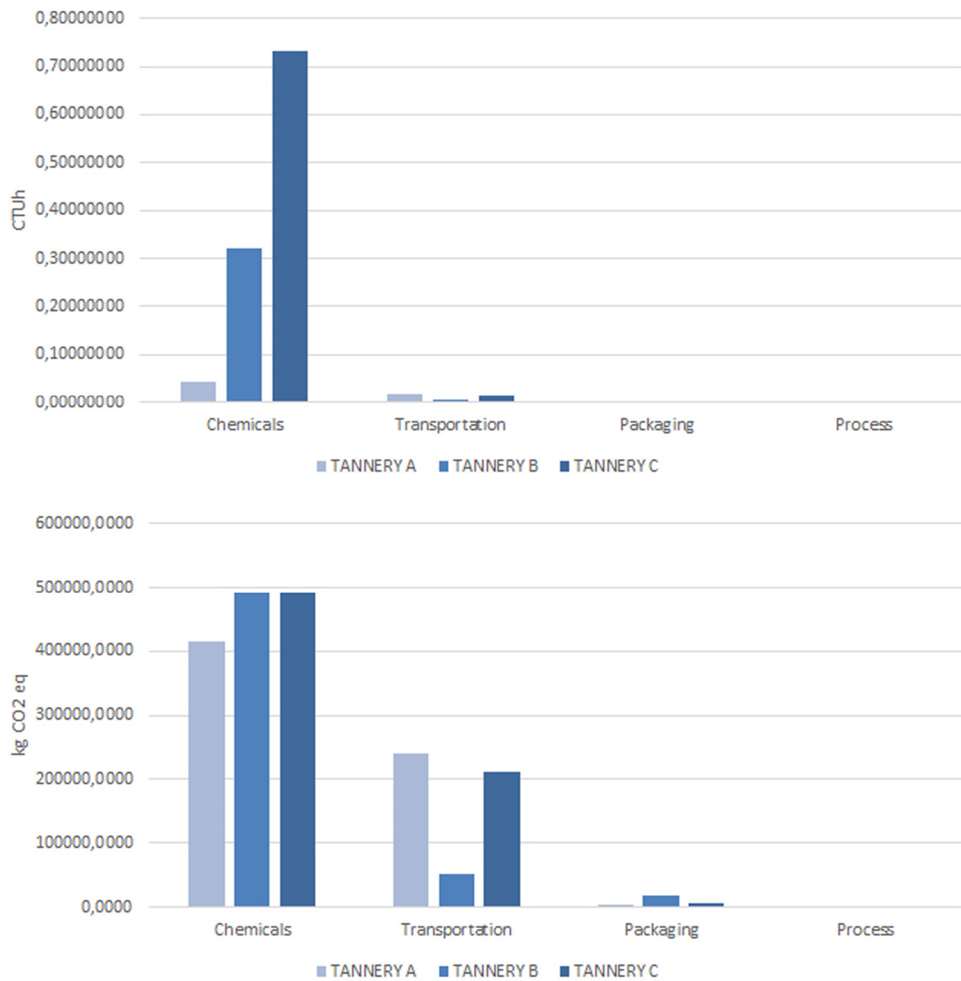

Fig. 9. Tannery comparison per the *Human Toxicity* indicator.

Table 2
Sustainable supplier selection by shoe upper factory B.

	Input from tannery A	Input from tannery B	Input from tannery C	Benefits in terms of climate change [kg CO_2 eq]
Scenario 'as-is'	1.01%	5.88%	93.11%	–
Scenario 1	0.00%	14.97%	85.03%	−16.15%
Scenario 2	4.75%	31.11%	64.14%	−44.52%

cow skin). The results summarised in Table 2 show that the current mix (i.e. scenario 'as-is') is not the most sustainable. By increasing the percentage of leather purchased from Tanneries A and B, shoe upper factory B could considerably reduce the environmental impacts of its production. This demonstrates the usefulness of the proposed platform in supporting companies in making decisions to improve internal and global eco-sustainability performance.

4.3. Discussion

The results described in the previous section are in line with the literature related to this field, demonstrating the validity of the proposed system. Several studies (Chen et al., 2014; Kılıç et al., 2018) confirm that the tanning process significantly contributes to the Global Warming, Photochemical oxidation, Acidification and Eutrophication because of air emissions of gases (e.g. CH4, NH3). Moreover, the study of Milà i Canals (2002) demonstrated how the large use of chemicals (especially the chromium oxide) by tanneries determines significant toxicological loads, both for human and freshwater. Other studies (Bacardit et al., 2014; Shi et al., 2016) demonstrated the greater sustainability of chrome-free tanning compared to chrome one, as resulted by the simulation of scenario 2.

Although the awareness about the contribution of cotton on the total impact of the shoe manufacturer and the shoe upper manufacturer was lacking, its negative influence on the environment is not surprising in terms of greenhouse effects (Scheffer, 2005), consumption of high amount of electrical and thermal energy (Bevilacqua et al., 2014) and global water use (Chapagain et al., 2006).

Concerning the main advantages related to the proposed platform, the implementation of the system in a real industrial context allow enhancing its innovative aspects and potentialities. It is the first tool that automatically correlates the traceability of production flows with the quantification of the environmental impact of a SC. It permitted to simplify the life cycle inventory that is usually the longest and the most error prone phase during an environmental assessment. It was observed that the use and the interconnection of traceability stations, IoT devices, and company data management systems contribute to reduce time dedicated to data collection, data inconsistence, and errors in data management, increasing data completeness and results accuracy. This evidence is also highlighted by differences emerged between SC actors that exploited the full potentialities of the system (e.g. shoe producer) and the SC actors that implemented manual traceability stations (e.g. tanneries) or untraced network actors (e.g. accessories suppliers). Although the system interfaces embedded the data checking (e.g. missing data), the latter found out more inconsistencies and typing errors than the former, as well as more time-consuming activities.

The proposed system also allowed updating data with minimal effort and easily simulating/comparing alternative scenarios to support the decision-making process. For example, by few clicks it was possible to replace lorries with more sustainable means of transport (e.g. ship or train), according to the distance and the route to cover, to substitute cotton with other materials or to modify the leather procurement mix from suppliers, quantifying possible benefits related to each choice.

The adaptability of the system to different production realities (company drivers, plant layout, material and information flows, production times, etc.) demonstrated its high flexibility and user-friendliness from both hardware (i.e. different stations and devices) and software (i.e. multi-platforms) perspectives.

Finally, the distributed architecture of the system that allows the separation of local (i.e. private) and global (i.e. shared) data, ensured data security and incentivised the participation and the propensity of SC actors to share relevant information about their operations. This aspect will play a key role to also encourage collaboration between tiers.

5. Conclusions

This study proposed a web-based platform to simultaneously support SC traceability and eco-sustainability. It was implemented in a leather shoe SC, which is a production chain incurring significant environmental impacts. Moreover, the full traceability of shoe components is generally a complicated task, especially upstream, owing to the large number of partners that collaborate in realising different input materials (leather), unfinished parts (soles), and final products (shoes).

Adopting such a platform, each partner of the network, as well as external stakeholders (e.g. final users), can be aware of the origins of raw materials, components, unfinished products, final products, and the elaboration each has undergone. Moreover, the collection, sharing, and elaboration of primary data support calculation of the environmental impacts of the entire SC, single companies, or single items, in order to identify the most important criticalities and suggest possible interventions. Such an analysis of a SC transport network permits localisation of all suppliers, traces the movement of goods, identifying less sustainable routes and, consequently, improving logistics. The opportunity to simulate and compare different scenarios supports 'green' procurement practices by identifying appropriate mixes of inputs and selecting the most sustainable suppliers.

Thus, the proposed platform is a valid tool for ESSCM, portfolio management, and decision-making, allowing SC performance improvement from several perspectives. Even if the case study did not allow to demonstrate the establishment of cooperative relationships among the involved companies, the adoption of this platform potentially fosters SC collaboration, because data, information and best practices can be shared between the actors involved in the same or different tiers. Moreover, because the platform is a decision-making tool for improving SC environmental sustainability, it can be leveraged to suggest industrial cooperation and reorganise SC flows.

The implementation of the platform in a leather shoe SC highlighted that most of its environmental impact originated from tanneries because of their use of chemicals, in particular chrome salts. Within company boundaries, other aspects that may require attention included are as follows: (i) cotton and corrugated board boxes used for the shoe packaging should be replaced by materials that are more environmentally friendly; (ii) shoe upper factories should limit the use of cotton for accessories, and (iii) insole producers should investigate alternative solutions to aluminium shanks and paperboard components. Additionally, goods logistics played a key role, especially upstream, where the network is more fragmented, and suppliers are dispersed worldwide.

Future work will study and implement new technologies for the automatic traceability of production lots at tanneries. This will increase the usability of the system and accuracy of its assessment, encouraging the creation of new partnerships in order to make its SC more sustainable. Furthermore, an algorithm for network optimisation should be developed to suggest interventions and opportunities to companies. Finally, other SCM issues as economic or social sustainability, should be investigated in order to have a more comprehensive overview of SC sustainability performance.

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