Software Support for Sustainable Supply Chain Configuration and Management

Andrea Emilio Rizzoli, Roberto Montemanni, Andrea Bettoni and Luca Canetta

Abstract A methodology for the inclusion of sustainability assessment in the design of supply chains is introduced, with the aim of taking into account a sustainability perspective in logistics and industrial allocation choices. The presented approach is based on the initial collection and organization of data related to all stages of the product life cycle and of the possible alternative choices to be made for each production and transport stage. An optimization algorithm is then used to prune the space of alternative solutions and an advanced and flexible graphical user interface allows the exploration of the solution space.

Keywords ICT for sustainability · Sustainability assessment of supply chains

1 Introduction

In the recent past, efforts towards the optimization of the supply chain have aimed at the minimization of costs and time: production had to be fast and cheap. Challenged to effectively balance stacks of strictly interrelated costs (inventory, transport, etc.), many companies decided to leverage on manufacturing costs by offshoring production activities to countries with lower labor costs. A side effect of

A.E. Rizzoli (✉) · R. Montemanni
SUPSI, Istituto Dalle Molle di Studi sull'Intelligenza Artificiale, Manno, Switzerland
e-mail: andrea@idsia.ch

R. Montemanni
e-mail: roberto@idsia.ch

A. Bettoni · L. Canetta
SUPSI, Istituto Sistemi e Tecnologie per la Produzione Sostenibile, Manno, Switzerland
e-mail: andrea.bettoni@supsi.ch

L. Canetta
e-mail: luca.canetta@supsi.ch

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such optimization was the intensive use of transportation to cover larger distances in a shorter time. An undesirable second-order side effect was the exploitation of the workforce, as lower income countries were ready to accept worse conditions for their workers [1] and higher impacts on the natural environment. These countries were not ready for an intensive industrialization from a legislative and an environmental regulatory point of view, even though some studies point to the role of self-regulation in countries such as China [2]. One result was increased CO_2 emissions due to longer transport to cover the larger distances.

Such negative side effects have caused an increased awareness among both customers and companies of sustainability and social responsibility issues in production processes [3], making the planning of production and the design of the supply chain an even more complex process, as new objectives and constraints have had to be taken into account. ICT has always been pervasive in supply chain management, as it has been regarded as an instrument to avoid undesirable oscillations and shocks in the supply chain [4]. Today, ICT can also support the design of complex supply chain processes, addressing the issue of the inclusion of a sustainability perspective. For instance, ICT can support the inclusion of life cycle assessment (LCA) in the performance evaluation of supply chains to deliver a comprehensive analysis encompassing all the activities included in its cradle-to-grave path [5]. Traditional supply chains usually cover the cradle-to-gate part of such a cycle, also called the product beginning of life, i.e. from the gathering of the primary resources to customer purchase. Taking a cradle-to-grave approach implies extending the analysis of the supply chain configuration and analysis to the activities linked to the usage phase (product middle of life), such as repair and maintenance, and to end of life, which comprises reverse logistics and re-use/ recycle processes.

In this chapter it is shown how sustainability assessment can be incorporated into supply chain design and management in order to address three main issues: first, including sustainability concerns in the design phase, rather than performing ex-post analyses which cannot change choices that have already been made; second, providing a structured approach to data collection, as the availability of data is the major shortcoming in making informed decisions; and eventually, finally supporting the choice of the better performing solution by providing a tool for the automatic calculation of the more sustainable supply chain among the possible available alternatives.

The inclusion of sustainability concerns in the design phase allows one to provide a real-time evaluation and consequent sustainability-driven product development. This leads to instantaneous sustainability-driven modifications of the design instead of following the classic design loop in which the LCA report is produced at the end of the design phase when it is no longer convenient to implement radical changes.

Secondly, sustainability-related data gathering is a critical issue, as it extends through every process running inside and outside the company, from raw material extraction down to the end of life of the product. This requires companies to widen their perspective in order to encompass not only the activities they directly manage but also to consider and measure the performance of the whole supply chain. To this end, a shared perspective needs to be established, and proper tools for reliable data gathering are also required.

In order to tackle the above described criticalities, this chapter presents a solution capable of supporting real-time sustainability assessment in the design phase of a whole product, production system and supply chain solution space. Achieving the stated objective implies the implementation of the following aspects:

- LCA must be integrated into supply chain design in order to provide feedback on sustainability performance of the supply chain during the design phase, and not only when the supply chain is in place (ex-ante vs. ex-post assessment);
- Data gathering must be assessment-oriented from the very beginning in order to avoid huge efforts at a later stage; this requires a holistic data structure capable of describing a widespread data set and adaptable to highly diverse scenarios;
- Exploration of the solution space, which can be a complex task because of the complex relationships between the involved companies at the various stages of the supply chain and the multidimensional impact of their processes on the various indicators pertaining to the three dimensions of sustainability (economic, social and environmental).

In the remainder of this chapter, we present the data model used to collect, organize and distribute the data related to each step in the supply chain [6]. We then present an approach to the design and configuration of efficient solutions for the supply chain [7]. Finally, we present a case study applying our methodology to the design of low-impact supply chains for the textile sector and demonstrating our techniques of facilitating the exploration of the solution space [8, 9].

2 The Data Model for Cradle-to-Grave Sustainability Assessment

Integrated environments for the assessment of sustainability impact are often composed of many software tools. A shared data model is the first step to effectively support the collaboration of the design tools required to evaluate the sustainability impact of a supply chain [10]. Here the involved design tools can store and retrieve the relevant information on the whole solution space. This sustainability model is conceived of as an extension to the established computational approaches to the LCA problem [11]. The data gathering process is indeed a critical and tricky step as it relies on many different sources, which are seldom harmonized and coherent. A common description language is then called for. To this end, the shared data model covers the three main aspects of a product in a lifecycle perspective: First, the product nature, both in its hierarchical structure and its physical properties; then the production process, which encompasses the whole life of a product from its raw material extraction to its end-of-life treatment; and finally the supply chain, which describes all the involved actors and the actual transport of resources that play a role in the product life.

This coherent and comprehensive description of product-process-supply chain is then used to perform a detailed assessment of its sustainability level. Indeed, the data model becomes the common platform on which all data-providing agents exchange information with the underlining system, thus allowing interaction between them and ensuring consistency of correlated data.

Inside the data model, five macro areas can be identified. The first area is core data entities that provide support to the other areas, providing elementary building blocks and descriptive bridges. Next, three specific areas encompass the corresponding three aspects of the production context, namely product, process and supply chain. The product area represents both the resources that comprise the product's physical structure and how customization choices, carried out by the customer, can change the physical structure of the product itself. The process area represents the operations that are connected by flows of materials as their input and

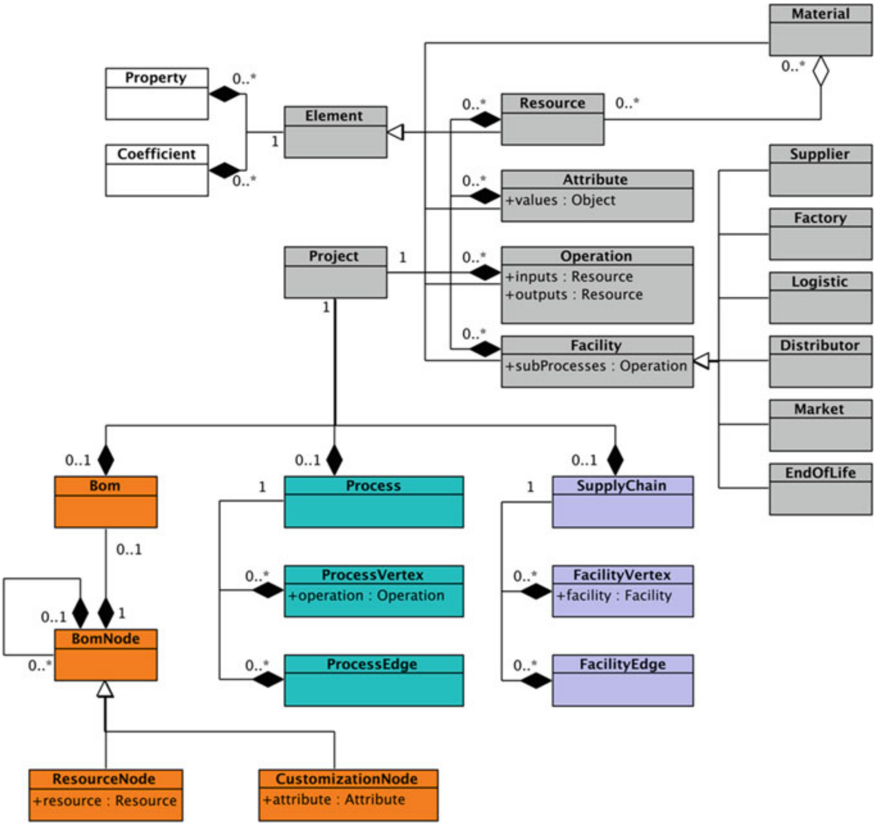


Fig. 1 UML class diagram of the shared data model

transformed output. These operations are themselves specified to reflect modification of the process caused by the application of the customer's customization choices. The supply chain area represents the facilities involved in the solution space. Between these facilities, transport of physical resources takes place that can be achieved following different paths and using a variety of transport means, generating variable sustainability impacts. A last area is dedicated to enabling a large flexibility of properties that are required for an assessment and linked to the various data entities describing the solution space of the product. This flexibility is achieved through a generic definition of assessment properties, representing the physical characteristics of the data entities used by the supply chain designer, described in Sect. 3, for its calculations.

The shared data model areas described above are depicted in Fig. 1, where a high-level class diagram comprising the most relevant classes is shown. For a detailed description, see [6, 12].

It is to be noted that although not strictly related to the data model structure, some limitations apply to this model: (i) single-functional processes only are considered; (ii) loop generation on the graph structure during computation is not allowed.

3 Efficient Design of Supply Chain Alternatives

The environmental footprint of a product can be computed by means of a life cycle impact assessment [13]. Such an analysis can be performed once all supply chain processes have been selected, the production sites have been identified, and the transportation options are set. The drawback of such an *ex-post* analysis is usually the limited capacities for providing any guidance in selecting the best supply. Here, a *supply chain designer* (originally described in [8]) is proposed as the core component for supply chain optimization: for each stage in the supply chain, it evaluates the potential alternatives (e.g. alternative production sites and processes, alternative transportation modes), and it then computes alternative supply chains to production managers according to the importance he or she ascribes to different factors such as economic, temporal, social or environmental aspects.

More specifically, the manager is asked to set the weights of the different factors (e.g. economic costs, impacts) involved in the optimization process leading to the most promising supply chain. In such a way he or she can find the best supply chain design according to the policies of the company. Such a process has to be iterative: the manager can fine tune in subsequent iterations the weights of the different factors based on the results and the expectations, thus obtaining different results until the set goals are met. The input of the optimization comes both from the contracts the company has with the different suppliers/carriers (mainly in terms of production/delivery costs and times) and from more general sources of information such as the environmental databases, in which general environmental impact information is provided for the different steps and processes of the supply chain. This general information is usually refined with first-hand knowledge about the suppliers of the company.

3.1 Mathematical Model

The production process of a product is typically represented in conventional LCA by decomposing it into a sequence of processes, which transform materials in order to obtain the desired output. Given such a sequence of processes, the optimization problem at the basis of the *supply chain designer* can be represented in mathematical terms on a directed graph $G = (V, A)$ where V is a set of nodes representing the stages of the supply chain process, node s is the starting node and node t is the final state (finished product at the destination warehouse). The arc set A contains all possible production/transport steps encountered in the supply chain, and walking arc $a = (i, j) \in A$ (with $i, j \in$ V) means that the product moves from state i to state j through process a. Notice that not all arcs are present (depending on the compatibility of successive production stages) and that the resulting graph is a layered graph, where at each layer there are alternative production histories of the product. A simplified graph is depicted in Fig. 2 (taken from [8]).

A set of labels is associated with each process/arc $a \in A$. They represent the indicators later used by the optimization in a weighted fashion. In detail, for each arc, the following labels/indicators are present: $cost(a)$, $susti$ [1] (a), $susti$ [2] (a), …, $susti[n](a)$ where the last n labels represent the different sustainability impacts considered during the calculation, such as global warming potential, water resource use, damage to ecosystem health, and so on. Labels are real numbers between 0 and 1 representing the indicator normalized between the lowest and the highest possible values for each category. This normalization makes it possible to compare (and weight) quantities that otherwise would have very different definition domains

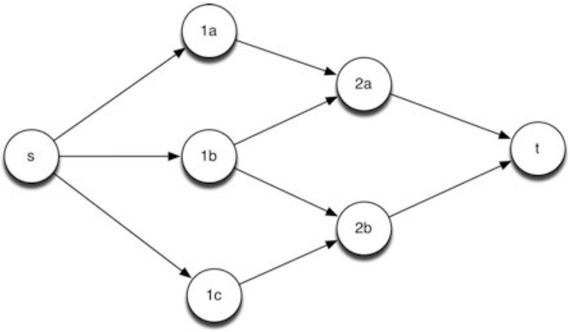


Fig. 2 An example of the graph associated with a supply chain. For each layer (production/transport process) different alternatives are present, with given interlayer compatibility

(ranging between 10^{-4} and 10^{4}). Note that in case the arc $a = (i, j)$ is associated with a production process, the indicators will only depend on the tail node j, and all arcs entering node j will contain the same indicators. Finally, observe that all arcs entering node t have all labels at 0 by construction.

A set of weights w_{cost}, $w_{susti[1]}$, $w_{susti[2]}$, …, $w_{susti[n]}$ has to be specified by the supply chain manager using the application. These weights are positive real numbers summing to 1 and are used to specify the importance of each one of the factors during the optimization.

The problem of finding the best supply chain, according to the weight selected by the user, reduces therefore to the well known *Shortest Path Problem* [14]. Given the weights, the path P from s to t minimizing the following quantity is the best path:

$$\sum_{a \in P}\left(w_{cost}cost(a) + \sum_{k=1}^{n} w_{susti[k]}susti[k](a)\right)$$

Because of the context in which the method is used, however, we prefer to present the user with the best k shortest paths, with k usually on the order of 10–15. In such a way the user is able to visually evaluate the solutions and possibly modify the weights of the various factors thus, aiming to best match the policies of the company, which often cannot be schematized into simple weights. A user interface will embed the optimization procedures previously described (see Sect. 4).

3.2 Optimization Algorithm

The algorithm used to retrieve the k shortest paths according to the given weighted combination of factors is the well known state-of-the-art approach presented in [15]. A detailed description of the algorithm is available in [7], to which we refer readers interested in the technicalities behind the intuitive idea. Note that in the case of supply chains, the required paths are provided with an extremely short computation time, thanks to the limited number of paths requested and to the limited dimension of the graphs associated with average supply chains.

4 Case Study: The EcoLogTex Project

The EcoLogTex project has implemented in a real world case the theoretical and methodological solutions proposed in the previous sections. In this project, a web-based software application for the *environmental design* of the cradle-to-gate supply chain of textile and apparel companies has been realized.

The main components of the EcoLogTeX software application are the following:

- *Benchmarker*: This is a web-based software application in which suppliers (of goods, processes, or services) enter the relevant data for their products and services, attracted by the gains in competitiveness as suppliers to the textile company, and thus providing the data for a holistic supply chain evaluation. The supplier has two advantages in using the tool: first, it can qualify as a potential supplier for the textile company; second, it obtains a quick check of its *sustainability performance* compared to its competitors, leading to an even higher quality of their offer. The data elicited by the benchmarker is then organized in a database structured according to the principles of the data model outlined in Sect. 2.
- *Supply chain designer*: This is a stand-alone software application for the design of sustainable supply chains. The tool can explore the potentially very complex current and alternative supply chain situations and identify the space for design alternatives, based on the background data from the *EcoInvent* database [16] as well as specific supplier data from the EcoLogTex *benchmarker*. This allows for continuous improvements towards a sustainable supply chain. A description of this component has been provided in Sect. 3.
- *Reporter*: This is a stand-alone software application for exploring the solution space and producing reports to be published on the company website regarding its supply chain sustainability. It uses the data provided by the suppliers, stored in the EcoLogTex database and confirmed by an independent party (e.g. the *EcoInvent* database).

4.1 From the Design of the Supply Chain to Exploration of the Results

In this section we briefly present the main features of the graphical user interface of the supply chain designer and offer some examples of the outputs produced by the reporter.

Figure 3 shows how the user sees the various steps of a supply chain, and Fig. 4 shows how the detailed data entry for each node is organized. The supply chain is represented by a tree with the root as the terminal node, as various components can contribute to the assembly of the final product, in this case a mixed wool-cotton shirt. In each node, which represents a process step, the user must select the potential suppliers, i.e. those suppliers who can deliver that particular process, but with different costs, time, and especially environmental impacts.

Once the different process steps, including the transport options, have been selected, the user can launch the optimization algorithm that solves the combinatorial optimization problem described in Sect. 3. Prior to the launch, the user

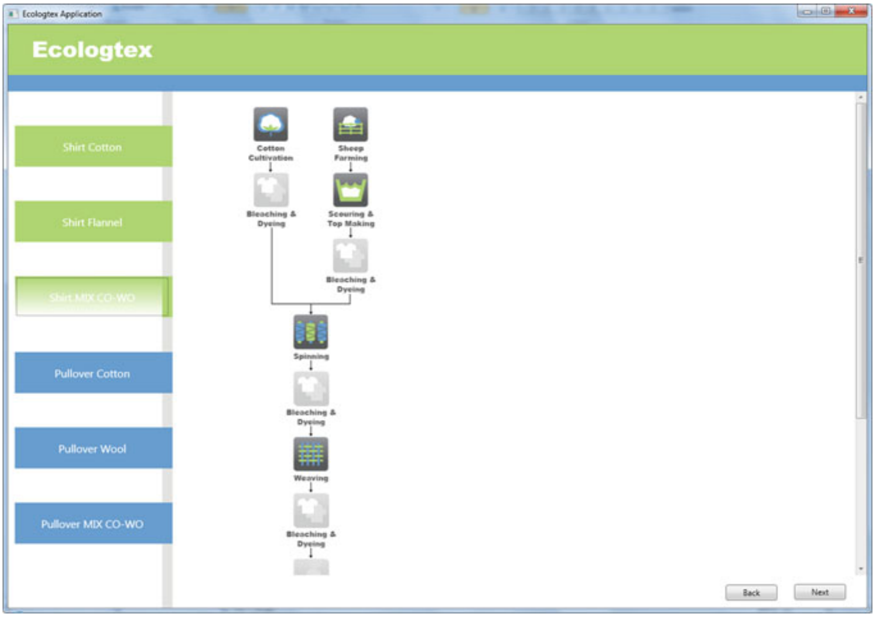
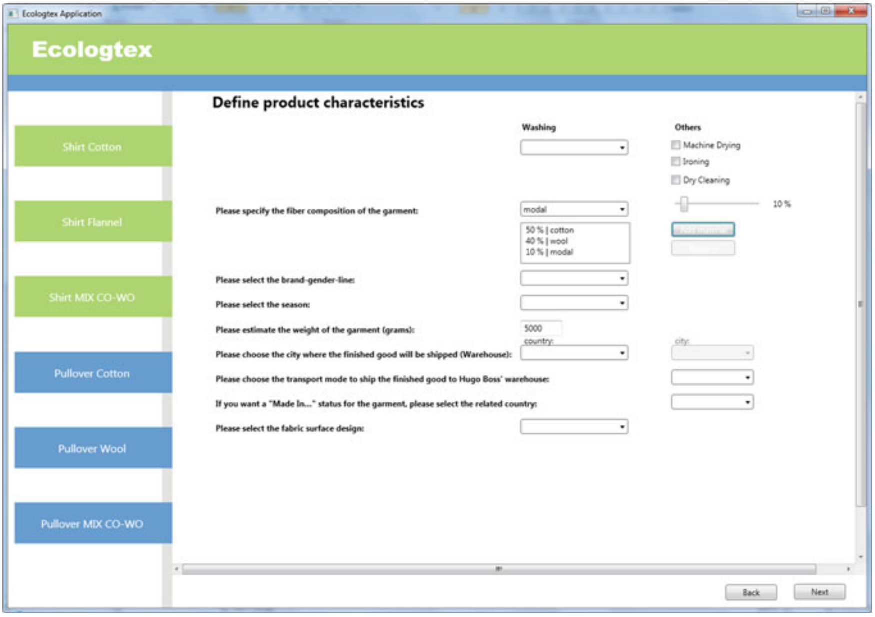


Fig. 3 The representation of the structure of a supply chain



Define product characteristics

Washing

Others
☐ Machine Drying
☐ Ironing
☐ Dry Cleaning
10 %

Please specify the fiber composition of the garment: modal
50 % | cotton
40 % | wool
10 % | modal

Please select the brand-gender-line:

Please select the season:

Please estimate the weight of the garment (grams): 5000

Please choose the city where the finished good will be shipped (Warehouse): country: city:

Please choose the transport mode to ship the finished good to Hugo Boss' warehouse:

If you want a "Made In..." status for the garment, please select the related country:

Please select the fabric surface design:

Fig. 4 The data entry mask for a specific process step must define the objective function by attributing weights to the different indicators, which include both cost and time, but also to the typical LCA indicators such as water depletion, marine eutrophication, climate change and the like (see [17] for the full set of indicators that are used in the objective function).

Computational experiments have been carried out on some realistic artificial scenarios, obtained by considering the characteristic of the real supply chains currently used by Hugo Boss for a few different products. In particular, a typical product has between 8 and 15 production stages, with a number of alternative factories/carriers ranging between 2 and 9 (with typical values below 4) for each stage. The range of values for most of the factors is fairly large: for example, a shipment can be either very fast, expensive, and with large environmental impacts, or slower, cheaper and more sustainable.

Results of the constructed instances proved that a few seconds are always sufficient to rank all possible supply chains (paths) according to the given weighted objective function. Note that in some cases more than one thousand paths are retrieved. As explained in Sect. 3, in the context of our application only a few paths (10–15) are presented to the user for each given combination of weights. This indicates that the algorithm described in Sect. 3 perfectly fits the needs of the project, since it runs in negligible time under the given conditions.

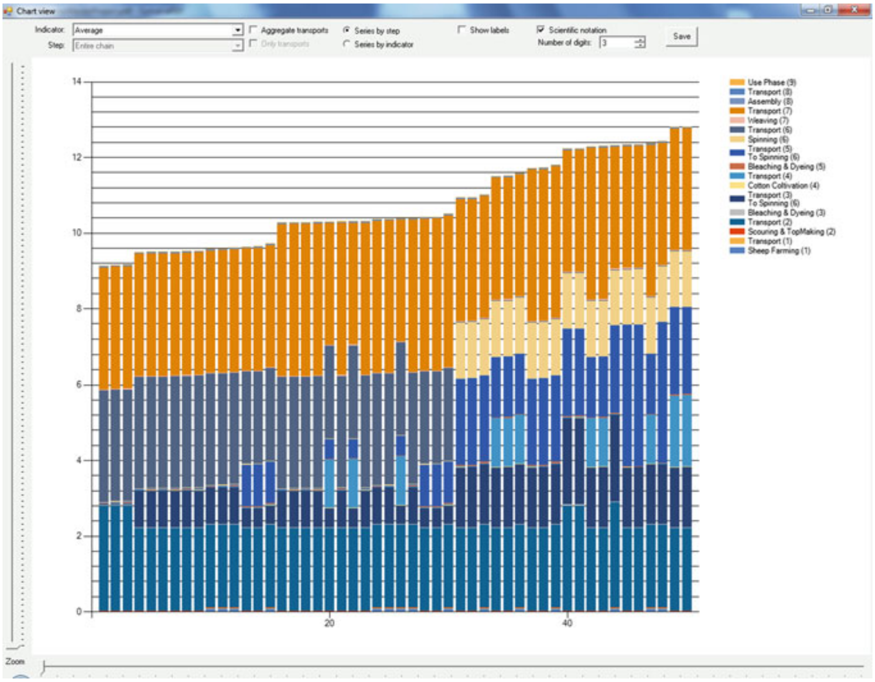
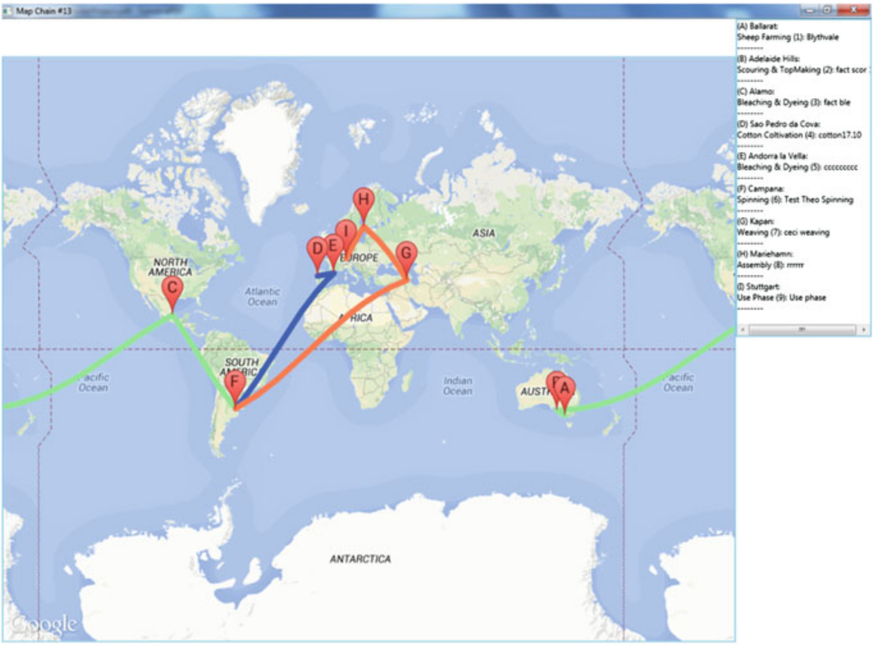

Indicator: Average
Step: Entire chain
☐ Aggregate transports
☐ Only transports
● Series by step
○ Series by indicator
☐ Show labels
☑ Scientific notation
Number of digits: 3

Fig. 5 An example of the chart view in the EcoLogTex reporter. The series (*colored bars*) represent the steps, and the values corresponding to the heights of columns and series are the normalized values of the indicators. Every column represents a chain



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(A) Ballarat:
Sheep Farming (1): Blythvale
---------
(B) Adelaide Hills:
Scouring & TopMaking (2): fact scor
---------
(C) Alamo:
Bleaching & Dyeing (3): fact ble
---------
(D) Sao Pedro da Cova:
Cotton Coltivation (4): cotton17.10
---------
(E) Andorra la Vella:
Bleaching & Dyeing (5): ccccccccc
---------
(F) Campana:
Spinning (6): Test Theo Spinning
---------
(G) Kapan:
Weaving (7): ceci weaving
---------
(H) Mariehamn:
Assembly (8): rrrrrr
---------
(I) Stuttgart:
Use Phase (9): Use phase
---------
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Fig. 6 The map view. In the figure we display a chain with two parallel sub-chains and a final common sub-chain: the *green* path A-B-C-F is the first sub-chain that is executed in parallel to the blue path D-E-F. In F there is the junction of the two paths, and the final common sub-chain is represented by the red path F-G-H-I

Once the algorithm has generated the k-best chains, the EcoLogTex reporter can be used to explore the ranked list of the most promising supply chain alternatives, as shown in Fig. 5. For each solution, the different enterprises carrying out the different working phases can be shown, with the respective value of the weighted objective function. For each production step, the values of the single optimization factors are also shown.

At this point the user can decide whether one of the proposed best chains can be accepted, or whether a re-run of the optimization algorithm, under a different set of weights for the various indicators, is needed.

Finally, the user can also display the whole supply chain on a geographical map to better appreciate its spatial extent, as shown in Fig. 6.

5 Conclusions and Perspectives

Supply chain configuration and management can strongly benefit from the adoption of a product life cycle approach and comprehensive sustainability assessment. On the basis of these considerations, an approach has been developed to address this very current supply chain research topic. In this chapter we presented a tool that integrates in a coherent way various cutting-edge bodies of knowledge, aiming at supporting this activity. The first contribution is linked to the development of a comprehensive data model that allows modeling all stages of the product life cycle and assessing the sustainability impacts of all the processes involved in the product life cycle. The tool also allows representing all the possible alternative choices for each production and transport stage in order to generate a set of potential supply chain configurations. The second contribution is a fast and reliable algorithm based on mathematical programming used for retrieving the most promising solutions for the design of an efficient supply chain, from a sustainability perspective. The algorithm evaluates life cycle impacts based on a shared data model, but they exclude issues related to allocation for multifunctional processes. An advanced and flexible graphical user interface has been developed for supporting the exploration of the proposed integrated tool. The interface allows tuning the optimization parameters dynamically according to the strategic decisions of the company. The optimization process is supported by the possibility of graphically easily comparing the performance obtained by a subset of promising supply chain configurations.

The integrated tool has already been successfully tested in realistic industrial scenarios in the apparel sector, even though it was preferable to start undertaking a partial validation focusing on environmental sustainability and cradle-to-gate supply chain processes.

The proposed tool, developed to provide a comprehensive sustainability assessment and to model all the processes belonging to a cradle-to-grave supply chain, will be further validated, involving a wider supply chain and a set of performance indicators. An interesting perspective is related to the improvement of the graphical user interface to support the optimization of the supply chain performance. This should consider a time horizon over which the supply chain has to simultaneously manage different processes for various product generations, ranging from production and delivery to the customers of the most recent products to reverse logistic activities for old products approaching their end of life stage.

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