chapter eleven

Sustainability assessments for mass customization supply chains

Carlo Brondi, Rosanna Fornasiero, and Davide Collatina

Contents

ABSTRACT

The evaluation of the environmental impact of production networks has been under debate during the last few years. Currently, there is a shift of production paradigm from mass production to customization and personalization.

The aim of this chapter is to evaluate the sustainability of supply chains, applying a model based on the integration of life cycle assessment (LCA) with discrete simulation to compare different customization policies in a networked context. In the developed model, the environmental impact of the supply chain is assessed through an innovative modular LCA where different levels of customization have been analyzed. The chapter then compares the scenarios based on variations of drivers such as lead time to the customer, quality in terms of scraps, and the level of sustainability of the suppliers. The model is validated by collecting data from a fashion-based case study taking into consideration the environmental impact of a certain batch production. The preliminary results highlight that specific decisional areas under the control of supply managers (e.g., supplier selection and manufacturing defects) can significantly affect the environmental impact of the whole supply chain.

11.1 Introduction

The quantitative assessment of environmental sustainability is a recurrent area of interest for evaluating production phases, transportation, and suppliers within the literature. Sustainability assessments also concern modern production paradigms such as knowledge-intensive services to customers (Gallouj et al., 2015). In particular, Petersen et al. (2011) address the issue whether the concepts of mass customization and sustainability are fundamentally compatible. The updated mass customization paradigm calls for both personalized outputs and cost/eco-efficiency tracking in order for companies to maintain their competitiveness and create value (Mourtzis and Doukas, 2014; Ueda et al., 2009). The development of customized production and its related services seems implicitly to call for new collaborative supply chains (Romeo et al., 2014) as well as for reliable models for sustainability characterization going beyond qualitative assessment (Kohtala, 2014). The preliminary involvement of consumers within product service systems, including referenced sustainability tracking, seems to also produce positive effects in fashion sectors (Armstrong et al., 2015). At the current stage, different studies have proposed alternatives for the design of sustainable supply chains (SSCs) and eco-efficient products in order to be compliant with the mass customization paradigm (Piplani et al., 2007; Lee and Huang, 2011; Govindan et al., 2014; Osorio et al., 2014), but the literature review emphasizes the lack of verification criteria in the presence of diverging possible effects due to customization policies (Kohtala, 2014). Positive environmental effects account for the reduction of preconsumer waste, lower transport emissions, minor product replacements, greater potential for remanufacturing, intermediary reduction, and use phase extension for customized products. Possible negative effects instead account for the augmented difficulties in product reuse, the need for energy/resource-intensive transformation processes,

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exposure to uncontrolled emissions in local environments, and the possible failure to replace traditional mass production.

From an industry perspective, despite widespread agreement on the importance of sustainability aspects for long-term competitive advantages, often companies need strong triggers in order to put into action initiatives for integrating these dimensions in their strategies. On one side, legal regulations, responsibility to stakeholders, customer demand, reputation loss, and environmental and social group pressures are often listed as triggers for companies to implement sustainability. On the other side, some barriers to implementing actions for an SSC are (Piplani et al., 2007)

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1. The cost of implementing measurement systems for sustainability
2. Problems defining a value for the output with respect to environmental outcomes
3. The perception that data to be collected from different actors in the network is not manageable and will have a low impact on the global outcome
4. Difficulties taking unpopular and high-priced decisions for the network

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In order to overcome these limits, researchers and managers are trying to answer the following questions:

- How should a supply chain accomplish the trade-off between economic and noneconomic objectives while making managerial decisions?
- What activities are necessary to implement an SSC?
- Which types of incentives are necessary to induce people to pursue sustainability objectives? (Noci, 1997)

When dealing with networked companies, the availability of data on time, quality, service, and so on of suppliers along the network is state of the art, while for environmental impact analyses there are still problems with the sharing of data that is considered confidential (e.g., energy consumption, water and heating release) and once the data is shared to make it homogeneous. Specific sectoral inventory data is useful to calculate the global warming potential (GWP) of a company and of a network.

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11.2 State of the art

In the current business environment, the purchasing process has become a critical activity for adding value to products and a vital determinant to ensure the competitiveness of a company. This process becomes more complicated when environmental issues are considered because *green* purchasing must consider the supplier's environmental responsibility, depending on product chain assets, in addition to traditional factors such as the supplier's costs, quality, lead time, and flexibility. The management of suppliers based on strict environmental compliance seems to be not sufficient in view of a more proactive or strategic approach. Noci (1997) designed a green vendor–rating system for the assessment of a supplier's environmental performance based on four environmental categories—namely, green competencies, current environmental efficiency, green image, and net life cycle cost. The main limit in attributing a unique environmental performance index to a company seems to be linked to the management of a reliable, quantitative set of scientific values that can be considered constant in different comparisons. While literature related to supplier evaluation is plentiful, the works on green supplier evaluation or supplier evaluation that considers environmental factors are rather limited (Handfield et al., 2002; Humphreys et al., 2003). Two general aspects seem, then, to emerge as relevant in the sustainability assessment of mass customization: from one side it seems important to identify the sustainability features for a proper assessment, while on the other hand the environmental assessment of scalable product chains requires specific modeling issues. These aspects are faced separately in the next two sections.

11.2.1 Sustainable supply chains in mass customization

The high variability of customer demand and legislative pressure in EU countries on environmental aspects push academic and industrial communities to tackle the question of how to implement sustainable production systems. In order to accomplish this objective, a strong integration among the units of the supply chain is necessary and can help to maintain and build a durable competitive advantage with respect to competitors. For this reason, in the last few years many approaches have been proposed in international journals to support the implementation of SSCs (Dyllick and Hockerts, 2002; Seuring and Muller, 2008). The result of this academic and corporate interest has been the achievement of important goals for the sustainable success of firms in terms of integrated supply chains, green supply chains, the ecology industry, and long-term competitive advantages.

Despite there being, in recent years, widespread agreement on the importance of sustainability aspects for long-term competitive advantages, often companies need strong triggers in order to put into action initiatives for integrating these dimensions. Legal regulations, responsibility to stakeholders, customer demand, reputation loss, and pressure from environmental and social groups are often listed as triggers for companies to implement sustainability.

Zhu et al. (2008a) identify five *green supply chain management* (GSCM) factors: internal environmental management (IEM), green purchasing

(GP), cooperation with customers (CC) including environmental requirements, eco-design practices (ECO), and investment recovery (IR). Zhu et al. (2008b) present the implications in GSCM for closing the loop of the supply chain.

It is clear that the adoption of green practices impacts on environmental results—for example, in terms of pollution reduction (Klassen and Whybark, 1999)—but at the same time companies need to take over other environmental dimensions without forgetting to pursue profit objectives. In the literature, we can find some references to the positive role that environmental management plays in order to achieve operational performance (and it is established that operational performance is strictly and positively linked to financial performance), linking the *lean* and the *green* approach to management.

Hart (1997) and Florida (1996) suggest that environmental management can also provide cost savings, by increasing efficiency in production processes and improving the firm's performance, by facilitating the creation of resources and capabilities as well as the ability to innovate (Porter and Van der Linde, 1995; Russo and Fouts, 1997; Reinhardt, 1999). Moreover, Rusinko (2007) suggests a positive impact of pollution prevention on cost savings and competitive advantage. Christmann (2000) draws on the resource-based view of the firm and finds a moderating effect of innovation and implementation on the relationship between environmental practice and cost advantage.

On the other hand, the literature also raises a trade-off issue between environmental initiatives and operational performance (Clark, 1994; Walley and Whitehead, 1994), but in more recent works the impact of the cost of compliance with environmental goals was evaluated (Yu et al., 2009). For this reason, a "lean and green" perspective is adopted in the development of the performance measurement system, in order to monitor and control the trade-offs resulting from the implementation of environmental management.

The current debate on the customization paradigm poses a number of further issues for the sustainability paradigm. Customer-driven manufacturing could in fact address the reduction of environmental impact since the closest link between manufacturer and customer can imply a reduction of the environmental load due to operation and distribution (e.g., electricity, heating, and transport). The reduction of item stock and the increase in the value of traditional products (Bernard et al., 2011; Zhang et al., 2011; Bruno et al., 2013) seem to contribute to reducing environmental impact, particularly in product distribution to customers, in its use, and in the eventual recovery phase. Proper product modularization and proper efficiency policies in factory management can be the best way to increase efficiency as well as to counterbalance the negative effects of customization. Another open issue concerns transportation reduction, which depends on the supply chain configuration. The downsizing of the transport network could, in fact, conflict with the reduction of the efficiency of economies of scale. According to some authors, the relative environmental contributions from the stages of supply, manufacture, and waste production are affected by a strong sectoral characterization (Su et al., 2015).

Different authors have proposed simulation and optimization techniques to manage such divergent aspects. Mourtzis et al. (2013, 2014) proposed a toolbox to deal with the conflicting supply chain drivers in a network setup, metaheuristic and artificial intelligence methods integrate assessment of carbon footprint limited to standard transport processes. A complete life cycle approach for supply chain carbon footprint modeling was proposed by Trappey et al. (2012) by using an I-O matrix in a real supply chain case based on three areas of investigation: materials, production, and logistics. Despite the completeness of the approach, assessment is developed in the presence of the same service model and by using sectoral data to assess the clustered carbon footprint. An effort to integrate LCA and business models with a mass customization perspective is made by Boër et al. (2013), where a complete reference set of environmental indicators for the modular subdivision of the whole product life cycle has been applied at the level of a single component, life cycle phase, and supplier. The detailed set of equations can, however, be difficult to implement in common multitier networks in which other life cycle inventory (LCI) indicators are available and the distinction between part manufacturing and the assembly phase is often not clear.

AU: The text "metaheuristic and artificial intelligence methods integrate assessment of carbon footprint limited to standard transport processes" is unclear. Please rewrite if possible.

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As a primary issue, then, a proper characterization of the real effects seems necessary (Su et al., 2015). In this respect, the environmental impact characterization due to current industrial practices is also affected by serious operative limits. In particular, the definition of a company's environmental performance is generally based uniquely on the type of transformation process or, instead, is referred to as standard operating conditions that are focused on a single product type. Real industrial practices are instead based on ever-changing production item batches.

11.2.2 Environmental impact assessment of networks for customization strategies

As mentioned in the introduction, it is important to underline that the customization process involves divergent environmental effects. On one hand, the simultaneous presence of these effects can lead to a higher impact from customization processes compared with processes for mass-produced items. Traditional processes can in fact benefit from scale economies. On the other hand, the comparison between a customized product and a standard product should require the same functional unit—that is, the performed service toward the final consumer. In this view, product customization is an additional service toward the consumer that

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changes the traditional functional unit of the mass customized products. According to these premises, environmental impact minimization can be relevant for the identification of the best implementation scenarios rather than a single comparison of a customized product against similar traditional products.

LCA can represent a proper methodology to assess product environmental sustainability cause the intrinsic perspective on the whole product life cycle (Hugo and Pistikopolous, 2005; Bojarski et al., 2009; New et al., 2010; Brondi et al., 2014; Sun et al., 2015). Nevertheless, the proper adoption of traditional LCA in the customized environment should overcome the following barriers:

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- *Alignment between the life cycle perspective and the business perspective*: Inventory schemes for physical flows within small-to-medium enterprises can require a business-compliant approach that can significantly differ from LCI schemes. Internal operations can be committed to external suppliers so that mass and energy tracking is interrupted. Furthermore, the capability to provide reliable data from companies should not overcome the limited extent of the product life cycle (i.e., from first supply level up to final product distribution). Corporate environmental policies usually have to decide how many product chain levels should be included within the data inventory process. Ideally, the entire value chain should be analyzed, but resources and data availability can impose serious constraints on the assessment models (Brondi et al., 2012; ISO/TS, 2014; Unep, 2015). In a factory perspective, the *knowledge horizon* of the product manager can cover the background phases up to a certain supplier and the foreground phases up to the gate for the customer (Figure 11.1).

AU: "small-to-medium enterprises" – please confirm this change is correct.
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- *Adaptation of inadequate data to new LCA studies* (Hagelaar and van der Vorst, 2002): Life cycle analysts can frequently abuse the literature and general-purpose databases in place of supply chain data in cases where the assessment involves a limited view on the product chain.
- *Misalignment between company environmental assessments and product design*: The designer and the life cycle analyst can require radically different procedures in order to modify the final solution (Brondi et al., 2012). Furthermore, the design of a product requires a set of parameters that can be insufficient for an environmental impact assessment.
- *Limited extent in the reuse of previous LCA studies* (Klöpffer, 2012): The literature suggests that a study review starts with a draft *goal and scope* chapter. In fact, each LCA is performed under specific assumptions and purposes; for example, an LCA for comparative assessment requires different rules from an LCA for internal assessment.

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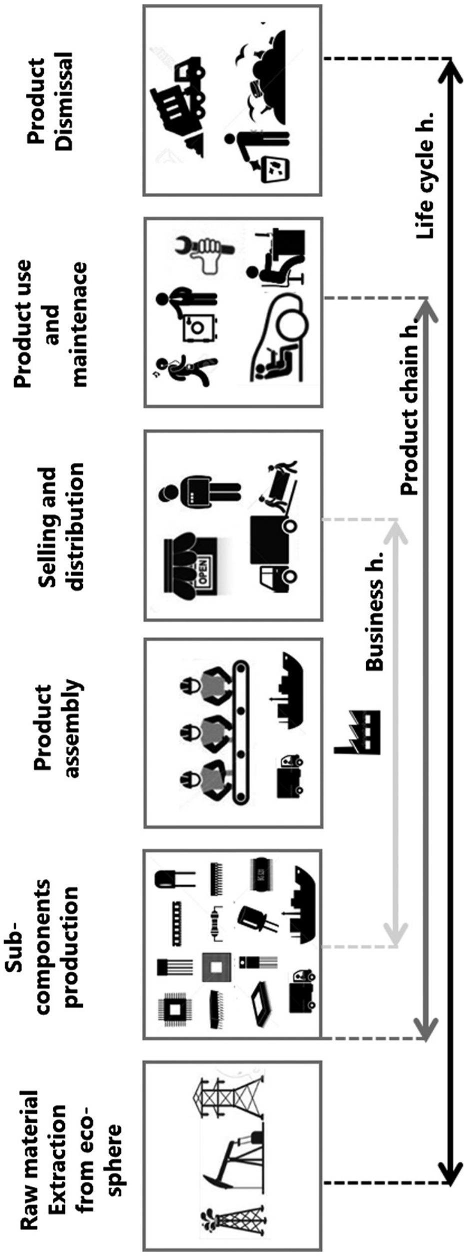

Figure 11.1 Knowledge horizons in modeling the environmental impact of the product chain.

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Changes in the functional unit, in single processes, or in the system boundaries can then revoke the study validity for other purposes.

- *Uncertainty in the life cycle determination*: Existing product benchmarks commonly provide results with reference to the entire life cycle of a single product. The proper determination of life cycles requires the statistical tracking of a certain stock of products. Such stock involves different life cycles. The combined variance of specific environmental drivers is then fundamental. As an example, economy of scale, transport networks, stock variance, and environmental profiles from different suppliers can influence the variance analysis.
- *Misalignment between consequential and attributional methodologies*: LCA studies that aim to optimize a supply chain should compare different configurations of technologies and materials. The resulting comparative studies (consequential methodologies) require the assessment of additional marginal effects that can be difficult to model (e.g., marginal demand for a certain choice and avoided impacts). On the other hand, noncomparative studies (attributional methodologies) focus on the life cycle for a specific product. In particular, attributional methodologies make use of allocation factors requiring an impact subdivision according to eventual coproducts and services.

11.3 Proposal for an integrated model of supply chain assessment

A modular parametric approach can introduce a flexible and precise way to assess the relative contributions of scalable supply chains within a product chain.

Such an approach structures the available data (e.g., information on energy and material input; quantitative emissions into the water, soil, and atmosphere; transport data from suppliers to focal companies) in terms of input and output impacts for each product chain node.

Further simulation of supply chain trade-offs, which also account for other quantitative indicators, assign performance indicators to each supplier. Other reference indicators for such assessments are the delivery time, the quality of the product, the flexibility, the inventory strategies, and the environmental profile.

As reported in the gray boxes in Figure 11.2, firstly, product chain modularization provides the set of quantitative data; then, dynamic simulation integrates this information and provides quantitative values for unavailable data. With such an approach, the simulation can perform assessments for several products and supply chain configurations. A final analysis of customized production models allows one to assess the sustainability due to different manufacturing scenarios within the make-to-order paradigm.

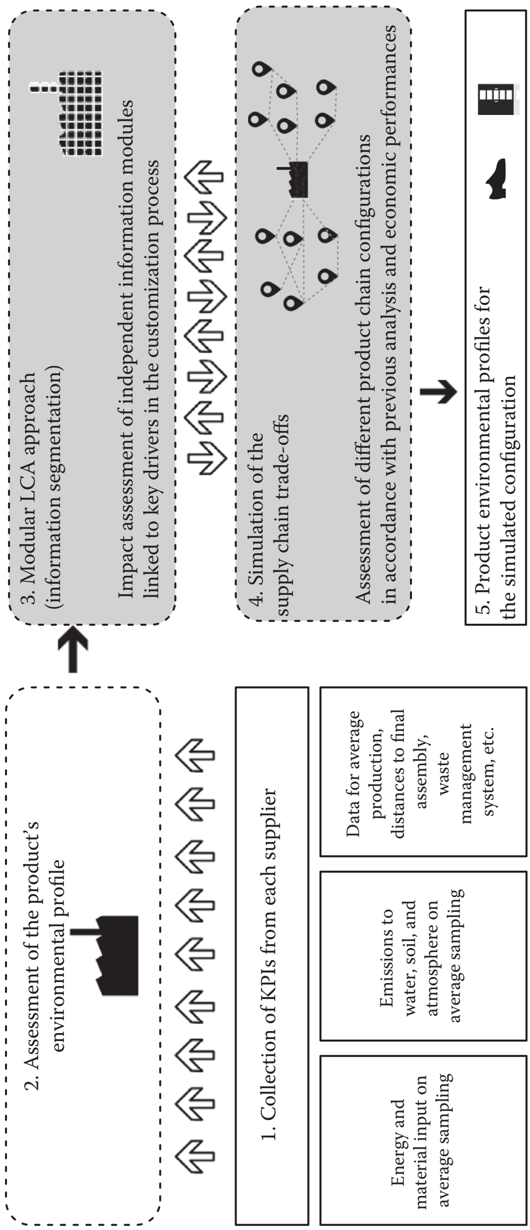

Figure 11.2 Integrated model for supply chain evaluation.

11.3.1 Modular LCA approach for supply chain modeling

The modularization of the impact assessment starts from a comparative LCA. As a first step, LCA execution is compliant with the LCA guidelines (DIN EN ISO 14040:2006/14044:2006). LCA consists of four phases: (1) definition of goal and scope, (2) inventory analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation.

The modular life cycle approach includes the definition of the examined system, functional units, system boundaries, allocation procedures, data quality requirements, and any other assumptions.

- *Goal and scope*: As opposed to traditional LCA scopes, which depend on a specific product and the intended use of the study, the modular approach aims to identify single information modules for each recurrent *macro flow* within the product chain. Macro flows are aggregated flows (i.e., specific products or services) commonly exchanged within the supply chain. According to the extent of optimization, both cradle-to-gate and cradle-to-grave perspectives can be adopted.
- *The LCI phase* is an inventory of input/output data with regard to the examined system involving the collection, calculation, and allocation of the necessary data. The modular life cycle requires tracking product chain data according to recurring flows for a wide range of possible products.
- *The LCIA phase* provides additional information to help assess a product system's LCI results in order to understand their environmental significance. The approach focuses on the environmental impact significance and the relative contribution of each flow. The results represent each individual impact from a comparative perspective.
- *Life cycle interpretation* discusses the results of the LCI or the LCIA as a basis for conclusions, recommendations, and decision making in accordance with the goal and scope definition. This phase compares single results in addition to other weighting factors such as times and cost drivers. The supply chain assessment model integrates the LCIA phase in order to identify the best supply chain configuration.

Equation 11.1 formalizes the modular approach in quantitative terms. Such quantification takes into account a series of modularizations for the traditional impact assessment.

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- *Modularization of single life cycle phases*: The impact assessment of the product life cycle is the sum of the environmental profiles of different phases (i.e., manufacturing phases or supplier operations). In particular, the indexing of such modules identifies the supply level from one player to another (i.e., from s–1 to s). The LCIA of the

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customized product is the sum of incremental contributions from different supply chain stages.

- *Modularization of the customized product*: A certain number of physical components form the customized product with reference to a specific supply chain configuration (i.e., a material type from a specific supplier). The environmental impact assessment of the customized product is the sum of environmental profiles for each different component.
- *Explication of the key manufacturing drivers*: With reference to the specific customized product, the approach identifies and clusters relevant drivers with a significant variance and potential environmental impact. Common drivers due to product customization are the material composition of a product, the product weight, the product chain transport, the warehouse stock for each supplier, and the material waste of a single operation. The environmental impact assessment of the customized product is the sum of environmental profiles depending on such key drivers.

From a supply chain perspective, each node of the network represents a single company, while an input–output model defines the flow inventory of a single company (Hart, 1997).

In more detail, firstly, the life cycle analyst assesses the impact of background flows (auxiliary flows and processing materials) and foreground flows (final products and emissions to nature) for a certain company. Such an approach requires tracking and collecting the flows crossing the physical factory boundaries with reference to the final product. Common flows are input energy vectors (e.g., the electricity and natural gas used for the operation of the production plant), input primary resources, (e.g., the water supply), output emissions to air and water (e.g., VOC, PTS, and wastewater), and output solid waste with related treatment (e.g., wastes from packaging and finishing activities, paints, and coatings). After the identification of such recurrent flows, the life cycle analyst calculates the respective environmental impact for a reference unit in compliancy with the LCA general rules. The results constitute a set of independent information modules for a company.

AU: Please provide definitions for VOC and PTS.

Subsequently, in a further calculation, the life cycle analyst gathers together and calibrates the information modules according to the overall mass and energy balance related to the product chain activities. While the impact of elementary flows (e.g., basic chemicals and energy vectors) requires standard values from international databases, specific materials and components require specific LCA study or, alternatively, the adoption of the same approach as the foregoing supplier.

The final evaluation of the impact assessment is inferred from a combination of the company inventory and life cycle studies for specific industry flows and elementary flows.

The following equations formalize the modular decomposition of the LCA approach in order to flexibly express the environmental profiles of a customizable item.

Equation 11.1 assesses the impact categories of the customized product as the sum of independent, previously calculated vectors. The final array expresses the cradle-to-gate assessment of a specific product from the raw material extraction up to the factory gate. The calculation method appears to be compliant with the supplier perspective. The same approach assesses different manufactured products within the same factory through a flexible supply chain and distribution methodology (Figure 11.3).

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$$e_{pn} = EP_{\text{Company}}(p_n, z) + EP_{\text{supply}}(p_n, z-1) \tag{11.1}$$

$$EP_{\text{Company}}(p_n, z) = \frac{m(p_n)}{M \cdot N} \cdot \left[\left[\sum_{i=1}^{I} \left(u_i \cdot \sum_{k=1}^{K} q_k(p_n) \right) \right]_{\text{Input}} + \left[\sum_{j=1}^{J} \left(u_j \cdot \sum_{f=1}^{F} q_f(p_n) \right) \right]_{\text{Output}} \right] \tag{11.2}$$

$$E_{\text{supply}}(p_n, z-1) = \sum_{s=1}^{S} q_s \cdot e_{ps} + \sum_{t=1}^{T} u_t \cdot \left(\sum_{r=1}^{R} l^t \cdot m_r^t(p_n) \cdot d_r^t(p_n) \right) \tag{11.3}$$

$$e_{pn} = EP_{\text{tare}}(p_n) + \sum_{d=1}^{D} X_d(p_n, c) \cdot u_d \tag{11.4}$$

The approach can be applied both in the presence of previous cradle-to-gate LCA studies for specific product components and to further analyze the intermediate suppliers up to raw material level. Furthermore, the same approach can be applied from the consumer's perspective by a simple extension of the product chain to the level $z + 1$.

Finally, Equation 11.4 modularizes the same impact categories according to different operational drivers in order to introduce an explicit dependency of the LCA calculation from the production management choices.

11.3.2 Simulation of supply chain trade-offs

The output of the modular LCA is used for the second stage of the model. Discrete event simulation is used as a tool that enables one to evaluate alternative production network configurations and operating procedures in a convenient way when optimization models are not practical (Bernard et al., 2011). The model is developed to compare different

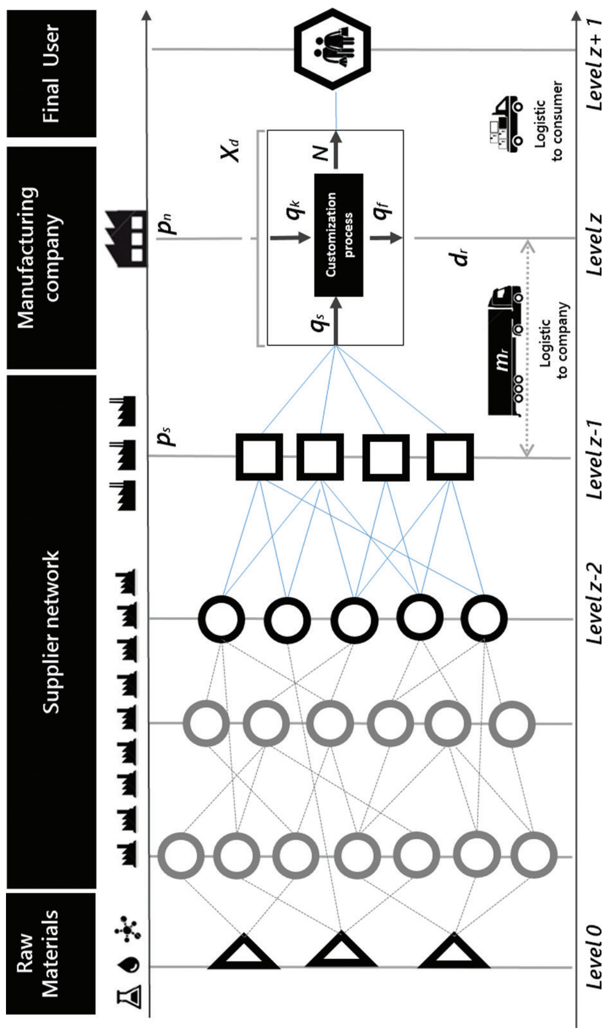

Figure 11.3 Modular representation of a product chain for a specific customized product.

scenarios with the initial configuration of the supply chain model. This part of the model gives companies the ability to create different configuration scenarios and to make what-if analyses to evaluate the trade-offs due to customization between different performance dimensions that are otherwise difficult to compare, such as delivery time and sustainability. For example, considering different customization policies, the need to shorten the delivery times to each customer can increase the number of deliveries, therefore increasing pollution. The model studies how to optimize the number of deliveries in the upstream supply chain without compromising delivery times to customers and without compromising sustainability. The model also evaluates the impact of applying different aggregations of orders to suppliers as a way to reduce their lead time and environmental impact.

The modeling of supply networks is often used as a way to check the balance of inventory, especially to compare standard production methods with just-in-time approaches. In the literature, three different approaches can be found: organizational, analytical, and simulation (Zhang et al., 2011). The first one relies on process modeling based on systems theory; however, the models developed with this approach are not dynamic and they do not take into account the system's behavior through time. The second one relies on mathematical formalization of the supply chains. These models, however, require approximations, usually restrictive, that can also be limited for considering time.

Simulation refers to a broad collection of methods and applications to mimic the behavior of real systems. Simulation models enable one to evaluate alternative system designs and operating procedures in a convenient way when the optimization of models is not practical due to the dimensions of the problem in terms of complexity. Moreover, simulation as support when testing alternatives on a real production system is usually too expensive and time consuming.

The model created for the specific case of comparing different customization strategies is based on the following starting points:

- The supply chain is based on a hierarchical relationship with the focal company: suppliers deliver to the company their materials and components on specific requests.
- Production orders are pulled by the customer orders; therefore, a make-to-order strategy is applied.
- It is assumed that there is one warehouse where all the materials and components are sent by the suppliers and are ready to be used according to the customer orders.
- Customer orders are received by the focal company and dispatched to suppliers with a fixed date policy and taking into consideration minimal safety stock.

- The customer orders are queued according to the request date from the customer with a first-in/first-out strategy.
- The performance of the suppliers is used to evaluate the overall performance of the supply network and is based on delivery time, quality (scraps), flexibility, and so on. For each of these indicators, the variance is also taken into consideration based on the real performance collected from the enterprise resource planning (ERP) of the focal company. AU: Please verify meaning inserted for ERP.
- Contractors are also part of the network structure—that is, companies working in parallel with the focal company when there is a capacity problem.
- The environmental profile is assigned to the three phases identified in the application of the modular LCA: suppliers, transports, and production at the focal company/contractors.

This model is modular and can be used and customized for different companies according to their specific data. Suppliers can be added according to the dimensions of the specific network and the performance adapted to the needs of the specific case.

11.3.2.1 Formulation of the model

The simulation allows one to verify the performance of different scenarios for each defined network configuration to analyze the effect of improving performance in the case of traditional or personalized products, and also considering the possibility of changing the number of suppliers and considering how much the overall performance will change when the performance of suppliers is improved.

Defining supplier i (where $i = 1, \ldots, n$) and order j (where $j = 1, \ldots, M$), the performance of each supplier is evaluated based on the following indicators:

- $T(i)$ is the delivery time of the supplier (i), evaluated as the average time to deliver an order. This performance is particularly relevant in customization because of the necessity of providing the customized product to customers in a short time, meaning high flexibility.
- $Q(i)$ is the quality of the supplier (i), evaluated as the average percentage of defective pieces in each delivered order. This performance is particularly relevant in the customization context because defective pieces are hardly tolerated by consumers willing to pay an even higher premium price for customized products; defective products create delays in delivery due to the required rework.

For what concerns the production orders that the focal company assigns to suppliers, their demand occurrence follows a normal distribution $N(\mu,\sigma)$, where μ is the mean of demand and σ is the standard deviation.

The values of μ and σ depend on the type of order (small or large), and σ in small orders is on average higher than in large orders, representing the high variability of the small orders.

The simulation is replicated to create different supply chain configurations. Then, each configuration is evaluated based on the following supply chain performance indicators:

- *Order lead time* (OLT) is the time from receipt of the order from the customer (i.e., the focal company's retailer) that starts the supply chain production process to the delivery of the product to the customer (that is, the end of the supply chain process).
- *Inventory volume* (IV) is the volume of the inventories of components that are transferred from suppliers and used at the product factory.

The creation of comparative supply chain configuration scenarios (i.e., scenarios 1, 2, etc.) is based on the variation of the suppliers' performance starting from scenario 0. In the simulation model, the production costs are not considered because it is assumed that they are not a discriminant in the choice of customization since it is demonstrated that customers are willing to pay a premium price for customized products (Alptkinoğlu and Corbett, 2008). Table 11.1 shows the to-be supply network configuration scenarios created with the simulation.

AU: Please provide full details of " Alptkinoğlu and Corbett" reference for inclusion in reference list.

11.3.3 Manufacturing scenarios

The definition of different manufacturing scenarios allows one to directly assess the environmental implications of customization policies. This means identifying recurring customization in industry practices, the degree of variability of the product, and the degree of variability in the related supply chain.

The customization scenarios aim to fix the driver variance for a certain product batch in the presence of a progressive increase in the product variance toward the final consumer. Table 11.1 reports the general assumptions made in mass production and mass customization.

11.3.3.1 Customization drivers

Customization strategies can vary according to the combined variations of technical, market, and organizational drivers. The following list reports the relevant drivers according to previous literature studies and to an analysis of several companies dealing with customization.

11.3.3.1.1 Operational drivers

- *Number of models within the same production batch*: Starting from a specific type of product, the number of models available can vary per

AU: Should the example of shoes be introduced as '...a specific type of product (e.g., shoes),...'?

Table 11.1 Manufacturing scenarios

Manufacturing scenarios	Description	Design changes	Supply chain changes
Mass production (current situation)	Supply matches a certain quantity with a minimal flexibility within a year. The modeling of material supply requires an average load per travel.	The bill of materials is fixed and design changes are limited to standard sizes and color changes.	Suppliers are located in various countries (according to the current location of the real case) according to cost and quality parameters.
Mass customization	Production follows the style preferences of the customer within a certain degree of freedom in the choice. This higher grade of selection includes a variability in design features, ergonomic features, material features, and aesthetical features.	The bill of materials can change in terms of component size and component type. The number of materials for the components and the number of suppliers increase by allowing the customer to change the material type within certain components for aesthetical, technical, or ergonomic reasons.	Accessories and components can be supplied in a local network (average distance from focal company is limited to a certain mileage), while suppliers of raw materials are kept unchanged. Possible variations of stored stock, extra consumption, and waste and transport depend on the consumer order sequence.

thousand of shoes produced. The change involves a limited improvement of ergonomic features and variations in the type of material for product components (in the case of shoes, it can be an increase in the types of leather for the upper and variations to the outer sole). The more extensively the customization is applied, the more the bill of materials of the pattern, while maintaining a consistency in terms of the components has a variance related to each component.

- *Processing materials and scrap rate*: The increase in the variability of the final product can affect the efficiency of the traditional manufacturing process. In particular, the requirement of material per pair product should include the gross material requirement. As an example, in comparison with mass production, customization can increase waste production with the concurrent manufacturing of different shapes for the upper within the same production batch.
- *Defectiveness rate*: Product defects depend heavily on technological and managerial processes that exist within a single company. Although it is difficult to quantify the change in defectiveness levels with the product variability, it is possible to assume that such defectiveness contributes to the increased complexity of manufacturing options. Defective products can affect environmental impact due the additional resource consumption for a single product and with the increased waste contribution.

AU: The sentence beginning "Although it is difficult to quantify" has changed. Please check the meaning.

- *Transportation*: The increase in the number of deliveries for a manufactured product seems to depend on supply chain management and the size of the production batches. In general, an increase in material types from different suppliers can imply a decrease in transport efficiency and in the load optimization. Such an effect can be registered both at the factory gate (more limited supplies) and in the output to consumer distribution (smaller lots at the points of sale).
- *Auxiliary material consumption*: The consumption of materials and auxiliary resources (consumables not integrated into the final product) in general has limited dependence on the variability of the product. In fact, the consumption of auxiliary materials depends on an increase in the variety of the product only within a limited amount. Instead, the technology for the production process significantly infers the consumption and emissions for each type of model. However, the growing complexity of the production processes may entail a limited increase in these consumptions.

11.3.3.1.2 Economical drivers

- *Unsold items*: Unsold items depend on the failure to predict the market demand. Despite the economic and environmental damage related to overproduction, the price elasticity of the demand for goods could reset the stocks of unsold items. In the case of customization, it is possible to assume that an increase in choice for consumers can better satisfy demand and reduce the unsold items.

- *Average product life cycle*: Some economic studies (Brodie et al., 2013) suggest that increased demand satisfaction has a limiting effect on the replacement of an asset. There is a lack of empirical links between the increasing customization of a product and the reduction of its replacement. However, it is possible to assume (within the further assumption that the satisfaction remains the same during the product use) that customized products fit better with customer needs and may increase their time of use, reducing new consumption in a certain period.
- *Order size from selling points*: Increasing market segmentation and increasing customization of products may increase the frequency of supplies to retailers, shops, and multistores. There is no reason to keep high stocks of customized items, and this can in fact be risky due to fluctuations in demand.
- *Time to service*: In a scenario of stable technologies, a lack of optimization within the product chain is highly dependent on the required time to service and the demand trend. Segmented markets with high variability may in fact require rapid production organization, with implications for the demand of related resources and environmental emissions.

11.3.3.1.3 Organizational drivers

- *Make-to-order supply chain*: A chain of suppliers that is organized according to the lean *make-to-order* paradigm with a reduced stock at the final assembler and a frequent supply depending on the customized product demand. This chain type requires efficient organization and a restrained time to market. Transportation can remain frequent and nonoptimal even if the assembler and suppliers are synchronized.

AU: The text "Transportation can remain frequent and nonoptimal" has changed. Please check the meaning.

- *Factory flexibility*: A flexible factory is able to meet a variable demand for customized products and a proper time to market. In order to perform such operations, the factory includes many production departments and an adequate internal materials stock.

11.4 Sustainability assessment for a customization case in a fashion company

11.4.1 Application of modular LCA

The application of a modular LCA to a footwear case enabled a comparative assessment of environmental burdens due to customization policies in a fashion company. The LCA involved a cradle-to-gate perspective on the footwear company, and the analysis took into account the product supply chain from raw materials acquisition up to product manufacturing and industrial waste disposal. The product's use and its dismissal were not included in the model. The modeling of the factory waste also included the waste treatment processes after the initial deposit. The analysis did not take into account the waste flows sent for economic recovery (e.g., material recycling, energy recovery, and composting). In this case, system boundaries were limited up to the facility gate where the recycling or recovery processes take place (i.e., transportation to the facility was included).

1. In the first stage, a classical LCA assessed the common recurrent flows for an Italian footwear company. The combination of such recurrent flows provided the total environmental profile for the factory in the reference period. Such impact results from the combination of the industry flows (e.g., the average energy used for each shoe pair) and the processing materials (e.g., the specific content of material per footwear type).
2. The use of data from international databases (e.g., Ecoinvent and Gabi) supported the LCA model, particularly for elementary flows. The formalization of environmental impact through impact categories is compliant with the CML 2011 standard and EPD system. The impact categories used to assess inventory flows were global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and photochemical ozone creation potential (POCP).
3. In the second stage, the modular LCA assessed the environmental impact variance due to the customization of a production batch under specific conditions. A number of company drivers address the variance assessment. In terms of technology options, we assumed that the production of customized footwear required the same resources as the current technologies.

AU: "CML 2011 standard and EPD" – do these abbreviations require definitions?

11.4.2 Life cycle inventory for the case study

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The methodology of data collection, compliant with the modular approach, allowed the acquisition of data sheets and inventory data from the examined company. At the factory level, the data accounts for mass and energy recurrent flows for an average yearly production of 477,569 footwear pairs.

Specific energy supply configurations referred to the energy mix of the utility serving the company (e.g., kWh supplied by a specific utility). In addition, the modeling of waste treatments complies with the European

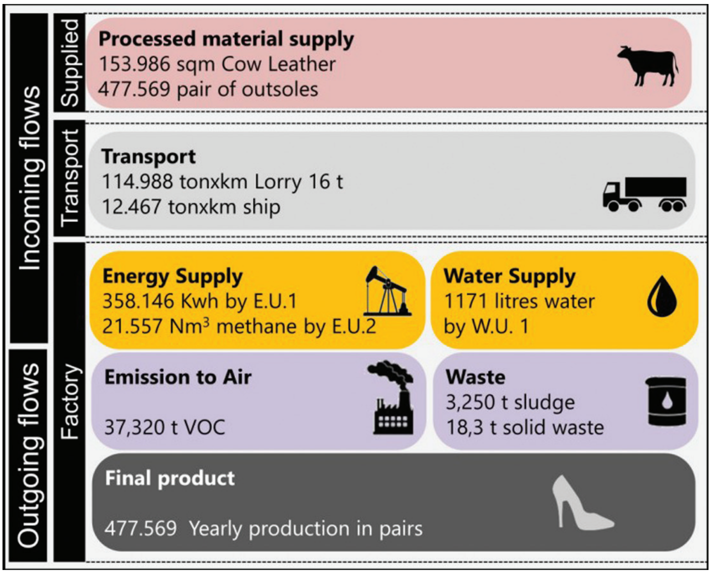

Figure 11.4 Inventory data for the definition of in- and outgoing flows.

Waste Catalogue (EWC) for industrial waste (e.g., recycled paint and varnish containing organic solvents).

The data inventory for different footwear models allowed the identification of the general impact for average footwear (Figure 11.4). Supply scenarios integrated the number of deliveries within a year, the distance between suppliers and factory, the means of transport, and the load capacity for each supply type. The stages from resource extraction up to the creation of process materials involve suppliers from large distances. For example, the production of leather requires breeding outside Europe, transport to European tanneries, and then the manufacturing of the materials. The stages from the acquisition of process materials to shoe manufacturing involve manufacturing at local levels, so the producers of components and the footwear manufacturing company are placed in a local district over 100 km. We lastly assume that the final footwear consumer stays in his or her local area (less than 200 km) (Figure 11.5).

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AU: Please verify location of Figure 11.5 cross reference

Different drivers are considered according to Equation 11.4 in order to better define the scenarios to be analyzed (Figure 11.6).

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A description of the product's physical features, the supply chain configuration, and the manufacturing features are reported in Table 11.2. The selection of these drivers defines a basic scenario in which each operational driver has a base value.

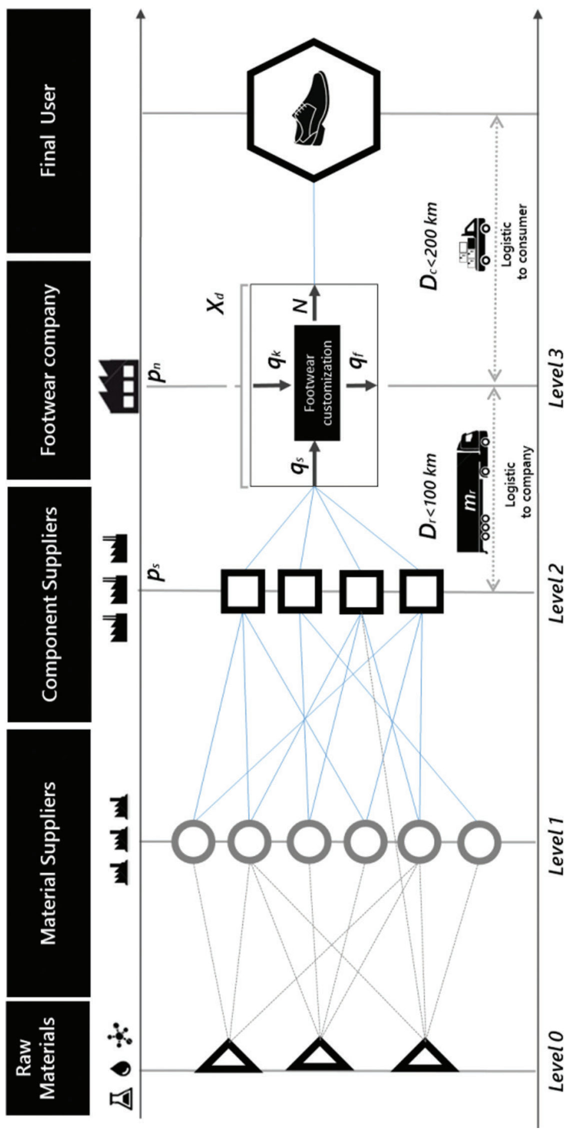

Figure 11.5 Model application to the study case.

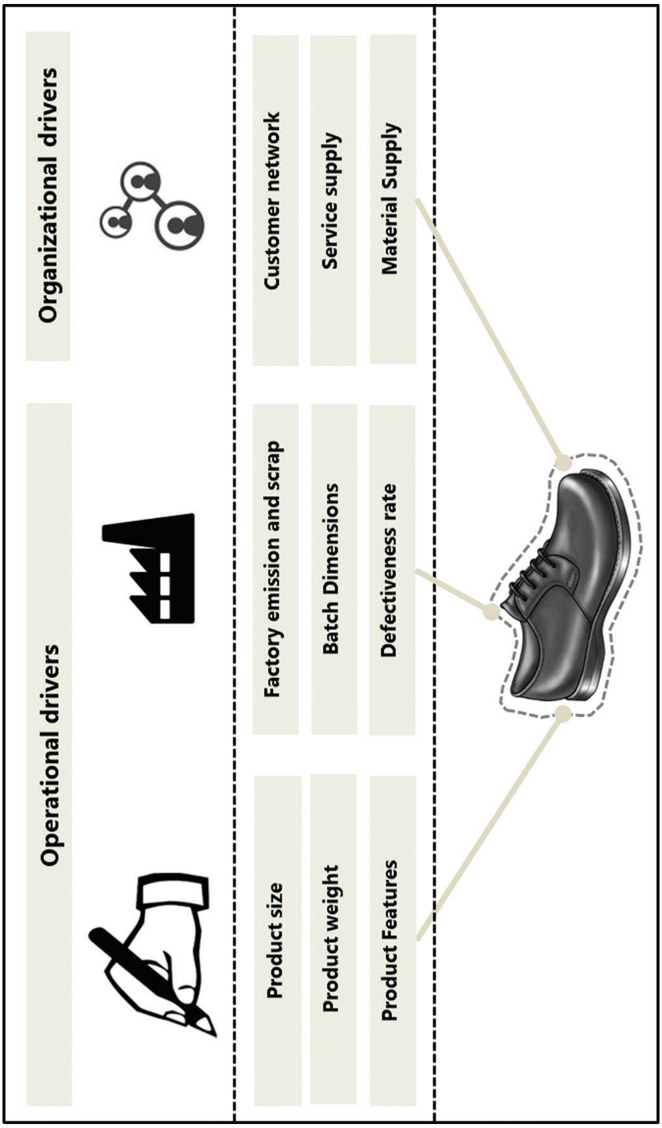

Figure 11.6 Operational drivers for the product customization.

Table 11.2 Product features

Product features	Sole	The sole is composed of ethylene-vinyl acetate and has a weight of 520 g
	Upper	The upper is composed of leather and has a total area of 1.5 m²/pair
	Material composition	Leather upper, polyurethane sole, other materials—polyester, nylon 6, elastane, spandex, conventional cotton, rayon viscose, ethylene-vinyl acetate
	Pair weight	920 g

11.4.3 Environmental impact due to customization activities

In the assumptions, the production batch remains constant (10,000 pairs), while changes in the product design are introduced within the same batch. It is assumed that each driver varies according to a range that has been defined for this work, in agreement with the literature data and empirical evidence. Each driver varied as reported in Table 11.3 and multiple impacts were analyzed to understand how the positive and negative influence of different drivers can impact the overall environmental performance.

In particular, the following environmental indicators are evaluated:

- Global warming potential (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question with the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval: for example, 100 years (GWP_{100}). GWP is expressed as a kilogram of carbon dioxide equivalents (whose GWP is standardized to 1).
- Ozone depletion potential (ODP) describes the decline in the total amount of ozone in the earth's stratosphere. ODP is expressed as the sum of ozone-depleting potential in kilogram CFC-11 equivalents (e.g., over a period of 20 years).
- Acidification potential (AP) measures acid gases that are released into the air or resulting from the reaction of the nonacid components of the emissions. The acidification potential is expressed in kilogram sulfur dioxide equivalents.
- Photochemical ozone creation potential (POCP) measures the emissions of gases that contribute to the creation of ground-level ozone. The POCP is expressed in kilogram ethene equivalents.
- Eutrophication potential (EP) measures the ecosystem's response to the addition of artificial or natural nutrients, mainly phosphates,

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AU: "sulfur dioxide" – please confirm this change is correct.

Table 11.3 Description of customization drivers and the related variance range

Driver		Description	Initial value	Maximum value
E_1	Scrap rate	The scrap rate can vary according to the efficiency of the cutting process for the upper. Such efficiency can be reduced by the alternation of different models within the same factory. A single supply could be oversized with respect to the batch size. The base value is based on "Waste generated in the leather products industry," UNIDO, 2000.	20% with respect to the bill of material values	60% with respect to the bill of material values
E_2	Transports	Transport depends on the number of deliveries to the factory, the distance between producer and suppliers, and freight load factors. According to the case study, the components supplier remains in an area with a radius of 50 km. Then the supply numbers increase. In the base scenario, an average truck type performs the supply in a single trip for the whole batch (9200 kg).	50 km	1000 km
E_3	Defectiveness rate	In the case study, the defectiveness rate can increase with the manufacturing complexity. Each defective pair requires a new production to maintain the batch dimensions. In the base scenario (mass production), the defectiveness amounts to 10 pairs per 10,000 shoe pairs.	0.1% with respect to the batch size	10% with respect to the batch size
E_4	Life cycle extension	This driver introduces a positive effect. Life cycle extension reduces product replacement that creates a minor provision of further resources from the eco-sphere in a certain period time. According to assumptions, the shoe pair can last more than 2 years while its effective average use amounts to 2 years.	2 years' duration (expected use phase)	3 years' duration
E_5	Material variance	The overall batch size is 10,000 pairs. The uppers of the shoe are made of different materials within the same production batch and for the same model. Every time a new material is added, the batch is split into smaller sub-batches. For example, two material types means that 5000 pairs are produced with one material and another 5000 pairs are produced with the other material type; three material types means 3.333 pairs per material type, and so on.	One material type for the upper (leather)	22 material types for the upper (5 leather types and 17 synthetic types)

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through detergents, fertilizers, or sewage, to an aquatic system. The emission of substances to water contributing to oxygen depletion is then expressed as kilogram phosphate equivalents.

AU: "phosphate" – please confirm this change is correct.

Appendices 11.1 through 11.5 report, respectively, the environmental impact due to customization activities for the five environmental indicators, GWP_{100}, AP, EP, ODP, and POCP.

It is important to emphasize that the results were calculated under the assumption that the technology framework remains the same, assuming that an increase in the level of customization is linked to an increase of the product model variability.

In the charts in the annexes, the variations of all the operational drivers mentioned in Table 11.3 (life cycle extension, scraps, defectiveness, transport, material variance) are normalized to a scale 1–100 to make them comparable. The starting situation is represented by a blue bar and all the bars above it represent the cases when the variations of the five drivers are such that they cause an increase in the environmental impact, while the bars below it represent a decrease in the environmental impact.

The results for the specific case study suggest the following conclusions:

- The customization process can have both positive and negative environmental impacts, and when it is linked to an increase in the possibility of using new materials, these may in fact include more eco-efficient than traditional materials and thus reduce the environmental impact.
- The most significant drivers to control the environmental impact are the choice of material type, the rate of defective parts, and the scrap rate.
- The positive effect on the environmental impact brought about by the life cycle extension of the use phase of the product, avoiding the use of new resources, balances increases in other drivers. Similarly, a more informed consumer choice on the test material could affect the impact on the final product.
- Impact categories are affected differently by the product variance; in the analyzed case, AP and ODP indicators doubled their impact according to the change of the operational parameters.
- The allocation rules can also significantly affect the background impacts. Standardization plays a role in determining the best supplier options for foreground sectors. A clear alignment between allocation rules and system boundary selections with respect to background suppliers (material producers) seems necessary in order to reduce the potentially high variability in LCA results.

11.4.4 Results of the simulation of customization scenarios

The simulation was based on the data collected from the ERP of the company and on the results of the modular LCA. Preliminary analysis of the data extracted from the ERP shows that the suppliers of the shoe company are asked to produce both large and small orders according to the needs of the company, with a wide range of order dimensions both in terms of the number of rows, the number of pieces per row, and the number of different items. According to the order dimensions, suppliers have different performances in terms of delivery time, product quality, and so on (see an example in Table 11.4). Before applying the simulation model, a Pareto analysis allowed suppliers to be categorized to identify the most strategic ones in terms of the total delivered amounts. In the case study, it emerges that some supplier performances, such as average delivery time, are linked to the order dimensions, while others are independent from them, such as average scraps. These performance indicators are taken into consideration in the simulation model and are used to create the scenarios for large and small orders.

According to the defined model, the customization strategies have been applied to choose the most suitable suppliers for each scenario, and a commercial simulator (Simio) was used to compare different scenarios based on suppliers' performances. The initial scenario was based on data collected from the footwear company, and it represents a simplified model of its network where most of the suppliers are considered. The model is based on the following assumptions:

- A contractor works in parallel with the shoe producer to manufacture the orders that can't be assembled by the shoe producer due to capacity limits.
- Some product models can be produced only by the shoe producer, others only by the contractor, and others by both of them.
- In cases where a product can be processed both by the shoe producer and by the contractor, it is sent to the one with the shortest queue.
- The shoe producer manages the materials necessary for the contractor and forwards them when necessary for production.
- The warehouse and the distribution center are located at the shoe producer's site.
- The working time of the contractor includes extra time both for the delivery of materials to the contractor and for shipping the final products to the distribution center.

The advantage of producing at the contractor is given by the fact that there is the possibility to shorten the queue of the company.

Table 11.4 Notations for Equations 11.1 through 11.4

Variable	Explanation
e_{pn}	Environmental profile for the customized product (EPCP): the vectorial array of data representing environmental impact of the production of one customized product p_n by a specific company.
EP_{Company}	Environmental contribution to the environmental profile of the product p_n by the company internal processes. It represents the environmental impact due to consumption and emission of company activities.
EP_{Supply}	Environmental contribution to the environmental profile of the product p_n by the company supply. It represents the cradle-to-gate environmental impact of supplied items for the production of a reference quantity of customized products p_n in the reference period. The bill of materials of the customized product can help to list such items. The *supply* refers to a specific level (i.e., the direct supply to the company).
$m(p_n)$	Weight (or alternatively the value) of the customized product p_n in the reference period.
M	Total weight (or alternatively the value) of the total production of the company in the reference period.
N	Total number of the total customized products p_n manufactured by the company in the reference period.
u_i	Vectorial array representing the environmental impact for an incoming unitary flow of energy/mass. The inventoried mass and flows are *not* included in the final product p_n. This vectorial array refers to a homogenous flow type both in terms of physical features (e.g., the same energy input type) and in terms of product chain features (e.g., the same supplier).
u_j	Vectorial array representing the environmental impact of an outgoing unit of energy/mass flow type. The inventoried mass and flows are wastes changing with the kind of production (p_n). This vectorial array refers to a homogeneous flow type both in terms of physical features (e.g., the same waste type) and in terms of product chain features (e.g., the same dismissal procedure).
q_k	Inventoried quantity for a specific incoming flow type.
q_f	Inventoried quantity for a specific outgoing flow type.
I	Total number of incoming flow types.
J	Total number of output flow types.
K	Number of total supplies for the incoming auxiliary flows *i* by the examined company in the reference period.
F	Number of total disposals for the outgoing flows *j* from the examined company in the reference period.

(*Continued*)

Table 11.4 (Continued) Notations for Equations 11.1 through 11.4

Variable	Explanation
e_{ps}	Environmental profile for the supplied items (EPSI): a vectorial array of data representing the environmental impact of the supplied item p_s that composes the final customized product p_n.
S	Total number of supplied items for the production of the customized product p_n.
q_s	Quantity of supplied items p_s that are required for a single unit of the customized product p_n.
u_t	Vectorial array of the environmental impact of a specific transport type t. The vector is assessed for 1 ton*km and for a set of predetermined impact categories.
T	Total number of transport types.
l	Load factor for a single round trip.
m	Mass of the supplied items, to or from the company, that is transported by the transport type t.
d	Distance covered by the transport t in a round trip.
R	Total number of round trips between the suppliers and the company for the production of the product p_n.
D	Number of customization drivers changing during the customization process.
X	Value of the customization driver in a specific manufacturing scenario c (e.g., the quantity of a specific waste).
u_s	Vectorial array representing the environmental impact of a unit of a specific operational driver that changes during the customization process.
EP_{tare}	Total contribution to the environmental profile of the product p_n due to operational drivers that remain unchanged during the customization process.
p_s	Items and services provided from specific suppliers at a specific tier level.
p_n	Customized product manufactured in the examined company.

The application of the modular LCA in the previous section showed that out of the three identified macrocategories (supplying process, transportation, production), the supplying process has a large impact on the overall sustainability of the network, and for this reason the scenarios are built mainly to evaluate how their performance can impact on the sustainability—in particular, considering the most important environmental indicator, the GWP.

As was described in the previous section, the scenarios defined in the LCA are used to link the level of customization (in terms of the number of product variations) with drivers such as transportation, scraps, defectiveness, and so on. The model is based on the same type of raw material (leather) being provided by the same suppliers or by similar suppliers to evaluate the environmental impact of their operative performance, besides the environmental impact of new materials. Therefore, starting from the standard production scenario, the other scenarios are analyzed according to possible changes in the operative performances of the suppliers, given the materials they can provide. A set of different what-if scenarios based on variations in the suppliers' performances has been defined in order to evaluate how changes in supplier performance can impact overall supply chain performance. In particular, it has been analyzed how improvements in their delivery time (from 10% to 35% of suppliers' lead time) and in product quality (from 10% to 35% in scraps) can affect the overall performance of the supply chain. Based on the data collected from the company and the established model, the performance of the supply network is dynamically evaluated, considering the value of the initial inventory, the average inventory during the analyzed period, and the average and maximum lead times to fulfill customers' orders (Table 11.5).

Preliminary results show that variations in the suppliers' lead times have a different impact according to the applied level of customization (i.e., the number of product variants). For simplicity, Figure 11.7 does not show the details of all the cases from 1 to 20 product variants but considers only

Table 11.5 Simulation scenarios

Description of the scenarios		Mass production	Product variation 2	Product variation 3	…	Production variation 20
SQ(i) = Scenarios with improvement in supplier quality (scraps)						
SQ1	−10%					
SQ2	−15%					
SQ3	−20%					
SQ4	−25%					
SQ5	−30%					
SQ6	−35%					
SL(i) = Improvement in supplier lead time						
SL1	−10%					
SL2	−15%					
SL3	−20%					
SL4	−25%					
SL5	−30%					
SL3	−35%					

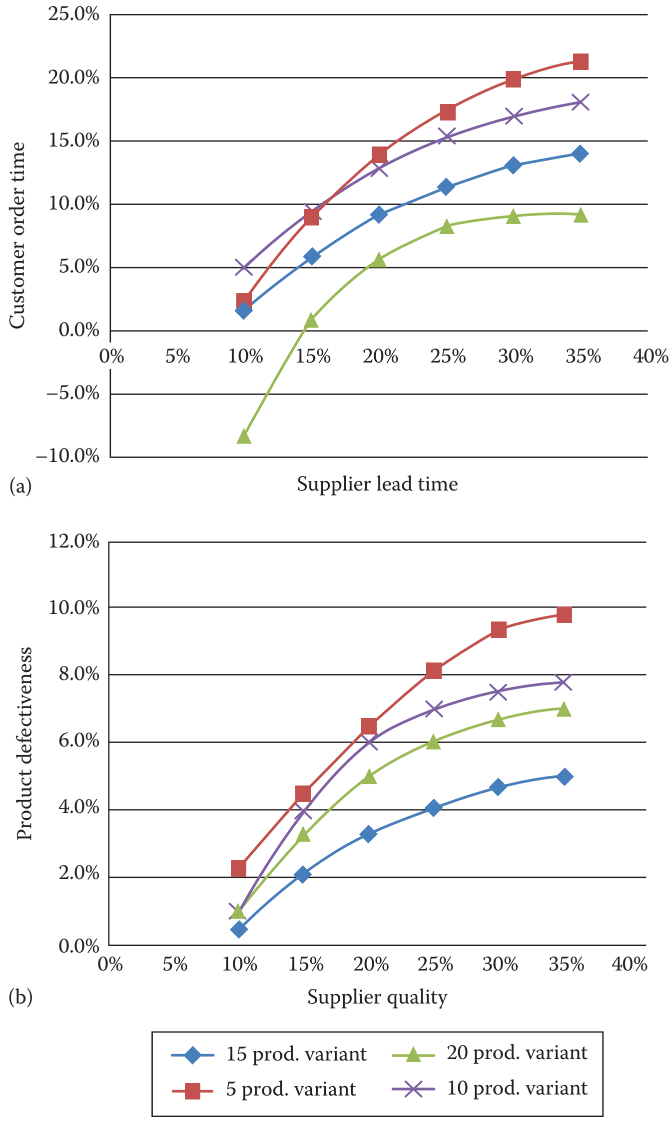

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Figure 11.7 Impact of improvement in suppliers' performance.

four cases of increasing customization, from 5 to 10 to 15 and 20 product variants. Figure 11.7a shows how an improvement in supplier lead time performance can bring about an improvement in the customer order time, which is more than the improvement caused by supplier quality in the product defectiveness represented in Figure 11.7b.

In fact, as for the impact of changes in products delivered by suppliers in terms of quality (less scraps), with the data of the specific company it turns out that a reduction in scraps gives a reduction in final product defectiveness. The level of scraps represents a limited share of production (5%), and for this reason the impact is more limited than in the case of lead time changes. An improvement in the scraps level of product components means less reworking and less mistakes that go from the suppliers to the final customer, and means less defectiveness during production. Generally speaking, improvements in the suppliers' performances bring different degrees of improvement to the overall supply chain performance, and many variables need to be taken into consideration. In this study, some of them have been considered and analyzed, but further studies will be necessary to complete the flow.

11.5 Conclusions and recommendations

The complexity of evaluating the environmental impact of supply chain modeling seems to require novel methodologies to properly identify the key decisional areas. In this chapter, a new approach has been presented based on the integration of LCA data with discrete simulation and has been tested in a specific case by collecting data from a footwear company and considering different customization strategies.

- The functional unit for manufacturing a product is commonly based on a single product. By adopting a factory perspective, it seems necessary since the LCI to shift the focus onto production batches rather than a single product. Such a shift could in fact include new inventory categories that represent more precisely the real hidden flows of customized production. Examples are the modeling of the distribution platform or the use pattern for a certain product. When the inventory is based on a batch, such an evaluation could include new variables more in line with mass and energy balance at the supply chain level.
- The chapter also analyzes variances due to different product chain configurations in the environmental impact, based on the simulation of multiple scenarios considering different degrees of variability of the operational drivers. In the preliminary results, it is highlighted that specific decisional areas under the control of product managers are also key drivers in environmental impact creation. Further studies in other sectors could better contextualize the environmental implications. In particular, aspects such as economies of scale, warehouse management, and the use of alternative technologies could significantly affect this analysis.

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The outcome of the model suggests that the proper implementation of customization practices could result in an environmental benefit. In general, it is possible to identify four subsequent scenarios for the implementation of sustainable customization practices (Figure 11.8).

- In the first scenario, *weak implementation*, customization focuses on limited aspects of the product such as design or some functional parameters without any framework to support consumption reduction or emissions. In this case, it becomes likely that the customized product will have a higher environmental impact.
- In the second scenario, *efficient customization*, dedicated tools can be implemented in a single factory perspective to minimize customization costs and consumption. In particular, emphasis is given to methods of effects quantification and data management from the manufacturer.
- In the third scenario, *knowledge-based customization*, personalization pushes onto multiple aspects concerning the use phase of the product and background phases so that the data concerning the whole product life cycle can be analyzed by the producer. This type of implementation makes clear the effects induced on the product chain and acts proactively to reduce these effects from a single-player perspective.
- In the fourth and final scenario, *sustainable customization*, data regarding the sustainability of the product is exchanged within the product chain with a standard protocol. The diffusion process involves the whole chain, starting from raw material producers up to the final consumer. Furthermore, distributed methods and tools for the quantification of the social and environmental effects related to the choice of customization concurrently support the product chain players (e.g., consumer, producer, material developer) at each stage. The diffusion of this type of information introduces emergent properties and feedback within the system. Such a framework, jointly with the increased decisional power of the buyer, can directly link the product's environmental profile with customization preferences.

Modeling based on simulation was used because it offers a realistic observation of supply chain behavior and allows an analysis of supply chain dynamics. It provides an observation of the behavior of the network over time, to understand the organizational decision-making process, analyze the interdependencies between the actors of the chain, and analyze the consistency between the coordination modes and the decisional policies. Moreover, simulation can be coupled with an optimization approach, to validate the relevance and the consequences of its results.

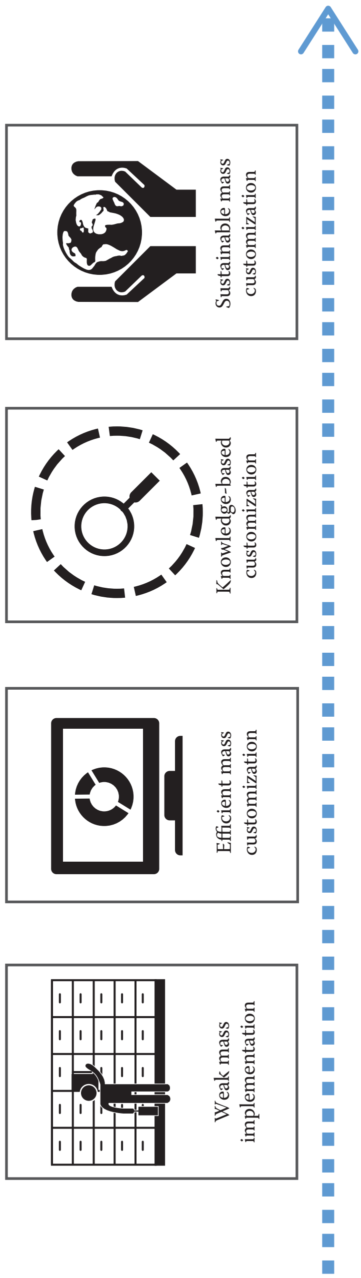

Figure 11.8 Scenarios for implementation of customization within the product chain.

Future developments in the model will be based on making available for companies reliable libraries of environmental impacts and on refining the simulation model to ease what-if analysis. Further analysis of the trade-offs between operative and sustainable performance is also necessary. From this perspective, the authors will further develop and customize the framework for other specific industrial case studies, with the definition of transversal methods and tools for sustainability performance analysis. The relationships between critical processes, improvement actions, and sustainability dimensions as well as suitable indicators will be deepened and updated.

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AU: Please provide text citation for "Armstrong et al. 2015" reference.

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AU: Please provide volume and page range for"Kohtala 2014" reference.

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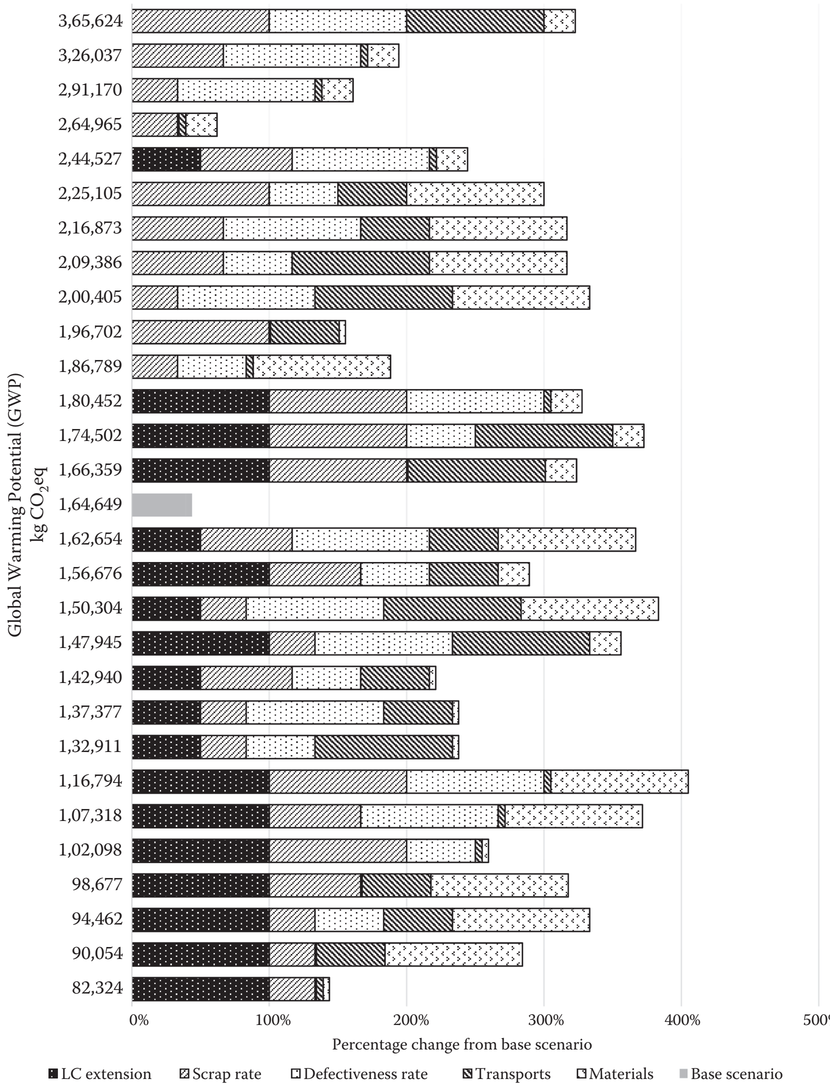
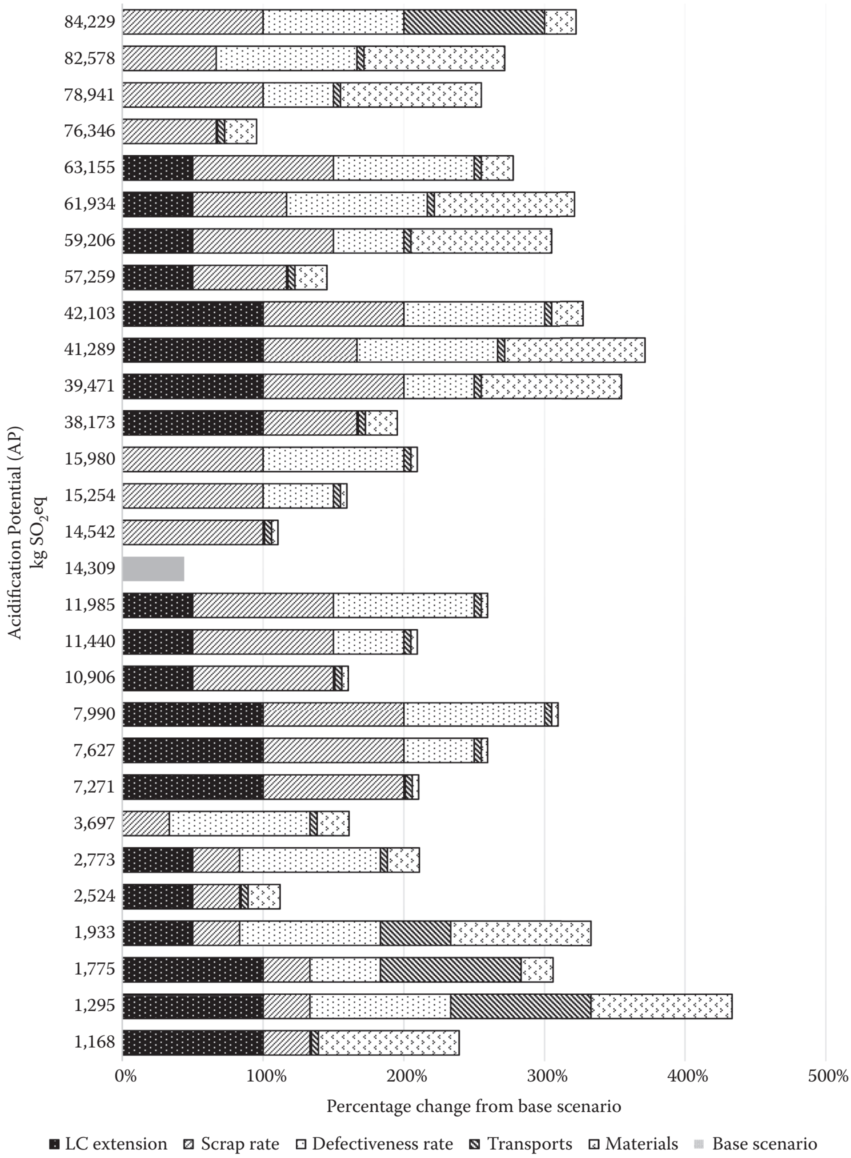
Appendix 11.1 Global warming potential (GWP_{100})

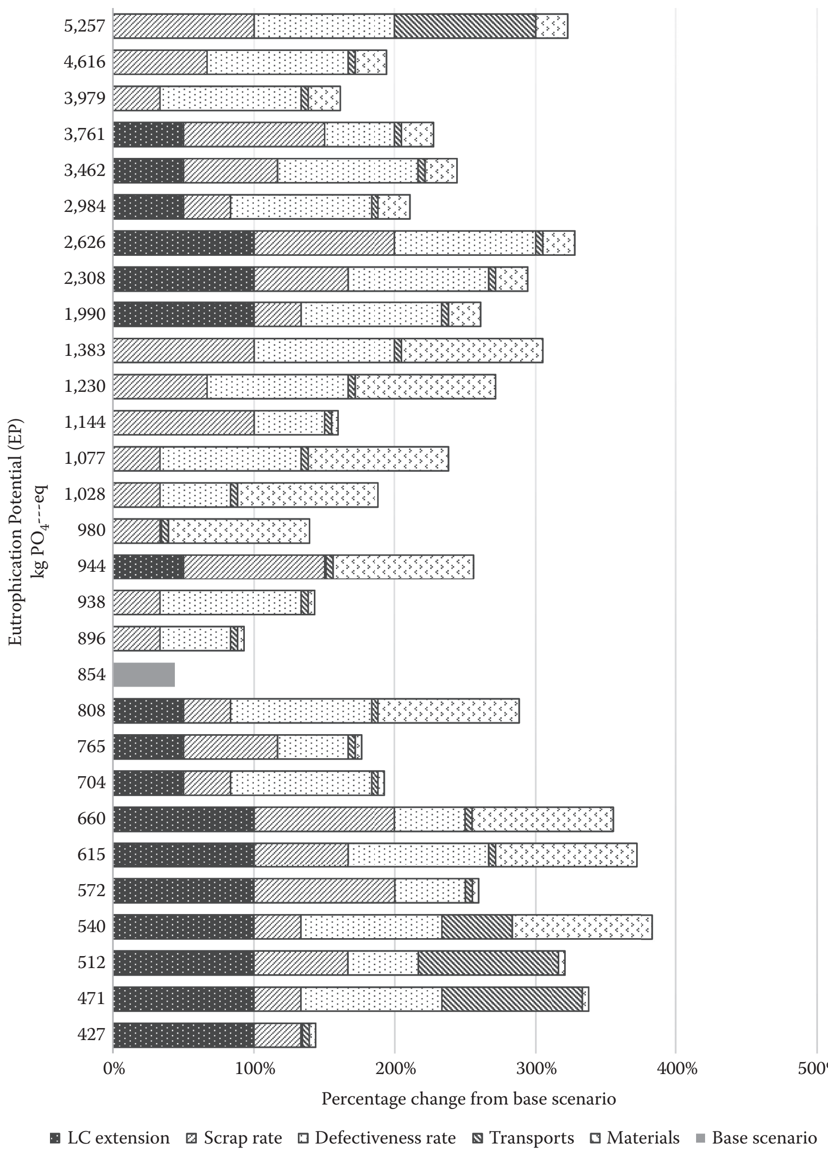
AU: Should y axis label be Global Warming Potential (GWP^{100}) as per the title of the appendix?



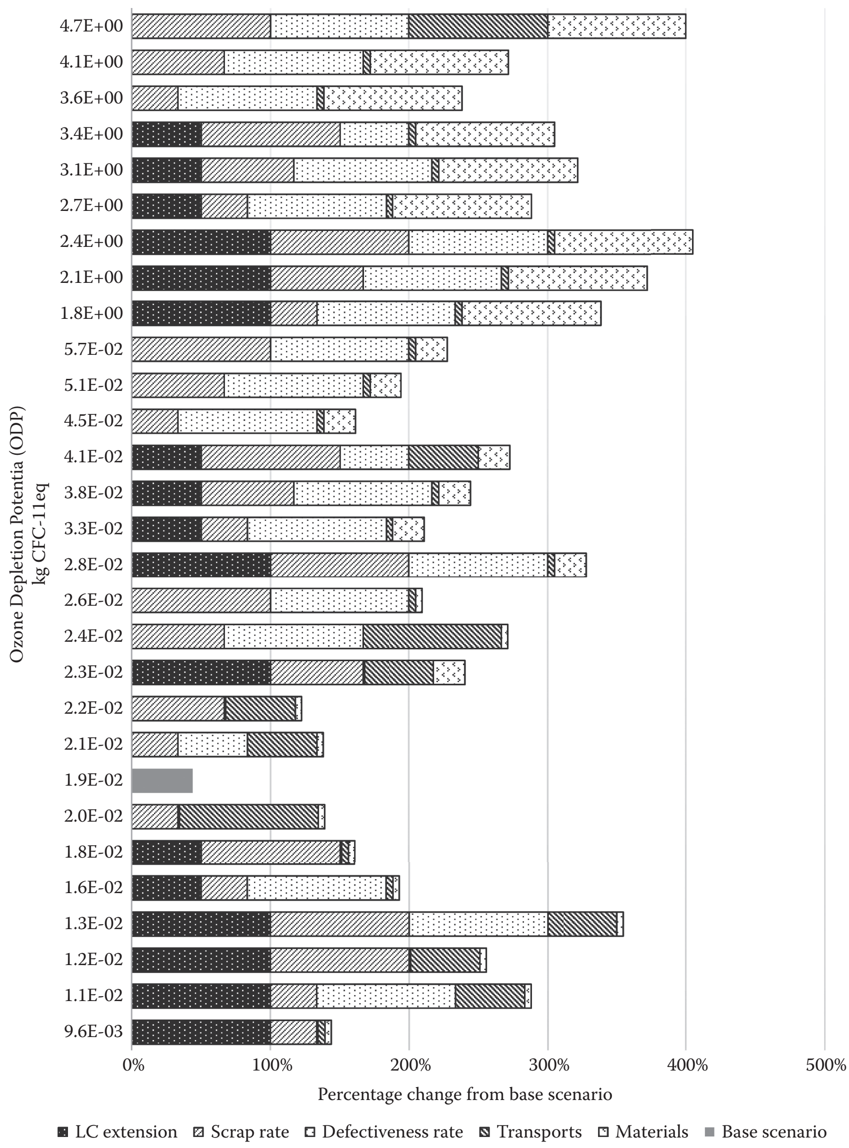
Appendix 11.2 Acidification potential (AP)



Appendix 11.3 Eutrophication potential (EP)



Appendix 11.4 Ozone depletion potential (ODP)



Appendix 11.5 Photochemical ozone creation potential (POCP)

AU: Label X axis has been changed to Photochemical ozone creation potential (POCP) to match appendix heading. Is this okay?