Claudio R. Boër · Paolo Pedrazzoli
Andrea Bettoni · Marzio Sorlini

Mass Customization and Sustainability

An Assessment Framework and Industrial Implementation

Springer

Mass Customization and Sustainability

Claudio R. Boër · Paolo Pedrazzoli
Andrea Bettoni · Marzio Sorlini

Mass Customization and Sustainability

An Assessment Framework and Industrial Implementation

Springer

Claudio R. Boër
Paolo Pedrazzoli
Andrea Bettoni
Marzio Sorlini
ICIMSI-SUPSI
Manno
Switzerland

ISBN 978-1-4471-5115-9 ISBN 978-1-4471-5116-6 (eBook)
DOI 10.1007/978-1-4471-5116-6
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2013936004

© Springer-Verlag London 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Acknowledgments

This work has been partly funded by the European Commission through S-MC-S (Sustainable Mass Customization—Mass Customization for Sustainability) project (Grant Agreement No: FoF.NMP.2010-2 260090–S-MC-S). The authors wish to acknowledge the Commission for its support. The authors also wish to acknowledge their gratitude and appreciation to all the S-MC-S project partners for their contribution during the development of various ideas and concepts presented.

The authors would like to sincerely thank Alessandro Fontana, who provided constant support, talked things over, read, wrote, offered comments and careful contributions for the entire editing process. A special thanks also goes to Andrea Barni for his punctual and prompt collaboration in Chapter V design and editing.

Contents

Chapter 1
Introduction

The society of man has evolved from agricultural to industrial centered, and presently, is living through a digital era. But even in this digital-communication centered world, products still need to be produced, to be manufactured. Indeed the service sector, without manufacturing, could not exist. Manufacturing evolution is articulated in various paradigms, as described in Table 1.1. A key trend of the latest years is certainly "mass customization," a market paradigm where the consumer is placed once again at the core of the business (as it happened for craft production). In ancient times and in different cultures, the word "business" was related to the deep sense of life. The Swedish called it "naring liv" or "food for life" and the Chinese called it "meaning of life," when using the old characters. This ancient terminology identified with "business" an action to provide something (food or meaning) for the life of the customer. Mass Customization brings this old way to see "business" back, and changes the way consumer products are designed, manufactured, delivered, and recycled.

Figure 1.1 depicts manufacturing evolution through time in relation to product variety and volumes. Manufacturing started with an artisan making a single product for a single customer, and, as such, was recognized as craft production. Manufacturing continued to evolve in the late 1800s during the Industrial Revolution, pioneering mass production at the beginning of the twentieth century. Later the market demanded more and more variety, forcing manufacturing to move toward the paradigm of mass customization: as pointed out by many scholars, Mass Customization can be defined as the capability to produce personalized goods, with near mass production costs and efficiency (Chap. 2 will later address in greater detail Mass Customization definition). It is recognized that the current and future manufacturing challenges are returning to those of the original craft production age, with the added advantages and complexities of today's advanced manufacturing systems and technologies. Therefore, one view of mass customization could be as having the ideals of craft production expressed through modern industrial technology.

Additionally, lately manufacturing is growing beyond the economic context into a social and ecological phenomenon, motivating companies to move toward sustainable manufacturing.

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_1, © Springer-Verlag London 2013

Table 1.1 Evolution of production paradigms

Paradigm	Craft production	Mass production	Flexible production	Mass customization	Sustainable production
Started	Long ago	1903	~1980	2000	2020?
Society needs	Customized products	Low-cost products	Variety of products	Customized product	Clean products
Market	Very small volumes per product, unique products	Demand > supply Steady demand	Supply > demand Smaller volume per product	Globalization Fluctuating demand	Environment
Business model	Sell-design-make-assemble	Design-make-assemble-sell	Design-make-sell-assemble	Design-sell-make-assemble	Design for environment-sell-make-assemble
Tech enabler	Know how	Interchangeable parts	Flexible production techs	Information technology	Nano/bio/material techs

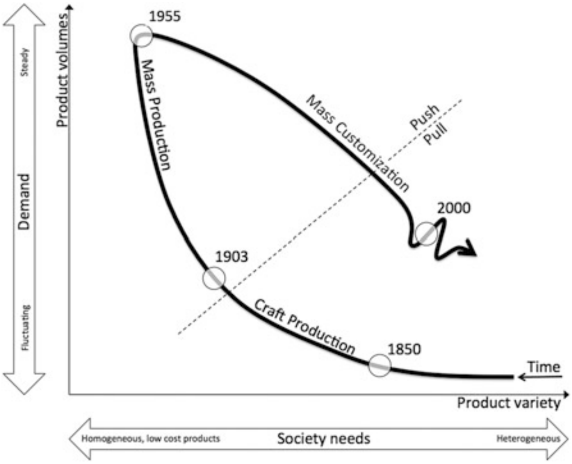


Fig. 1.1 Evolution of manufacturing

Manufacturing is, therefore, now confronted with many new "business goals" that are not only related to pure profit but also to the life and aspirations for future generations. The "company," that is the actor creating value for the consumer, has to go back to its etymological origin of the Latin word "cum + panis," or sharing the bread.

To adapt to global competitive pressures, modern industries must then develop methods and enabling technologies toward a *personalized*, *customer oriented*, and *sustainable* manufacturing. This statement is well understood by many companies, shared by policy maker at the European Commission (e.g., as per the "Factory of the Future" multi-annual roadmap), and empowered by the current and future funding programmes for industrial research (FP7 and Horizon 2020). Manufacturers are demanded to merge the need to be reactive toward customer needs and wishes (customized products), with the requisite to be proactive toward ecological and social impact (sustainable products).

This vision points out two key concepts whose impact on manufacturing is complex and interdepended: Customization and Sustainability. A key question to be addressed is whether Mass Customization can be regarded as one of the main driving forces to achieve effective Sustainability, and thus a key enabler to implement this envisioned personalized sustainable production, or a burden.

This new vision places a very strenuous challenge to the entire company organization, whose procedures and management approaches then require a thorough revision. This is certainly true for any product but in particular for shoe production, as footwear manufacturing is increasingly confronted with a progressive reduction in the size of production batches. Combined with the variability of styles, this tends to overstretch the traditional work organization and, with a demand for minimizing delivery times, manufacturing support systems do not as yet approach the levels of flexibility and quick response required for the production of mass customized products. However, since a noticeable demand for such products is becoming evident among shoe consumers, footwear companies will soon have to confront these kinds of technical challenges.

This book is meant first to provide the theoretical background and a practical implementation roadmap to comprehend and apply Mass Customization. It will then provide a comprehensive handbook to understand and measure Sustainability. Eventually we will analyse the two concepts of mass customization and sustainability side by side, to lay a meaningful context toward the definition of a framework for their actual confrontation. The last chapter will portray the current efforts in RTD in this field.

The contents can be summarized as follows.

Chapter 2. *Mass Customization theory applied to industry*—Nowadays, Mass Customization is an established production paradigm in many manufacturing contexts, with remarkable application experiences in many industries. Here we provide a shared and acknowledged definition of "Mass Customization" and we explore its instantiations itemizing triggers, historical evolution, and vocabulary. Beyond the theoretical foundations of the concept, which are the real application examples in representative industrial contexts? How can we provide evidence of successful implementations? Significant case histories are here explored and major obtained results discussed, with the goal to identify future evolution paths.

Chapter 3. *Sustainability and how to measure it*—The label "Sustainable" is today a bottom-line requirement: as a matter of fact, Sustainability has become a common basic goal for many national and international organizations including industries, governments, NGOs, and universities. However, in spite of the nearly universal recognition that Sustainability has received, companies still struggle with the full understanding of the concept and, but just secondly, with its financial viability. This chapter provides a comprehensive handbook for the practical implementation of a sustainable assessment model, from concept understanding to indexes computation formulas.

Chapter 4. *Assessment of sustainable Mass Customization*—What are the performances of a mass customized production systems as far as sustainability is concerned? Which lifecycle phases raise the higher burden to "future generations willing to meet their own needs"? By applying the developed Assessment Model in a real case of mass customized production, we will highlight the intrinsic characteristics of the considered sectors when it comes to sustainability.

Chapter 5. *The RTD contribution: Ideas and Future Trends*—Several different EU research initiatives were meant to provide solutions to the aforementioned challenges. These experiences are here presented: their main findings, key concepts, and roadmaps are pointed out, grouped, and discussed.

Chapter 6. *Mass Customization and Sustainability*—This chapter addresses the link between Mass Customization and Sustainability. We will here propose a framework for the two concepts of confrontation.

By this book, the reader will familiarize with the concept of Mass Customization in theory and practice, being then capable to evaluate industrial realities and to propose roadmaps for a viable MC implementation. He will also acquire the capability to assess a product, process, and supply-chain configuration over several sustainability indicators, which are realistically explained here with a clear guide for application. The reader will be also given hints on future trends and research ideas, to be held as inspiration for personal developments and implementation. In a nutshell, by this book, he will be able to answer to the following questions:

- What's Mass Customization and how can it be formalized?
- What's Mass Customization in practical terms?
- What's Sustainability and how can I measure it?
- What are the actual research initiatives and future trends?
- Is there a link between Mass Customization and Sustainability?

Chapter 2
Mass Customization Theory and Implementation Framework

2.1 Mass Customization Definition

The term "mass customization," abridged with MC, was anticipated by Stan Davis in the book, "Future Perfect," in 1987: "the same large number of customers can be reached as in mass markets… and simultaneously they can be treated individually as in the customized markets of pre-industrial economies" (Davis 1987). Pine in 1993 introduced an industrial perspective in the new-born concept and defined mass customization as "providing tremendous variety and individual customization, at prices comparable to standard goods and services" to enable the production of products and services "with enough variety and customization that nearly everyone finds exactly what they want" (Pine and Davis 1993).

In 2001, Tseng and Jiao provided a popular and intuitive definition: Mass customization corresponds to "the technologies and systems to deliver goods and services that meet individual customers' needs with near mass production efficiency" (Tseng and Jiao 2001).

In 2007 Pine was back again to his definition of mass customization and revised it as "the low-cost, high volume, efficient production of individually customized offerings" (Piller 2007a). To reach this efficiency requirement, a mass customization system should possess a stable although still flexible and responsive set of processes, that are capable to deliver a finite number of customization options. As a result, the costs associated with mass customization should lead to a price level similar to the mass produced product.

Finally Piller, who devoted consistent efforts in MC related research, provided his definition of mass customization, focusing on key concepts that really distinguish mass customization from similar approaches. While taking into account the previous approaches to Mass Customization concept definition, we choose to start from the work done by Frank Piller. "Mass Customization refers to customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment." (Piller

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_2, © Springer-Verlag London 2013

2004; Boër and Dulio 2007). Following Piller's argument and work, this definition can be further decomposed into four statements (Piller 2004):

2.1.1 ITEM 1: Customer Co-design

Customers are integrated into value creation by defining and configuring an individual solution. Customization is about the concretization of the end-user needs and desires into concrete product specifications. A tool is then needed: whether a paper catalog, listing variants and combinations, or a digital configuration software, the co-design is empowered by a proper mean. The footwear sector offers several examples of web-based tools meant to provide these functions: Mi-Adidas, Converse, Footjoy, Keds, Left, Morgan Miller, Nikeid, Otabo, Ryz, Vans, Preschoolians, Timberland.

2.1.2 ITEM 2: The Needs of Each Individual Customer

The co-design procedure, mentioned in ITEM 1, is an action that concretizes the customization potential, expressed by all the possible products configurations (the degree of customization offered by the manufacturer), into a single customized product. The goal is then to correctly identify the customization options and dimensions meant to satisfy the customer needs. To better express the level of customization offered, three dimensions are highlighted: fit, style, or functionality (Piller 2004, Boër and Dulio 2007) (Fig. 2.1). *Style* (*aesthetic design*) relates to modifications aiming at sensual or optical senses, i.e., selecting colors, styles, applications, cuts… Many mass customization offerings are based on the possibility to co-design the outer appearance of a product. This kind of customization is often rather easy to implement in manufacturing, demanding a late degree of postponement. *Fit and comfort* (*measurements*) is based on the fit of a product with the dimensions of the recipient, i.e., tailoring a product according to a body measurement or the dimensions of a room or other physical objects. In the case of footwear, this means to measure the two feet in 3D and extract the necessary information to choose the best fitting last or even to make the personalized one. It is the most difficult dimension to achieve in both manufacturing and customer interaction, demanding expensive and complex systems to gather the customers' dimensions exactly and transfer them into a product. *Functionality* addresses issues like selecting speed, precision, power, cushioning, output devices, interfaces, connectivity, upgradeability, or similar technical attributes of an offering. These dimensions of customization offered may be plotted on a three-branch radar graph, as shown in the picture above. By grading the three axes with a given customization scale, by then evaluating the level of personalization offered in each dimension, and by eventually connecting the resulting points, we obtain different

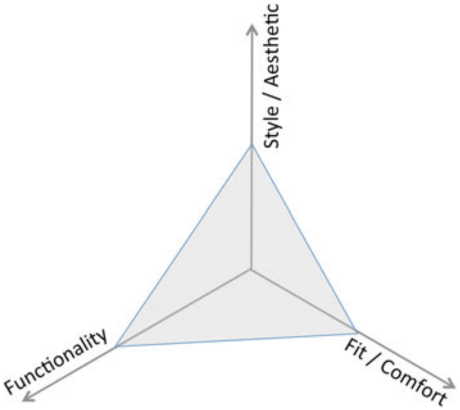


Fig. 2.1 The customization axes

triangles describing different customization scenarios. Each triangle represents the offer proposed to the customer, i.e., the degree of customization he will be able to take advantage from (Fig 2.1).

It is important to highlight that the final customer, as a single entity, differently from what happens within the co-design in ITEM-1, does not individually impact the company choices in defining the customization dimensions of the product: those options are defined eliciting the "needs of the many" by market research, surveys, and anticipation of trends.

2.1.3 ITEM 3: Stable Solution Space

The term solution space represents "the pre-existing capability and degrees of freedom built into a given manufacturer's production system" (Piller 2004). A successful mass customization system is characterized by a stable while flexible processes distributed along the whole supply network, used to deliver high variety goods, with "near mass production efficiency." This generally implies that the customization options are limited to certain product features. Customers perform co-design activities (ITEM-1) within a list of options and predefined components, that were chosen, thanks to surveys and analysis (ITEM-2), before their customization activity. Those options were defined trying to meet the needs of the individual customer, by analyzing the needs of the many. There is a strict link among (1) the "needs of the many," that define a potential solution space from the desires and point of view of the customers, (2) the "capability and degrees of freedom built into a given production system," that defines a potential solution space coping with technological and economical consideration of the manufacturer, and (3) the "company specific strategy and policies," that may limit the customization offer due to tactical considerations (this is the case of a shoe company that limits the combination of colors to given pre-accepted sets, to

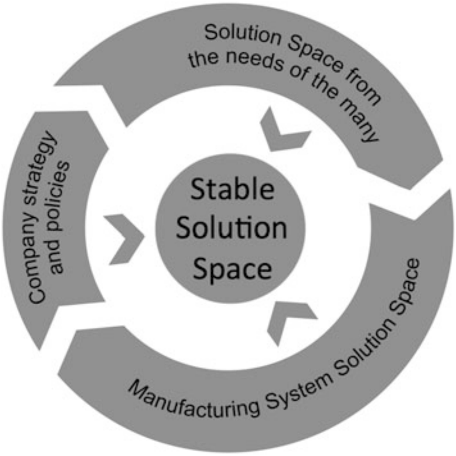


Fig. 2.2 The recursive design of the stable solution space

preserve the brand style, or do not give the possibility to move along the "aesthetic dimension," again to preserve brand name, but are eager to promote fitting). Thus the stable solution space (SSS) is the result of an interaction of those three elements (see Fig. 2.2), whose KPIs (Key Performances Indicator) may significantly differ from one another.

Once defined, the SSS represents: (1) the yet undifferentiated product blueprints (that is the sum of all the potential customization options for the MC product); (2) the capability and degrees of freedom of the production system; (3) the adequate supply chain capable to support the product variants.

Figure 2.3 shows the mapping of the SSS onto the four ITEMs of the Mass Customization definition: the SSS is defined thanks to the interaction of the desires of the customers (mapped on MC ITEM 2) and of the potential solution space coping with technological and economical consideration of the manufacturer (mapped on MC ITEM 3).

The SSS, as mentioned before, represents the potential product configurations, the production system and the supply chain meant to manufacture the final product (again Fig. 2.3). The potential product configurations are the starting points used by "customer co-design tools," ITEM-1, in order to define the specification of the final goods (e.g., the "product configurators" for the personalization available in the websites for shoe personalization aforementioned). Figure 2.3 anticipates also the relation with the MC ITEM 4, hereinafter described: the adequate price.

2.1.4 ITEM 4: Adequate Price

Mass customization practice and studies (see for example Piller 2013) show that consumers are frequently willing to pay a premium price for customization to reflect the increment of utility they gain from a product that better fits their needs

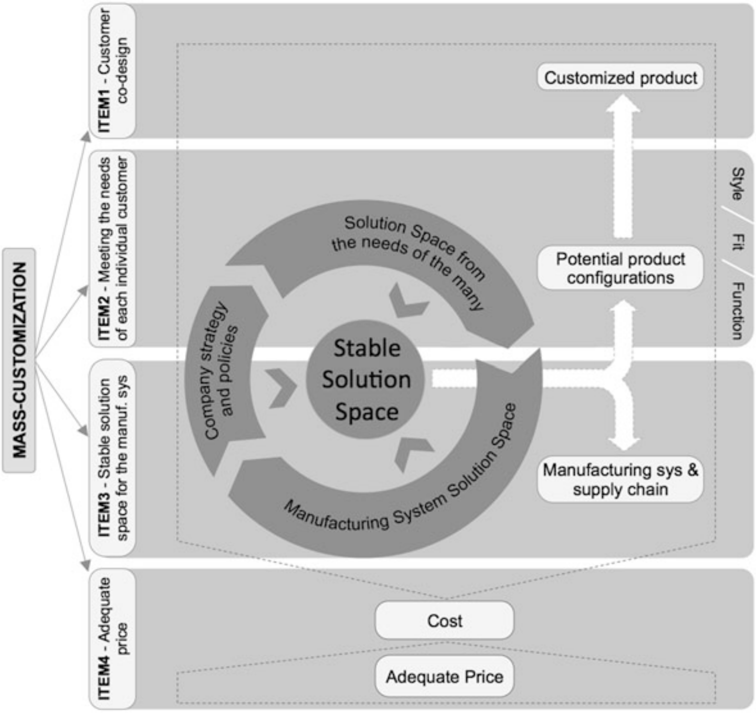


Fig. 2.3 The stable solution space mapped on the mass customization items

than the standard product. Mass customized goods are targeting the same market segment that was purchasing the standard goods before, but with adequate price increase.

The SSS is then subject to another constrain, as again shown in Fig. 2.3 by the large arrows with dotted lines. The number and type of product options, the related manufacturing system and the adequate supply chain contribute to define the cost for the final customized product. This cost must be compatible with an adequate price so that the customized product does not target a different market segment, if compared with the standard one. The EUROShoE project (Boër and Dulio 2007) demonstrated, by relevant consumer analysis, that in footwear a premium price for customized shoes of 20–40 % is acceptable… It is worth noticing that if we consider the premium price percentage, a luxury brand with a small number of products asks for a higher profit margin (per product) than a cheap brand where the overall “premium” profit is distributed on wider (also mass) volumes. This is still a debate in the MC community if a luxury brand like Ferrari, with its all personalized cars, can be taken as an example of MC or if it is more pertinent the Fiat 500, where customization is at a much lesser degree, but much closer to the “mass” concept (especially considering the low premium price asked for these, few, customizations). The same applies in the footwear sector, of course.

2.2 A Template to Jump in

This book has a predominantly applicative attitude: providing actual, practical, and intuitive tools to entrepreneurs aiming at implementing MC within their businesses is one of the main goals pursued. The template here presented (Fig. 2.4) and the following discussion and examples are meant to enable prospective (but also current) MC adopters to identify MC implementation procedures suitable for their businesses, and to qualitatively investigate and assess their approaches in comparison to others'.

In the last 15 years, many researchers have approached the MC theme from a wide spectrum of points of view (see the four research domains cited in Fogliatto et al. (2012)) and many industrial case studies have also been cited as relevant examples of MC implementation in real industrial environments. This notwithstanding, it appears to be difficult for an apprentice entrepreneur to understand the best path he can follow in order to actually implement MC within its business. Many times an entrepreneur asks: "How can I *adopt* MC within my business?" With the hereinafter-discussed methodology, this chapter aims at supporting this businessman in finding valuable answers to this question. For this reason, the point of view of this chapter is different (and probably complementary) from others' approaches in the literature. Three are the elements the proposed methodology is composed of:

1. a template with seven blocks chosen as the building elements of an MC company business environment (Fig. 2.4). A good starting point to successfully implement an MC transformation is the exploitation of a roadmap, that it is here actualized with a conceptual template that everybody can understand and that

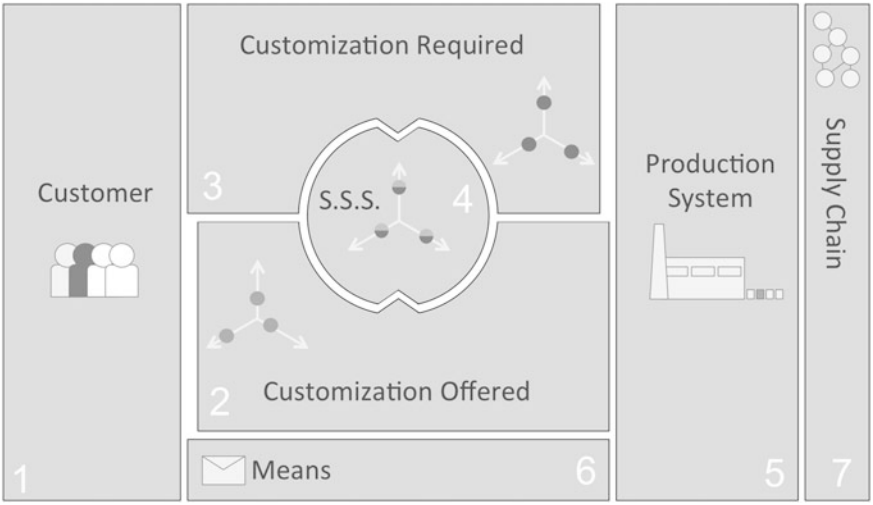


Fig. 2.4 The mass customization implementation template

facilitates discussion. In the following paragraphs we propose such a template (MCIT—Mass Customization Implementation Template), which allows to describe and to think through the MC options and implementation issues;
2. a set of questions supporting the entrepreneur in understanding the key elements to be considered for each block of the MCIT. Specific topics and challenges have to be faced for each building element while implementing Mass Customization. Answering to these will support in taking a step closer to the actual implementation of MC;
3. real-case examples providing actual answers that existing MC businesses gave to these questions.

The MCIT template is thus meant to describe different situations where any company can jump-in into the most appropriate block, to easily describe and explore different alternatives. There is not a correct starting block, or an exact time or logical sequence to walk through the blocks. Each MC implementation will have different genesis, needs, and paths: the template will support the implementer by providing inspiration and making the right questions, not to forget essential aspects. Examples taken from the literature are finally meant both to provide concrete responses and to suggest applicable implementation paths.

Block* 1—*CUSTOMER: Customers are at the core of any production paradigm, not just MC. Without customers, no production system may work for long. We have to carefully address the following questions, to pave the way for a sound MC business implementation:

What's the Target Market? This deals with the identification of a group of customers that we decide to aim toward. A well-defined target market is a key element to successful MC implementation. Different segmentation approaches may apply.

E.g., different segmentation dimensions can be taken into account in order to identify the target customers of an MC offer. Adopted elements are the same of traditional marketing approaches: age, sex, location, spending power, sector-specific categories,… It is important to notice that the relevance of the segmentation elements is usually different in traditional and MC businesses (attitude toward customization is often correlated with products contexts of application, but also with the spending power). In some cases, segmentation has allowed to define a path from pilot to large-scale MC applications. The **mi adidas** customization initiative (Seifert 2006) was structured in four sequential phases. Segmentation allowed to identify a promising market context where to test the pilot service (2001) on 300 customers from six European countries (geographical segmentation), all athletes (activity-related segmentation) interested in customizing soccer footwear (sector-specific element of segmentation). In phase 2 (late 2001), other segments were explored relaxing some of these constraints: not only athletes but any sportive customer, not only European, but also from U.S., not only soccer, but also running footwear. In phases III and IV, any kind of sport was addressed all over the world. In this case, segmentation has been thus used to approach MC gradually, starting with a test addressing the customer segment virtually more interested in product customization, then applying lessons learnt also to other segments.

Usually MC initiatives start with the goal to answer to increasingly demanding customers, asking for more customized products or for a wider product portfolio. This happened, for example, in **Andersen' Windows** (Gamble et al. 2003), a U.S.-based manufacturer of windows for the home building industry. Until the mid 80s, Andersen was a mass producer of a variety of standard windows in large batches. Increasingly demanding customers forced the company to widen its product portfolio, including new product lines, new options, and a wide set of add-ins. Andersen was driven to move toward MC in order to be able to answer to changing needs of its current market segment. Almost the same happened for **Nike id** (Mistler 2001): mi adidas allowed the German company to steal customers to Nike, which implemented its own MC strategy in order to retain market shares in existing segments. Sometimes, MC allowed to identify a different market segment, such in NIBC (Suresh 1996), the National Industrial Bicycle Company of Japan, where an MC adoption project started with the goal to answer to customers asking for customized solutions, and ended identifying a precise market segment interested in this kind of solutions, thus keeping the mass production facilities active. Characterizing a completely new market segment is also the challenge an (MC) start-up has to face. Interesting examples are **CHIP-N-DOUGH**, a cookie company in U.S. enabling its customer to place corporate logos on the cookie tins, or **ZYRRA**, a company providing women with *bras that really fit* (Tahmincioglu 2007). In both these cases, these start-up companies have had to investigate the market segment to address, almost from scratch.

What's the Expected Volume? The estimated volume of MC products sold for a future period is a key driver to assess profitability and properly design the production system.

E.g., Pondering the expected volume of the addressed market segment is fundamental for both estimating the envisaged turnover, but also to size the commensurate investments or the needed *production* capabilities. Internet-based MC initiatives such as Picaboo (2013) or LuLu (2013) have had to size their servers and adopted database software according to the amount of data to be handled.

What's the expected degree of customer satisfaction in relation with balance Price/Personalization? We have to address ITEM 4 of the MC definition. Consumers are willing to pay a premium price for customization, to reflect the increment of perceived value, and the balance of this equation must be addressed from the very beginning of the MC implementation.

E.g., MC entrepreneur has to understand the premium price a customer is willing to pay for a given degree of customization. This investigation is expected to provide valuable insights on the value perception of a given customer and to judge whether the required investments enabling this kind of customization affect the final product price less than (or, at least, equal to) the granted premium price. Many scientists investigated this topic from a micro-economics perspective, while we try to deal with this topic empirically citing a couple of examples. Christi Andersen, one of the owner of the already mentioned **Zyrra** personalized bras producer, says their target customers do not even ask the price of the custom products, and she also says that "Zyrra's intended demographic is women who are 30 or older and who have made a little money and have less patience in finding this stuff" (Verghese 2007). This highlights at least two elements: (1) customization can be worth a lot and (2) this is true just for given customers, thus it is important to accurately select the target market. Another interesting example is the widely cited **Dell** mass customization initiative. This sentence has been published on their website (Williams 2010): "In the past, we utilized a single direct configure to order model and we gave our customers a cascade of options to choose from when configuring a product specifically for their needs. This was, and still is, a great model for custom configuration where our customers value and *will pay* for this service but it has become too complex and *costly* for significant portions of consumer and some portions of our commercial businesses. As a result, we are addressing this complexity and added cost with client reinvention." This statement seems to imply that: (1) MC has a price, (2) some customers are willing to pay for this additional value, and (3) some others do not. If there's no match between your target segment price expectations and your increased costs, your MC initiative is likely to fail.

Satisfaction with involvement in design? Satisfaction is the result of a comparison between expectation and experiences. Customer satisfaction is categorized by Franke and Piller (2003), in (1) satisfaction related with the decision made, once got the product, and (2) satisfaction with the experience of getting the product, by co-designing it. We address here the second item: we have to clearly picture the customization experience we want to offer, tackling the perceived value associated with each related customization feature, and define the impact on the block 3.

E.g., Co-designing or simply letting the customer to autonomously design its own product has two roles within the MC context: on one side it is an enabler, namely the means a company can use in order to acquire its customers' requirements; on the other, it is part of the offered value: the customer is interested in buying both the product and the customization service; he's willing to pay for the design experience. While implementing an MC strategy, the entrepreneur has to accurately ponder the co-design phase considering both the customization dimensions that fit its market segment expectations and the constraints coming from its manufacturing process and supply chain. Various examples can be mentioned highlighting the need to heterogeneously grading this element. **ChemStation** (Gilmore and Pine 2000), a U.S.-based manufacturer of soap intended for industrial applications (e.g., car washes and cleaning factory floors) decided to mass customize a product that most of its competitors treat as a commodity. After analyzing each customer's needs, ChemStation custom-formulates the right mixture of soap, which goes into a standard ChemStation tank on the customer's premises. Through constant monitoring of its tanks, the company learns each customer's usage pattern and presciently delivers more soap before the customer has to ask. In this example, the co-design experience of the customer is really low: needs and expectations are gathered by the manufacturer merely analyzing its customer behavior and practices. As reported in the mentioned book, this approach "eliminates the need for customers to spend time creating or reviewing orders. They do not know which soap formulation they have, how much is in inventory, or when the soap was delivered. They only know—and care—that the soap works and is always there when they need it." **Acumin Corporation** (Wind and Rangaswamy 2001) enabled its customers to create their own specialized mix of vitamins. A tool available at their website called "SmartSelect" asked customers about their lifestyles and health and created a personalized nutritional supplement the user could modify and order. Given the complexity of the knowledge required for defining a recipe starting from physical characteristics, the company decided to create a sort of decision support system, partially embedding this knowledge. The customer was asked to express elements any customer can formalize, such as health status, sports activities, physical characteristics, just giving the final option to personalize the vitamin mix. A completely free design of the recipe would have discouraged many potential customers to use the service. **Customatix** (Piller 2008b) allowed footwear customers to design their own sneakers, choosing colors, symbols, and fabrics. The company was one of the first competitors entering the MC arena at the beginning of 2000s. Its online configurators were really powerful for that time, giving users a great amount of choices, resulting in millions of possible alternative configurations of the final product. The company then failed and "consumers not really educated in mass customization configurators" is one of the reasons mentioned by its former CEO for this failure. Here's an interesting 2002's feedback from a Customatix user (Customatix 2002): "when I checked out www.customatix.com, I was ecstatic to see that I could design my own shoes and have them shipped to my doorstep. So I went to work. I created the most obnoxious pair of tennis shoes possible, with pink and navy blue lining. You can influence the design on practically every inch of your shoe, from adding a devil on the tongue to having silver shoelaces. […] When the shoes arrived, everyone was pretty much speechless because they were so ridiculous. But they are mine, designed by me, just for me."

These examples highlight the importance of a careful investigation of customer needs both in terms of product/service envisaged characteristics and of required (and transposable) customization dimensions.

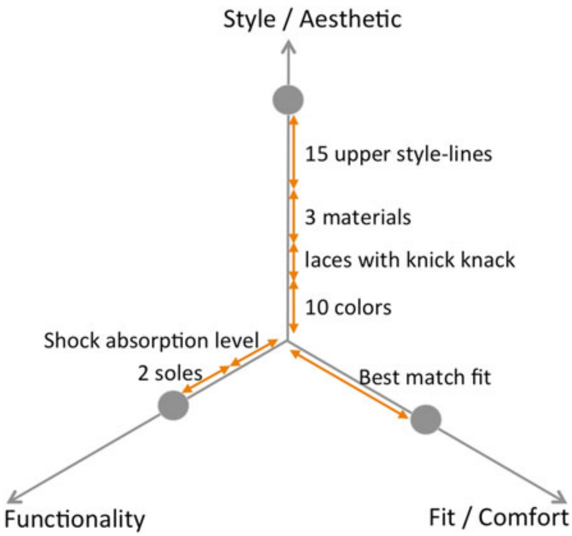
Block 2—CUSTOMIZATION OFFERED: customization refers here to the use of manufacturing technology to satisfy differences in terms of expectation between individuals.

What degree of customization can our current manufacturing system offer? How much does it cost to extend this degree? As seen in Sect. 2.1 of this chapter, we may plot on a radar graph the three dimensions of customization offered (fit-comfort, style-aesthetic, function) and by grading the three axes with a specific customization scale given by the sector we are confronting with, we can visualize an overview of what our system can offer. Within this block we create, define, and discuss the radar graph related with what we can/want to offer.

The style-aesthetics axis represents how the production system can cope with fulfilling personalization, by providing, e.g., choices of fabrics, colors, style-lines, accessories, etc. Figure 2.5 provides an example tied to the footwear sector. The final evaluation of customization offered (pictured by the position of the circle on the style/aesthetic axis) is built by adding four different options offered: number of possible colors, knick-knack applied to laces, material, and style-line of the upper. When mapping these options, we take into consideration the effort and the level of complexity from the point of view of the manufacturing system by estimating different "arrows" lengths that contribute to build up the final level of customization offered. In the example, we estimate that providing different style-lines (which impact on knifes and knitting sector of the factory) is far more complex than offering knick-knack of choice. Thus, this final estimation represents also the level of capability of the manufacturing system.

The Fit-Comfort axis represents how the production system can cope with single customer fitting. In the shoe sector, we propose an ideal graduations of this axis, where longer arrows correspond to major effort: (1) standard set of grading (2) best match fit—examination of each customer foot in order to march it to an existing library of lasts and related upper and sole, with a much higher granularity (3) tailor made—examination of each customer foot in order to make an individual last. For instance, the capability to satisfy fitting is very low if the customer buys a

Fig. 2.5 Production system capabilities mapped on the customization axes



shoe built from a standard set of grading (first level). We can consider another scenario, still based on standard grading shoes but with a higher capability to satisfy fitting: the best fitting shoe is chosen after an examination of the customer foot (second level). Then a scenario, where we use a foot examination in order to match it to an existing library of lasts with a much higher granularity, has a better capability to satisfy fitting (third level). However, the production of that shoe will require a very high effort by the whole system, because the shoe is made on demand and in lot-size-one. The maximum level (fourth level) is reached with the examination of each customer foot in order to make an individual last. In the example given in Fig. 2.5, the production system can provide best match fit capability.

The functionality axis represents how the production system can cope with technical solutions that implement specific functional requirements such as precision, cushioning, interfaces, connectivity, shock absorption, flexibility, transpiration, thermal requirements… Back to Fig. 2.5 and to the footwear sector, the manufacturing system is capable, by introducing different cushions in the sole, to provide different levels of shock absorption, and offers two different sole profiles, for running or trekking.

The construction of this radar graph is a mandatory step to gather, discuss on, summarize, and easily present product customization attributes from the perspective of the manufacturing system.

E.g., The degree of customization our production process and supply chain currently allow and the costs related with an extension of this are strictly sector-specific. Manufacturing machines able to produce multi-color electronic boards would be of less importance than mixers used to manufacture multi-color inks. The enabled level of customization has also to be carefully pondered from a cost point of view: sometimes, existing manufacturing technologies have been designed for big batches of standard products. They can also run lot-size-one productions, but with setup costs drastically affecting the final cost of the single product. Customization offered is *embedded* in the options provided within the co-design phase. Different options can be given to final customers, depending on brand strategy but, above all, on brand capability to offer customization options. Comparing, for example, the customization website of the two major competitors in the footwear industry, we can derive some interesting hints on what "customization offered" does it mean. Various online and literature resources (see, for example, Strauss 2007, Soccerleats 2010) compare **NIKEiD** and **mi adidas**. The two web-based tools have many functions in common: in both cases you have to start from an existing model (you are not allowed to create your own model), you can choose different color combination, and select a word printed on the shoe. However, the mi adidas shoe is actually created from the ground up for the user's feet, with personal measurements. This option is paid in terms of price: in mi adidas you can just choose among a few number of high-price models (no cheaper options are given). Going to the MC T-shirts manufacturers sector and comparing the customization tools, we can notice great differences among **Bivolino**, **Spreadshirts**, **Spamshirts**, **Signatures Network**, **Shirtsweb**, **ShirtPainter**, … and many others competitors. In some cases you can select among different models, materials, colors, custom- or pre-defined sentences, sometimes not. Sometimes shirts are shipped locally, in other cases worldwide, this is because *behind* the offered customization, different production processes and supply chains provide heterogeneous degrees of enabled customization. In an interview (Piller 2007b), the Spreadshirts CEO argued: "When people visit one of Spreadshirts manufacturing sites, they are often surprised. They expected a big machine, somebody pressing a few buttons and a customized shirt to emerge. Instead they find real manufacturing. Real people taking real apparel from shelves (hard till impossible to replace with robots at a competitive price with nowadays tech), real people preparing the designs, real people pressing the shirts, real people doing quality control and packaging." Human-intensive productions are probably more flexible than a "big machine," here resulting in a wider set of customization options.

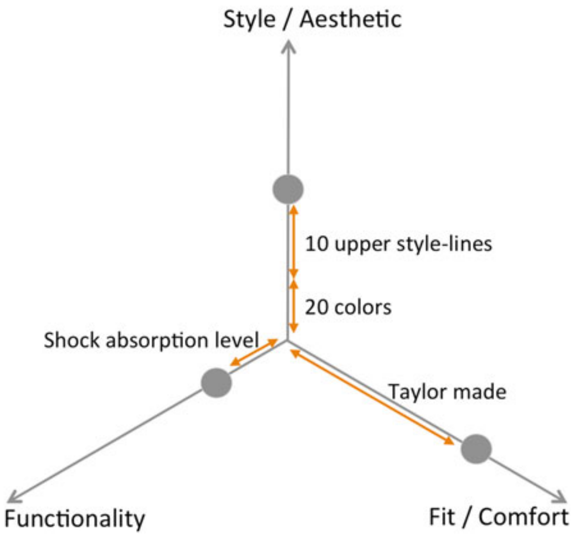
Block* 3—*CUSTOMIZATION REQUIRED: customization refers here to the expectations expressed by our target group.

What options of customization does our customer want? Again we exploit the radar graph to categorize and plot the three aspects of customization required by our customers (fit-comfort, style-aesthetic, function) and by grading the three axes with a specific customization scale given by the sector we are confronting with, we can visualize an overview of the main customization demand trends. Within this block we create, define, and discuss the radar graph related with what the customer expects.

Same considerations on the nature of the axes apply as per the previous paragraph, but seen from the customer point of view. Figure 2.6 provides an example linked to the footwear sector. The final evaluation of the customization required (pictured by the position of the circles on the three axis) is built by assessing the different options offered. When mapping these options, we take into consideration the perceived value of that option from the point of view of the customer by estimating different "arrows" lengths that contribute to build up the final level of customization required. In the example, we estimate that providing different style-lines is more important than offering color option, that is nevertheless required. Note that arrows of specific length may vary from the "customization offered" graph, because here we reflect a different type of evaluation. Indeed, this assessment does not represent the level of capability of the manufacturing system, but the customization desires that must be faced. The construction of this radar graph, as per the previous one, is a mandatory step to gather, discuss on, summarize, and easily present product personalization attributes from the perspective of the customer.

E.g., Questions a prospective MC entrepreneur has here to answer are: how can I collect the customization dimensions and degrees "my market segment" asks for? How can I ponder and rank them? One of the research projects we describe in Chap. 6 (**Dorothy**) addressed this issue for the footwear industry contemplating two design steps for a "new season collection": the "Basic Design" and the "Shoe Customer Driven Design". The *Basic Design of the Shoe* addresses concept, component design, and

Fig. 2.6 Customers requirements mapped on the customization axes



customization design. The customer impacts even in this very first stage, thanks to a mass data acquisition campaign meant to drive the shoe concept and to gather required customization dimensions. The *Shoe Customer Driven Design* is the more "traditional" (in an MC competitive environment) co-design phase, where the customer interacts with the manufacturer in order to create his own pair of shoes within the *boundaries* outlined thanks to the output of the Basic Design. This two-step approach would be valid especially when customization dimensions are accurately targeted in the first phase. Examples cited answering to the "*Satisfaction with involvement in design*?" show how much a wrong or partial understanding of the customization dimensions required by the customer can result into a wrong offer.

Different ways of investigating customers' attitude toward (and requirements concerning) mass customization have been (consciously or unconsciously) explored by MC companies from different sectors. One of the most direct ways to face the problem is evidenced in the Cemex (2013) experience. CEMEX is one of the world's largest building materials suppliers and cement producers based in Mexico. They mass customized the service of delivering their ready-mix concrete to their customers (Pine and Gilmore 2011). Individual building sites often have tight deadlines for pouring the concrete to fit the weather and their construction schedules, with traffic conditions often being a significant impediment to on-time delivery. So CEMEX developed an operational system called GINCO to handle all of its logistics, including GPS locators on each of its trucks. Customers can now order the product just 2 h before they need it. The system finds the truck with the proper mixtures in the correct amounts and dispatches them to the right place in the right time. CEMEX simply found an MC answer to a single customer requirement they registered in their everyday experience.

As already mentioned, **Andersen** (Gamble et al. 2003) is a manufacturer of windows for the home building industry. They acted as mass producers until many of their customers asked for a wider product portfolio, with more options and personalization opportunities. In an effort to meet these requests, they widened their product lines, resulting into a really complex and time-spending quotation process. Customers were asked to provide data and selections for over ten pages of quotation request, sometimes needing the support of a technical consultant from Andersen or from the shop. This complexity also affected the final quality of the products provided and forced the company to investigate alternative patterns. They solved the problem by equipping their retailers with a PC-based interactive software easily driving the customer through the selection process. Unlike CEMEX, Andersen firstly answered to customers' needs using an ineffective solution, then redirecting their choices in a second shot. This was something like a "trial and error" approach.

Other companies adopted a more rational path, structuring a multi-phases strategy, such as the four steps **mi adidas** went through before reaching a full

MC implementation (see description given answering to *What's the Target Market?* question), but also the cautionary approach used by Lands' End (2013), the American clothing specialized in casual clothing, luggage, and home furnishings. As reported (Stevieawards 2002), before launching custom dress shirts, Lands' End Custom focused primarily on the fit of custom products. When customers began to request Custom dress shirts, Lands' End broadened this focus to include both fit and options on the clothing… This allowed these two companies to abate the overall risk related with their MC initiative: they started investing a few and testing on small groups, then broadening the degree of customization offered in accordance to the expectations of the wider market segment they were addressing.

A similar approach was used by Lutron (2013), a U.S. company producing lighting switches and dimmers for various markets. According to reports (Hart 2006), Lutron has been able to customize its lighting systems to individual specifications while maintaining low costs thanks to modularization of components. Lutron developed its strategy in response to a competitive threat by General Electric, entering the market with low-cost solutions and found a solution to the emerging problems thanks to a strict interaction with its "gold" customers (i.e., architects and interior designers), which expressed the need to customize some of the elements of the offered products. Lutron experience is quite similar to Lands' End or mi adidas ones, even if they were more focused on understanding the customization dimensions. They actually implemented something we can call a "co-design of the customization dimensions."

Block* 4—*STABLE SOLUTION SPACE: the SSS represents both the product blueprints (i.e., the sum of all the potential customization options for the MC product) and the capability and degrees of freedom of the production system and its supply chain. It is thus the synthesis of the analysis performed in the "customization offered" and "customization required" blocks. Within the SSS Block, we confront the personalization needs derived by the analysis or anticipation of customer needs with the actual or anticipated capability of the production system. This is where we discuss the final configuration of the MC implementation we are going to implement. Specific questions to be answered are:

Are the customization needs highlighted covered by our production system? We must discuss here whether the needs from the customer meet a proper capability in the production system (existing or designed) and whether unsatisfied needs can trigger a manufacturing system upgrade. The analysis done here is strictly linked with Block 5 investigation (production system).

Do the personalization potential expressed by our manufacturing system find the customer interested? We confront our manufacturing system capability with the market requirements, deciding whether to scale the system down or to push (by marketing, for example) new needs for the customer.

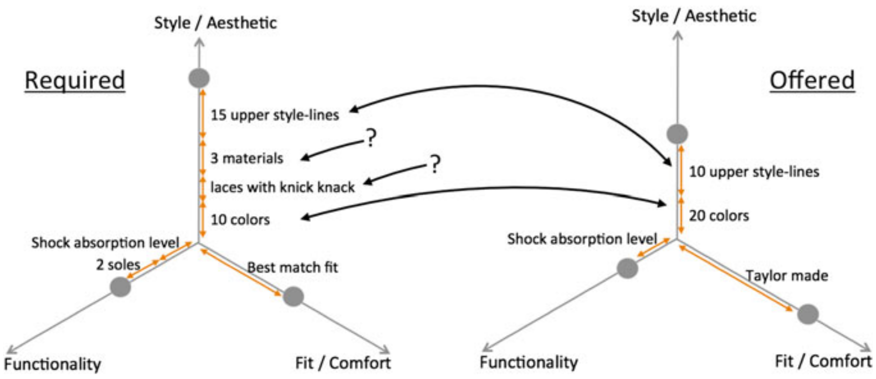


Fig. 2.7 Comparing the required customization with the offered one

Figure 2.7 uses the examples made in blocks 2 and 3. By analyzing the two radar graphs we highlight that the manufacturing system can easily cope with the "number of colors" requirements (or that this capability to further personalize colors can be pushed further to the market), but that we need to modify the manufacturing system to be able to cope with the other Style/Aesthetic requirements. This can trigger the discussion whether we want to modify the system or not, thus accepting not to be able to offer all the options that were considered to compose the personalization required.

E.g., A useful example on the consequences of an inaccurate management of the gaps between the different elements of the solution space can be the MC experience by **LEGO**, the popular Danish toys manufacturer. The company (Piller 2005) has experimented with mass customization since 2001, getting to the ambitious *Lego Factory* (then *Design byME*), a really advanced toolkit enabling users to create (and share) their own designs and order the corresponding bricks. The created solutions were really expensive and did not accept returns. The initiative shut down in early 2012. On the website[1] they reported: "the original Design byMe vision was for a unique customization service, where consumers could design whatever they imagined on their computer, and buy the real model in their own LEGO box. Design byMe attracted several million people each year to build a huge range of amazing creations using the LEGO digital designer (LDD) software. Despite this success, the overall Design byMe experience has struggled to live up to the quality standards for a LEGO service. As a result, the LEGO® Design byME service was closed in January 2012". Different reasons have been mentioned for such a shutdown: too many errors in the delivered orders, design tool not calibrated on children ability… in the first case, there's a gap between the

---

[1] http://ldd.lego.com/en-us/subpages/designbyme/?domainredir=designbyme.lego.com.

"promised" customization and the actually "offered" one, as a result of a gap between the production process (thus the offered customization) and the required customization. In the second case, technical characteristics of the customization means are not adequate to market segment characteristics (i.e., mass customization toolkit usage alphabetization).

How to manage these gaps in order to reach an SSS? Different solutions can be proposed in different contexts: LEGO closed its MC service, **Zyrra** (the MC bras manufacturer) focused on a specific market segment, **Dell** limited the number of options given to its customer (as reported in *What's the expected degree of customer satisfaction in relation with balance Price/ Personalization?*), Timbuk2 (2013) started combining MC and standard products (Piller 2008a). The prospective MC entrepreneur has obviously to avoid business re-definition while running.

Block 5—PRODUCTION SYSTEM: The production system is composed by a set of workers, machines, equipment, and organizational means arranged along a material-information flow whose scope is to transform raw material and information into the final product. As far as our template is concerned, we need to address the following issues.

Do the production means need to evolve toward specific Customization technologies? Do we fully exploit the customization opportunities given by our current production processes? The customization option offered may impact significantly the production technologies. This is clearly a sector-specific issue. In footwear, moving toward a tailor-made production has several implications. As an example, if the "upper" parts have to be cut on a specific measured size, the standard production mean (i.e., knives: a cutting tool of a given shape, pressed on the leather so that it cuts exactly that shape, over and over) is no longer usable, as the shape varies from customer to customer and we cannot obviously create a different knife for each one of them. Thus the "cutting table" is introduced: a numerical control driven cutting device that can perform any desired shape. This is generally slower, more expensive (and thus its introduction must be carefully pondered) but far more flexible.

Do the skills and attitude of the current human operators fit? In case of a highly labor-intensive manufacturing, it becomes important to evaluate the capability of the workforce to adapt to continuously changing specs and workloads.

How does the Product Design impact on the Production Process? Here we must discuss with the production managers how the personalized product design, whose final configuration is not known till the order is done, impacts the production process, in terms of testing its flexibility and capability to work efficiently on a variegated demand.

E.g., Analyzing MC industrial experiences, it emerged that in many cases the production process had to be completely revised in order to widen the degree of customization offered by the company. The already mentioned **Dell** MC initiative is much more than the customization service offered online. As reported in a detailed study performed on the company before the revision of their MC project (Kepczyk 2001), the Dell production process is based on a lean approach, with minimum WIP, abated setup times, standard components assembled to form non-standard final products, strong partnership with suppliers, full tracing of the production flows, and smart management of the faulty elements.

Going back to the **Andersen' Windows** (Gamble et al. 2003) example, in order to properly take care of all the different orders coming from the customers, the company had to implement a tracking system following each order along the entire production chain and, furthermore, had to redesign both the product (in a modular way) and the production process handling lot-size-one production, thus completely abating setup time and costs and radically reducing the inventory of completed products.

Motorola Pager Division (Pine and Davis 1993) is another well-known example of successful MC implementation triggered by a high degree of market turbulence in the 1980s, when Japanese companies entered the U.S. pager market with high-quality products with low prices. Motorola put together a cross-functional team to design a new manufacturing process and assembly line to produce its Bravo line of pagers. This team was charged with creating a completely automated, computer-integrated assembly line yielding tremendous economies of scale but with lot-size-one. All the technology would be purchased off the shelf. The team completely re-engineered the Bravo pager, cutting to 134 the number of parts designed for robotic assembly. The pager had 29 millions of possible variations each producible with zero setup. The manufacturing time was cut from 5 to 2 h. Motorola also re-defined the entire business cycle, from the salesperson until final shipping.

By contrast, technology can also be the trigger for customization: digital textile printing allows near-zero setup times with economically sustainable small lots. Digital printing was born primarily for samples manufacturing, thus its customization attitude is somehow a side effect. Innovative materials such as shape memory alloys are really promising candidate to support mass customization applications (completely different shapes can be taken in a given status—of temperature, acidity, …—by elements that are completely identical in another status. Exploiting this property would allow to perform costly manufacturing operations in this second status and customization in the first). Many examples can be cited where technology is surely an enabler (such as GPS locating CEMEX trucks). In other cases, human flexibility is the only "must have" element (such as in the cited Spreadshirt example).

Block* 6—*MEANS: Mass Customization foresees design and sales activities before production takes place. Customers need to be engaged to design their unique products that meet their requirements (the design can include simulation, so that customers can virtually try the product). Thus customization experience (block 1) and the means through which this is accomplished are of supreme importance.

How and where does the co-design takes place? The customization experience is offered through specific channels. These can be a web-based tool (option preferred by shoe manufacturers who highly invest on aesthetic customization) or a coaching session in a shop, where the customer is "measured" and guided through options. The co-design option and mean selected must address both utilitarian options while empowering uniqueness. But there's a deceitful threat to be thoughtfully addressed: asking the consumer to identify the features of a product with almost no constraint could generate choice complexity and might result in "mass confusion" (Huffman and Kahn 1998).

How do we rise awareness on our product? Communicating with customers is always fundamental, but it becomes essential especially for innovative products or products that are delivered in an innovative way. This implies that proper communication means have to be created and adapted in accordance to the target customer segment and to the peculiarities of the MC offer.

How do we deliver? Delivery costs are often a major problem for MC products: while traditional business to consumer markets rely on a numbered set of clearly located retailers, shops, re-sellers, resulting into a "one to many" delivery network, in modern business configurations, such as the MC productions, products are (usually) delivered directly to the final customers, creating a "one to *almost* infinite" delivery network, where delivery routes are not predictable and optimization of logistics operations is left in delivery service suppliers' hands.

E.g., Internet-based co-design tools are one of the most important enablers of MC initiatives. We can mention again **Dell**, **Timbuk2**, **Lego**, **mi adidas**, **NIKEiD**, **Zazzle**, **Yankee candles**, **Customatix**, **McGraw Hill** custom college textbooks (Albright and Lam 2006), **Acumins**, **Lands' End**, **reflect.com** (Kurt 2003), and many others, all offering online configurators where the final user can configure its customized solution. These customization experiences are sometimes assisted, such as in **Zyrra** business, where the company sells bras through home parties, in which one of the company's salespeople takes 12 different measurements for each customer. Customers then choose colors and trim within properly organized events (also strengthening customer acceptance of the product) such as in the first phases of the **mi adidas** initiative, or in the shop. In other cases, means used to gather customer preferences are indirect, such as the **ChemStation** MC service, based on autonomously learnt customer needs.

American Art Resources (2013) is meant to commission and install artwork, from huge sculptures to photographs of historic buildings, for health-care facilities. Through the website, hospitals and other health-care facilities commission art pieces to a network of about 1,900 artists working in practically every possible medium, including painting, photography, fiber, ceramics, and drawing. In this case, the MEANS is the core business: the website enables suppliers and customers to meet, with different customers accessing "mass customized" artworks.

Block 7—SUPPLY CHAIN: Mass Customization requires an agile supply chain whose speed and flexibility can support the manufacturing system toward the realization of customer needs.

Can the supply chain cope with the erraticism in terms of variations and volumes imposed by my MC implementation? Which kind of contract/relationship do we have with our suppliers? Which is our negotiation power with them? Which is the benefit they would derive from a redefined agreement? The prospective MC entrepreneurs have to focus on all these issues in order to size the customization potential enabled by their supplier and supply chain configuration. Though the capability of our production system is critical in defining our mass customization capability, also the significance of supply chain and logistics management in empowering mass customization strategies is to be taken into serious consideration as it becomes of capital importance to procure appropriate and accurate supplies for the timely manufacture and delivery of individualized product.

How does this flexibility impact costs? When facing the above-mentioned issues, we have to address the typical cost increase connected with flexible and small-lots procurement.

E.g., In some MC examples, the supply chain is fundamental: creating strong, though flexible, relationships with suppliers is mandatory to access a wide variety of components in a timely and inexpensive way.

TaylorMade is a good example on how a well-performing supply chain can make the difference in an MC strategy implementation process (Bowman 2002). The company is the number-two maker of clubs. In early 2000 the market was steady, with near-zero growth and TaylorMade competitors outperformed company's performances in delivering custom-made golf clubs. Actually, TaylorMade had one of the slowest supply chains requiring between 30 and 90 days to recognize demand changes at the retail level, 5 more to update the forecast, 7 to convert it to a materials plan, 5 to release assembly or purchase orders, 60-day lead-time with vendors, and 8 days for converting to a required shipment. In a 3-year program costing close to $10 m, TaylorMade stabilized and improved basic business processes, developed enhanced supply-chain capabilities, including fast delivery of customized product, installed a set of new software applications. All these investments resulted into a renewed competitive positioning of the company within the market, with lead times comparable with competitors' ones and higher quality product.

In other cases, MC is implemented just in the final steps of the manufacturing process. In that case, supply chain is just marginally affected by the MC strategy implementation process. **Lenscrafter** (Albright and Lam 2006) is an international retailer of prescription eyewear that has customized products to individual customers at a cost comparable to mass-produced goods. Each Lenscrafters store maintains a production facility to avoid the costs and delays of sending prescriptions to labs that use batch production techniques. The result is a prescription lens quickly delivered to an individual customer. In this case, customization is directly implemented in the shop and strongly connected with the customization experience (with really short lead times).

2.3 How to Use the MCIT Template

As mentioned, we may step into the template in different blocks. There is no right starting block, or exact logical sequence: each MC implementation will have its own genesis, sector specificity, and evolution paths. As a usage example, we may think that we have production system that offers, thanks to his machinery, customization potential unexploited: can I offer something different to my customers? We'll step in to the "production system" block (Fig. 2.8), and characterize our manufacturing plant from an MC point of view, getting inspiration from the issues and suggestion early in this chapter mentioned. This should be done in team, possibly heterogeneous, using a blackboard and many post-it (this approach is valid in the first steps of any factory-wide and business-wide significant change implementation, e.g., in a lean implementation). Once done, we have then to think about the changes and challenges that our supply chain will have to cope with. Similarly we have to characterize the new customization level offered, that will be targeted to a specific market segment to be pointed out clearly. The "means" to make information flow from the customer to the factory will be the next logical step to be investigated. By answering systematically, block by block in the MCIT template, to the questions above highlighted, we will be drafting our implementation and qualitatively investigate our approach.

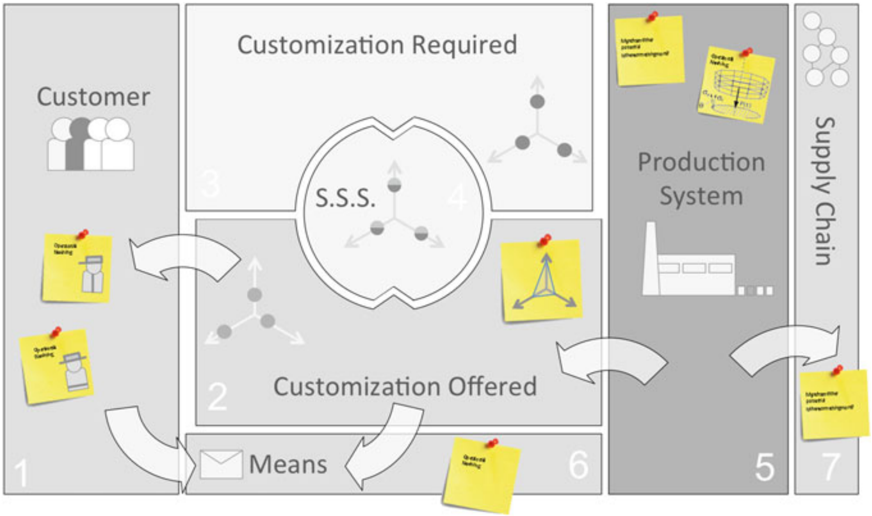


Fig. 2.8 An example of the strategy generation on the MCIT

2.4 Conclusions

This chapter confirms the predominantly applicative attitude of this work by providing a practical and intuitive guide for entrepreneurs aiming at implementing MC. To work with and fill the MCIT template is an important step toward the acknowledgment of the complexity of an MC instantiation: it is not just about a customizable product. The chapter provides a method, procedures, and ideas suitable for MC businesses' development to get off on the right foot (even if mentioning feet may seem a little bit too self-referring).

Bibliography

Albright T, Lam M (2006) Managerial accounting and continuous improvement initiatives: a retrospective and framework. J Manage Issues 18(2):157–174

Americanartresources (2013) http://www.americanartresources.com/index.htm. Accessed 22 Jan 2013

Boër CR, Dulio S (2007) Mass customization and footwear: myth, salvation or reality?. Springer, London

Bowman RJ (2002) Taylor made drives supply-chain efficiency with 24 hour club. http://www.supplychainbrain.com/content/industry-verticals/retail/single-article-page/article/taylormade-drives-supply-chain-efficiency-with-24-hour-club. Accessed 22 Jan 2013

CEMEX (2013) www.cemex.com. Accessed 22 Jan 2013

Customatix (2002). Online blog http://www.k955.com/internetm/jan02.htm. Accessed 22 Jan 2013

Davis S (1987) Future perfect. Basic Books, New York

Fogliatto FS, da Silveira GJC, Borenstein D (2012) The mass customization decade: an updated review of the literature. Int J Prod Econ 138(1):14–25

Franke N, Piller F (2003) Key research issues in user interaction with user toolkits in a mass customization system. Int J Technol Manage 26(5/6):578–599

Gamble PR, Stone M, Woodcock N, Foss B (2003) Up close and personal? Customer relationship marketing @ work. Kogan Page Business Books, London

Gilmore JH, Pine J (2000) Markets of one: creating customer-unique value through mass customization. Harvard Business School Publishing, Boston

Hart CW (2006) Creating competitive advantage through mass customization. http://www.spiregroup.biz/pdfs/06-04-07%20Creating%20Competitive%20Advantage%20through%20Mass%20Customization.pdf. Accessed 22 Jan 2013

Huffman C, Kahn BE (1998) Variety for sale: mass customization or mass confusion. J Retail 74(4):491–513

Kepczyk RH (2001) Mass customization: the dell way. http://www.itpna.com/Vision/2001/010523%20Mass%20Customization-The%20Dell%20Way.htm. Accessed 22 Jan 2013

Kurt P (2003) Mass customization is not an oxymoron at Reflect.com. http://www.internetretailer.com/2003/03/28/mass-customization-is-not-an-oxymoron-at-reflect-com. Accessed 22 Jan 2013

Landsend (2013) www.landsend.com. Accessed 22 Jan 2013

Lulu (2013) www.lulu.com. Accessed 22 Jan 2013

Lutron (2013) www.lutron.com. Accessed 22 Jan 2013

Mistler WT (2001). Mass customization strategies in the computer, automotive, and retail industries: trends and analysis. http://www.mne.psu.edu/simpson/courses/me546/projects/bill.mistler.MSpaper.pdf. Accessed 22 Jan 2013

Picaboo (2013) www.picaboo.com. Accessed 22 Jan 2013

Piller FT (2004) Mass customization: reflections on the state of the concept. Int J Flex Manuf Syst 16:313–334

Piller FT (2005) Lego bridges mass customization and open innovation with LEGO-Factory website: children become toymakers and can design and produce sets of their dreams. http://mass-customization.blogs.com/mass_customization_open_i/2005/08/lego_factory_ch.html. Accessed 22 Jan 2013

Piller FT (2007a) Observations on the present and future of mass customization. Int J Flex Manuf Syst 19(4):630–636

Piller FT (2007b) How mass customization really works—Spreadshirt. http://mass-customization.blogs.com/mass_customization_open_i/2007/05/how_mass_custom_1.html. Accessed 22 Jan 2013

Piller FT (2008a) Interview: Rickshaw Bagworks' co-founder rob Honeycutt on mass customization of bags and more. http://mass-customization.blogs.com/mass_customization_open_i/2008/04/interview-ricks.html. Accessed 22 Jan 2013

Piller FT (2008b) RYZwear.com: applying the threadless concept to footwear. http://mass-customization.de/footwear. Accessed 22 Jan 2013

Piller FT (2013) Mass customization and open innovation news, a blog by Frank T. Piller http://www.mass-customization.de. Accessed 22 Jan 2013

Pine J, Davis S (1993) Mass customization: the new frontier in business competition. Harvard Business Press, Boston

Pine J, Gilmore JH (2011) The experience economy, Updated Edition. Harvard Business School Publishing, Boston

Seifert RW (2006) The "mi adidas" mass customization initiative. http://www.imd.org/uupload/www01/documents/millenniumcases/IMD-6-0249_Mi_Adidas.pdf. Accessed 22 Jan 2013

Soccerleats (2010). Mi Adidas vs Nike ID—which to choose. http://www.soccercleats101.com/2010/08/01/mi-adidas-vs-nike-id-which-to-choose. Accessed 22 Jan 2013

Stevieawards (2002). Lands' end custom dress shirts. http://www.stevieawards.com/pubs/iba/awards/171_1373_7955.cfm

Strauss WA (2007) Transitions: the state of the automotive industry—a summary. Chicago Fed Letter, 242a

Suresh K (1996) From mass production to mass customization: the case of the national industrial bicycle company of Japan. Eur Manage J 14(5):442–450

Tahmincioglu E (2007). Breaking the mold. Bloomberg Businessweek Magazine. http://www.businessweek.com/stories/2007-04-22/breaking-the-mold. Accessed 22 Jan 2013

Timbuk2 (2013) www.timbuk2.com. Accessed 22 Jan 2013

Tseng MM, Jiao J (2001) Mass customization. In: Salvendy G (ed) Handbook of industrial engineering, 3rd edn. Wiley, New York

Verghese M (2007). Zyrra supports women's needs. http://www.browndailyherald.com/features/zyrra-supports-women-s-needs-1.1672836#.UP4-yqVUPWR. Accessed 22 Jan 2013

Williams RL (2010). Client reinvention: building the most flexible and effective value chain. http://en.community.dell.com/dell-blogs/dell-shares/b/dell-shares/archive/2010/03/11/client-reinvention-building-the-most-flexible-and-effective-value-chain.aspx. Accessed 22 Jan 2013

Wind J, Rangaswamy A (2001) Customerization: the next revolution in mass customization. J Interact Mark 15(1):13–32

Chapter 3
Sustainability Assessment Model

3.1 Introduction

The concept of sustainability, in the way we understand the term now, first appeared in 1987, within the Brundtland Report, defined as "to meet the needs of the present generation without compromising the ability of future generations to meet their own needs." Later, as the concept gained popularity, hundreds of definitions were proposed, in academic debates and business arenas, referring to a more ethical, more green, and more transparent way of doing business. Today, the label of "sustainable" is a bottom-line requirement: as a matter of fact, Sustainability has become a common basic goal for many national and international organizations including industries, governments, NGOs, and universities. However, in spite of the nearly universal recognition that Sustainability has received, companies still struggle with the full understanding of the concept and with its financial viability.

So the first problem lies with understanding: in the jungle of definitions, and to be able to point out the link with mass customization, we try hereinafter to set some cornerstones, exploring the three sustainability pillars, economical, environmental, and social, and proposing practical indexes to build-up an effective assessment model. The assessment model represents a quantitative (meaning numbers: clear, reliable, and exploitable) measurement of environmental, economic, and social performances: the use of numbers will transform the well-recognized but sometimes vague concept of sustainability into a powerful tool that decision-makers can understand and apply in their everyday work.

The development of this sustainability assessment model (SAM), meant to be a practical and usable tool, lays its foundations on an extensive literature review: this revealed a considerable amount of methodologies addressing the evaluation of sustainability of product, manufacturing system, and supply chain. However, indicators found in the literature proved to be unbalanced or too much qualitative to be concretely applied, and, additionally, to be incomplete at least at social level. The main innovation here promoted lies in the development of an holistic set of indicators capable to evaluate sustainability considering the *Stable Solution Space* (as defined in Chap. 2) as a whole: the product is produced within a defined

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_3,

manufacturing system and delivered by a supply network, and all these entities are involved in determining the final sustainability level of the Solution Space.

The assessment results have been related to a single unit of product, thus fostering an immediate perception of the burden set to the environment, society, and economy connected to the final act of buying.

Section 3.2 deals with the explanation why some indicators have been chosen rather than others, while Sect. 3.3 presents the actual indicators and their calculation formula.

3.2 Assessment Indexes Selection

The first step is to define the criteria used in the identification of the suitable indexes. The identification activity then started with a literature review of sustainability assessment indexes trying to figure out those most frequently used to measure the performances of solution spaces (product, production system, and supply chain). This preliminary list highlighted that many sustainability areas could be analyzed through indicators taken from existing sources, but also that some indexes should be created ad hoc for the our SAM.

3.2.1 Selection Criteria

This section presents the criteria used in the selection of the sustainability indicators. Since the literature analysis highlighted a considerable amount of existing indexes used by academic institutions and industries for the evaluation of sustainability performances, the need for a criteria allowing the selection of the most suitable indicators as far as the assessment model aim is concerned emerged soon. For this reason, a list of selection criteria has been developed:

- *Measurable*: the indicator is measurable. The measured impact and its sources can be translated and conveyed in a quantitative measure.
- *Understandable*: the indicator is easy to understand, even by people who are not experts. People do not end up arguing over what the indicator means.
- *Exploitable and Relevant*: the indicator measures something that is important to the company implementing it for highlighting existing problems and enhancing its performances.
- *Balanced and fitted*: the selected indicators provide a comprehensive view of the key issues. There isn't any overlapping over same issues or incoherence between indicators.
- *Potential for influencing change*: the evidences collected will be useful for the decision-makers inside the companies. The indicators enable decision-makers to understand what the necessary corrective actions are.

- *Reliable*: the process that transforms the input data into the final indicator outcome provides a measure that can be trusted.
- *Achievable*, based on accessible data: the information is available or can be gathered while there is still time to act.
- *Comprehensive* (*product/process/supply chain*): an indicator is desirable to be applicable to the different design entities: product, manufacturing, and supply chain. Including all the design level, the indicator allows the overall assessment of the sustainability and the mass customization of the product system.
- *Flexible*: an indicator must be flexible and multipurpose, that is, it can be applied to different kind of products, production process, and supply chains.
- *Established*: an indicator, and the way to calculate it, is desirable to show a large consensus in the academic and industrial environments especially if the indicator addresses some sustainability or mass customization areas that are studied by long time and the industrial application is well established.

3.2.2 Identification of the Assessment Indexes

This section is meant to present the identification of the assessment indexes performed through either the selection of the existing indicators (using the above-listed criteria), their adaptation, or thanks to the development of ad-hoc indicators. The presentation of the indicators selection is carried out into the three sustainability areas: Environmental, Economic and Social.

3.2.2.1 Environmental Indicators Selection

Thanks to the lifecycle assessment (LCA) methodology, the evaluation of the environmental performances of products and companies is quite an established issue. The state of the art analysis on the environmental indicators provided a very long list of environmental indexes. In this analysis, different sources of environmental indicators have been considered namely:

- Literature: i.e., Azapagic and Perdan (2000); Krajnc and Glavic (2003); Wright et al. (1997); Veleva and Ellenbecker (2001);
- Lifecycle impact assessment methodologies (LCIA): i.e., ReCiPe (2009), Eco-indicator 99 (1999), Eco-indicator 95 (1999), CML (2001a, b), BEES, EDIP (2003), Impact (2002), TRACI 2, EPD (2007);
- Indexes series: i.e., global reporting index (GRI), Dow Jones Sustainability World Index (DJSI 2010), and FTSE4Good;
- Software products for LCA and product design: i.e., EIME, SimaPro, and GaBi (LCA software) and SolidWorks (CAD).
- Sustainability oriented methodologies allowing the development of sustainable products, manufacturing systems, and supply networks: i.e., Design for

Environment (DfE) (Fiksel 1996; Mascle and Zhao 2008), environmental conscious manufacturing (ECM) (Gungor and Gupta 1999), and GreenSCOR.

As suggested by Guinée (2002), a preliminary selection of the environmental indicators has been performed considering the positioning of the focal point of the indicators in the cause-effect chain that is meant to describe the environmental mechanism from "exchanges" to "endpoints." In the impact chain, the "exchange" represents the flow of matter and resources between the environment and the techno-sphere. The "endpoint" is the "thing" to be protected, such as trees, rivers, and human health. "Midpoint" refers to all the elements in an environmental mechanism that fall between environmental exchanges and endpoints. An example of an "exchange" is the emission of chlorofluorocarbon (CFC) gases, which causes a depletion of the ozone layer in the stratosphere (midpoint), which results in increased levels of radiation (midpoint) that eventually cause a certain number of people to die from skin cancer (endpoint).

The LCIA and the related impact category indicators could be distinguished into two main approaches, differing in what the indicator is meant to measure along this cause-effect chain.

The first approach, known as problem-oriented, is characterized by category indicators close to the environmental intervention that are driven by the environmental problems. This kind of indicators, called also midpoint, are meant to translate impacts into environmental themes (e.g., global warming, acidification, human toxicity, etc.). The second approach, known as damage-oriented, is characterized by category indicators close to environmental areas of protection. This kind of indicators, called also endpoint indicators, are meant to model the potential environmental damage on value items due to the environmental interventions, translating the environmental impacts into issues of concern such as human health, natural environment, and natural resources.

It is evident that endpoint indicators have a higher level of uncertainty compared to midpoint indicators, since they require the definition of a model to translate emissions into actual damage, enhancing the complexity level of the environmental assessment. In order to avoid the uncertainty introduced by the damage-oriented approach, the SAM assessment model is based on problem-oriented indicators. Although some of the analyzed mentioned LCIA methodologies are damage oriented, it is possible anyhow to extract the midpoint indicators.

The first list derived from literature of the possible environmental indicators to be used in the assessment model is reported in Table 3.1, that also shows the sources of the indicators. Table 3.1 provide a ranking of the indicators based on the application of the *Established* criteria (the last of those mentioned in the previous section), since each row of the table reports if the indicator is cited in a particular software, LCIA methodology, index system, etc., and then provides the total number of the indicator occurrences. This allows evaluating the academic and industrial consensus in the use of the indicator and in the definition of its calculation formula.

Table 3.1 Indicators versus *established* criterion

Indicator	EIME	Solid works	ReCiPe	Eco-99	Eco-95	CML 2001	BEES	EDIP 2003	Impact 2002	TRACI 2	EPD 2007	GRI	DJSI	FTSE 4Good	DfE	ECM	Green SCOR	[A]	[B]	[C]	[D]	TOT
Global warming potential	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	20
Acidification potential	1	1	1	1	1	1	1	1	1	1	1					1	1	1	1	2	1	18
Abiotic resources depletion	1		1	1	1	1	1	1	1	1	1	1			1	1		1	1		1	16
Photochemical ozone creation potential	1		1	1	1	1	1	1	1	1	1	1				1	1	1	1	1		16
Stratospheric ozone depletion potential	1		1	1	1	1	1	1	1	1	1	1				1	1	1	1	1		16
Water eutrophication potential	1	1	1	1	1	1	1	1	1	1	1					1		1	1	1		15
Eco toxicity potential	2		1	1		1	2	1	2	1								1		1	1	14
Waste generation					1		1	1				1	1		1	1	2	1	2	1	1	14
Energy depletion	1	1										1	1		1	1		1	1		2	10
Water depletion	1		1				1			1		1	1			1			1		1	9
Human toxicity potential			1			1		1	1									1		1	1	7
Land use			1	1			1		1	1								1				6
Material recyclability															1	1	1	1	1			5
Ionizing radiation emission			1	1		1			1													4
Carcinogens emissions				1	1															1		3
Human health potential							1			1												2
Winter smog potential				1	1																	2
Hazardous waste production	1							1														2
Biotic resource depletion (biodiversity)												1						1				2
Smell emission						1																1
Heavy metal emitted to air					1																	1
Heavy metal emitted to water					1																	1
Pesticides emission					1																	1
respiratory effects potential									1													1

(continued)

Table 3.1 (continued)

Indicator	EIME	Solid works	ReCiPe	Eco-99	Eco-95	CML 2001	BEES	EDIP 2003	Impact 2002	TRACI 2	EPD 2007	GRI	DJSI	FTSE 4Good	DfE	ECM	Green SCOR	[A]	[B]	[C]	[D]	TOT
Particulate matter formation			1																			1
Raw material efficiency															1	1	1		1			4
Product durability															1			1	1			3
Revenues from eco-products																			1			1
Env. improv. above compliance levels																		1				1
Product env. labels																			1			1
Presence and quality of the env. policy													1	1								2
Quality and N. of env. reports													1	1								2
N. of env. certif.													2	1				2				5

[A] = Azapagic and Perdan (2000); [B] = Krajnc and Glavic (2003); [C] = Wright et al. (1997); [D] = Veleva and Ellenbecker (2001)

As stated above, the ranking of the environmental indicators listed in Table 3.1 has been carried out applying the selection criterion “established,” as defined in Sect. 3.2.1. Table 3.2 provides the match between the other selection criteria and the indicators, with the exception of the *established* criterion, already taken into consideration.

The results of the first selection, visualized in Table 3.2, are summarized hereinafter.

The indicators “Carcinogens Emissions,” “Heavy Metal Emitted to Air,” “Heavy Metal Emitted to Water,” “Pesticides Emissions,” “Respiratory Effects Potential” have been considered not to be *balanced and fitting* as the “Human Toxicity Potential” and the “Eco toxicity Potential” indicators are meant to assess the same environmental issues with a more comprehensive perspective.

The indicator “Smell Emissions” is not *measurable* since it is subjected to objective data (chemicals analysis and sensor methodologies), but also to subjective data (nuisance analysis through surveys). The subjective aspect of the indicator implies also that it cannot be based on accessible data so that smell is not *achievable*.

The literature review shows that actually the calculation methodology of the indicator “Biotic Resource Depletion (biodiversity)” has not yet reached a wide agreement on the academic and the industrial communities. This indicator is difficult to be *measured*, it is not *reliable*, there are few available data allowing its calculation and its *understandability* is negatively affected by the various different assessment methodologies developed in the literature.

“Raw Material Efficiency” indicator encompasses a broad range of concepts and idea about the efficient use of natural resources, but a clear definition of the “material efficiency” is missing so that this indicator is neither *measurable* nor *achievable*. Moreover, this indicator is not *balanced* since it overlaps more structured indicators concerning the efficient use of raw materials (i.e., “Material Recyclability,” “Abiotic Resources Depletion”).

The indicators “Waste Generation” and “Hazardous Waste Production” could be integrated into one indicator evaluating the total amount of waste created by the solution space activities and then distinguishing between hazardous and non-hazardous waste.

“Product Durability” is a qualitative characteristic of the product that is hard to be *measured*. The prediction of the expected life span of the product in years does not provide a measure of its durability. Moreover, this indicator is not *comprehensive* since it measures only the product characteristics, ignoring the manufacturing system and the supply chain.

In order to be fully *understandable* and not to convey misleading information, the “Revenues from Eco-products” indicator requires a precise and shared definition of what is intended to be an “eco-product.” A product is never in absolute eco, rather it is “more green” than a chosen reference product. The necessity to have a reference product introduces a sort of uncertainty in the calculation of this indicator making it not *reliable*.

Table 3.2 Candidate environmental indicators versus selection criteria

Environmental area of concern	Indicator	Measurable	Understandable	Exploitable	Balanced	Potential for influencing change	Reliable	Achievable	Comprehensive (product/ manufacturing/ supply chain)	Flexible
Emissions	Global warming potential	X	X	X	X	X	X	X	X	X
	Acidification potential	X	X	X	X	X	X	X	X	X
	Photochemical ozone creation potential	X	X	X	X	X	X	X	X	X
	Stratospheric ozone depletion potential	X	X	X	X	X	X	X	X	X
	Water eutrophication potential	X	X	X	X	X	X	X	X	X
	Eco toxicity potential	X	X	X	X	X	X	X	X	X
	Human toxicity potential	X	X	X	X	X	X	X	X	X
	Carcinogens emissions	X	X	X		X	X	X	X	X
	Ionizing radiation emission	X	X	X	X	X	X	X	X	X
	Human health potential	X	X	X	X	X	X	X	X	X
	Winter smog potential	X	X	X	X	X	X	X	X	X
	Smell emissions		X	X	X	X			X	X
	Heavy metal emitted to air	X	X	X		X	X	X	X	X
	Heavy metal emitted to water	X	X	X		X	X	X	X	X
	Pesticides emissions	X	X	X		X	X	X	X	X
	Respiratory effects potential	X	X	X		X	X	X	X	X
	Particulate matter formation	X	X	X	X	X	X	X	X	X
Use of resources	Abiotic resources depletion	X	X	X	X	X	X	X	X	X
	Biotic resource depletion			X	X	X			X	X
	Raw material efficiency		X	X		X	X		X	X
	Energy depletion	X	X	X	X	X	X	X	X	X
	Water depletion	X	X	X	X	X	X	X	X	X
	Land use	X	X	X	X	X	X	X	X	X

(continued)

Table 3.2 (continued)

Environmental area of concern	Indicator	Measurable	Understandable	Exploitable	Balanced	Potential for influencing change	Reliable	Achievable	Comprehensive (product/ manufacturing/ supply chain)	Flexible
Waste	Material recyclability	X	X	X	X	X	X	X		X
	Waste generation	X	X	X	X	X	X	X	X	X
	Hazardous waste production	X	X	X		X	X	X	X	X
Product	Product durability			X	X	X				X
	Revenues from eco-products	X		X	X	X		X		X
	Product with environmental labels	X	X	X	X	X	X	X		X
Company	Quality and N. of env. reports		X		X		X	X	X	X
	Presence and quality of the env. policy		X		X		X	X	X	X
	Env. improvements above the compliance levels				X			X	X	X
	N. of voluntary env. certifications	X	X		X		X	X	X	X

The “Presence and quality of the environmental policy,” “Quality and Number of Environmental Reports,” and the “Number of Voluntary Environmental Certifications of the company and its suppliers” indicators are not *exploitable*, *relevant*, and *influencing change*, since they do not properly highlight the existing problems within the company, scarcely enabling decisionmakers to understand which are the necessary corrective actions. Moreover, “Quality of the environmental policy” and “Quality of Environmental Reports” are not *measurable* in a quantitative and objective way.

Though Azapagic and Perdan (2000) provided a calculation formula for the “Environmental improvements above the compliance levels” indicator, its *measurability* and *understandability* are low since it is subjected to the vague definition of “substance that are of general environmental concern but are not legislated.” Moreover, this kind of indicator may lead to expensive corrective action that is not focusing on the core environmental performances of the company.

Combining the results of the analysis performed through the selection criteria summarized in Tables 3.1 and 3.2, the list of the environmental indicators has been obtained and it is presented in Sect. 3.2.3, where the definitions of the indicators and their unit of measure are also provided.

3.2.2.2 Economic Indicators Selection

Achieving economical sustainability means to use resources in an efficient way in order to provide long-term benefits with minimal waste. In other terms, it aims at maximizing the level of quality while minimizing the costs (Global Reporting Initiative 2000–2011). The assessment of the economic sustainability can be referred to different unit of analysis: a single organization, a country, or an industry. At the organizational level, standards and global reporting state that the economical sustainability can be assessed considering the direct economic value (as revenue) and operating costs. In the literature, some contributions are focused on the assessment of economical sustainability of specific industries. In this case, the assessment is based on the measurement of efficiency and profitability levels (Hang et al. 2011). Finally, some researches consider a district (state or country) and base the assessment on national economy and production competitiveness (Corbiere et al. 2011).

According to the aim of the SAM assessment model, the selection of indicators considers the organization level and, in particular, the unit of analysis includes product, production system, and supply chain of a new solution space. In Table 3.3, the list of indicators selected to measure the economic sustainability clustered according to Profitability, Risk Management, Investment (tech. and competences), and Efficiency categories is presented. Indicators are introduced linking them to the selection criteria.

Table 3.3 SAM economical area of concerns and indicators versus selection criteria

Economical area of concern	Indicator	Measurable	Understandable	Exploitable	Balanced	Potential for influencing change	Reliable	Achievable	Comprehensive (product/ manufacturing/ supply chain)	Flexible
Profitability	Unitary expected gross profit	X	X	X	X	X	X	X	X	X
	Product lifecycle cost	X	X			X	X			X
Risk management	Supply risk	X	X	X		X	X	X		X
Investment (tech. and competences)	R&D investment intensity	X	X	X	X	X	X	X		X
Efficiency	Unitary production cost	X	X	X	X	X	X	X	X	X
	Production lead time	X	X	X	X	X	X	X	X	X
	Variability of production lead time	X	X	X	X	X	X	X	X	X
	Value added time	X	X	X	X	X	X	X	X	X
	Throughput rate	X	X	X	X	X	X	X	X	X
	Capacity utilization rate	X		X	X	X	X	X		X

3.2.2.3 Social Indicators Selection

Social indicators have not achieved the same level of maturity as environmental ones yet. This can be explained by the focus given during last decades on the environmental dimension of sustainability. The literature of social sustainability assessment methods and indexes shows that lifecycle thinking has also emerged in the social assessment of products, but there are no standards yet, neither methodologies nor indicators. The efforts here are meant to foster the characterization of social impact of products all over their lifecycles, facilitating by the standardization of the life social evaluation methods. The relevance of a reference here investigated is tributary of (1) its frequency in sustainability literature and (2) its date of issue or last update (the nearest the latter, the more relevant is the reference).

Jensen and Remmen (2006) gave insights on lifecycle management and its integration in sustainability dimensions, including social one. GRI (2006a, b) established sustainability reporting guidelines applicable to several organizations. Kruse et al. (2009) proposed a socioeconomic indicators system that has been also applied to a case study demonstrating applicability. Benoît and Bernard (2009) provided more guidance for the establishment of a social lifecycle assessment (S-LCA). Dreyer (2009), Dreyer et al. (2010a, b) attempted to formalize the S-LCA by proposing a methodology that was applied to different case studies.

Investigated literature also includes initiatives that provide comprehensive indicators but they are not applicable at enterprise level such as UN (2001, 2007). Further literature on social sustainability indicators can be found in Jorgensen et al. (2008). The authors presented a review meant to highlight areas of agreement and disagreement in S-LCA. Thus the survey included several initiatives that are not extensively mentioned.

Results of the literature survey are presented in Table 3.4. It can be noticed that several indicators are overlapping. In order to allow a seamless selection process, indicators that measure same aspects are grouped, and then the most relevant indicators depicting these aspects are selected. In some cases, the existing indicators are quite generic, thus proposing new ones related to same aspects is inevitable. The grouping and selection results are illustrated in Table 3.5.

As mentioned in the beginning of this section, social dimension assessment is not well established yet despite several indicators and methods proposals. Our indicators attempt to fill this gap and to broaden the evaluation scope. In order to fully cover working condition and workforce aspects, three more indicators have been proposed, namely workforce turnover intensity (WTI), multi-skilled operators (MSO), and product social features (PSF).

Table 3.4 Candidate social indicators versus selection criteria

	Aspects/indicators	Measurable	Understandable	Exploitable	Balanced	Potential for influencing change	Reliable	Achievable	Comprehensive (product/ manufacturing/ SC)	Flexible
Workforce	Hazard	X	X	X	X		X		X	X
	Risk exposure at work		X	X	X	X	X	X	X	X
	Accidents avoided	X	X		X					X
	Fair wages	X	X	X	X	X	X	X		X
	Right of labor organizations		X	X	X		X	X		X
	Minorities and ingenuous people				X					X
	Forced and child labor	X	X	X	X	X	X			X
	Training/education	X	X	X	X	X	X	X	X	X
	Freedom of association and collective bargaining		X		X		X			X
	Working hours	X	X	X	X	X	X	X	X	X
	Equal opportunities/discrimination	X	X	X	X		X			X
	Health and safety	X	X	X	X	X	X	X		X
	Social benefits/social security	X	X	X	X	X	X	X		X
	Employment	X	X	X	X	X	X	X		X
	Labor/management relations									X
	Occupational Health and safety	X	X	X	X	X	X	X		X
	Diversity and equal opportunity	X	X	X	X		X			X
	Employment benefits	X	X	X	X	X	X	X		X
	Investment and procurement practices	X	X	X	X	X	X	X		X
	Security practices		X	X	X		X	X	X	X
	Access to bathroom/potable									X
	Industry concentration									X
	Distance travelled	X	X		X		X			X

(continued)

Table 3.4 (continued)

	Aspects/indicators	Measurable	Understandable	Exploitable	Balanced	Potential for influencing change	Reliable	Achievable	Comprehensive (product/ manufacturing/ SC)	Flexible
Product	Customer health and safety	X	X	X	X	X		X	X	X
	Product and service labeling	X	X	X	X	X	X	X		X
	Marketing communications	X	X	X	X	X	X	X	X	X
	Customer privacy		X							
	Compliance	X	X	X	X	X	X	X	X	X
	Safer products	X	X	X	X	X		X	X	X
	Feedback Mechanism			X	X	X	X	X		X
	Transparency		X							X
	End of life responsibility	X	X	X	X	X	X	X	X	X
Local community	Access to material resources	X	X	X	X	X	X	X		X
	Delocalization and migration cultural heritage	X	X	X	X	X	X	X		X
	Safe and healthy living conditions	X	X	X	X	X	X	X	X	X
	Respect of indigenous rights									X
	Community engagement									X
	Local employment	X	X	X	X	X	X	X	X	X
	Secure living conditions		X	X	X	X		X	X	X
	Human rights									X
	Community development	X	X	X	X	X	X	X		X
	Corruption		X	X	X	X		X		X
	Public policy									X
	Anti-competitive behavior									X
	Compliance								X	X
	Public commitments to sustainability issues									X
	Contribution to economic development	X	X	X	X	X	X	X		X
	Prevention and mitigation of armed conflicts									X
	Technology development									X
	Taxes paid	X	X	X	X	X	X	X		X
Value chain actors	Fair competition									X
	Promoting social responsibility	X	X	X	X	X	X	X	X	X
	Supplier relationships									X
	Respect of intellectual property rights									X

Table 3.5 Indicators selection

Area of concern	Aspects/indicators	SAM assessment model indicators
Workforce	Hazard	Injuries intensity
	Risk exposure at work	
	Accidents avoided	
	Fair wages	Income level
	Social benefits/Social security	
	Employment benefits	
	Right of labor organizations	–
	Minorities and ingenuous people	–
	Forced and child labor	Child labor
	Training/education	Staff development investment
	Freedom of association and collective bargaining	–
	Working hours	Worked hours
	Equal opportunities/discrimination	Income distribution
	Health and safety	Safety expenditures intensity
	Occupational health and safety	
	Security practices	
	Employment	Employment opportunity
	Labor/management relations	–
	Diversity and equal opportunity	–
	Investment and procurement practices	–
	Access to bathroom/potable	–
	Industry concentration	–
	Distance travelled	–
Product	Customer health and safety	–
	Product and service labeling	–
	Marketing communications	Product responsibility
	Compliance	
	Transparency	
	Customer privacy	–
	Safer products	–
	Feedback mechanism	–
	End of life responsibility	–
Local community	Access to material resources	–
	Delocalization and migration cultural heritage	–
	Safe and healthy living conditions	–
	Respect of indigenous rights	–
	Community engagement	–
	Local employment	Employment opportunity
	Secure living conditions	–
	Human rights	–
	Community development	Charitable contributions intensity local supply
	Contribution to economic development	
	Corruption	–
	Public policy	–
	Anti-competitive behavior	–
	Compliance	–
	Public commitments to sustainability issues	–
	Prevention and mitigation of armed conflicts	–
	Technology development	–
	Taxes paid	–

(continued)

Table 3.5 (continued)

Area of concern	Aspects/indicators	SAM assessment model indicators
Value chain actors	Fair competition	–
	Promoting social responsibility	–
	Supplier relationships	–
	Respect of intellectual property rights	–

3.2.3 Indicators List

This section is meant to summarize the list of the selected indicators presenting their definition and their unit of measure. The indicators have been grouped into three subsets considering the sustainability pillars: Environmental indicators, Economic indicators, Social indicators (Tables 3.6, 3.7, 3.8).

3.3 Environmental Indicators Calculation Formulas

The development of the environmental indicators calculation formulas is based on the LCA methodology, using the “Impact Potential” entities defined in Sect. 3.3.1.

Section 3.3.2 addresses the selection of the LCIA to be used for the calculation of the Impact Potential.

Section 3.3.3 is meant to list the lifecycle inventory (LCI) and LCIA databases containing the information needed to calculate the Impact Potentials. Eventually the calculation formulas of the indicators allowing the Assessment of the environmental impact of the solution space are presented.

3.3.1 Development of the Impact Potentials

The environmental interventions that occur during the solution space lifecycle generate flows of matter and energy between technosphere and nature. The LCI analysis lists the flows crossing the system boundaries assigning the LCI results to the impact categories that are the classes representing environmental issues of concern. LCI results provide the starting point for LCIA that is meant to measure the magnitude of the potential environmental impacts of the solution space. The LCIA could be performed through various methodologies that are characterized by a category indicator, a characterization model, and characterization factors. LCIA methodologies translate the input and the output of a process described by the LCI into effects on an environmental impact category measured through the category indicator value. This translation is performed by the characterization factors that are meant to measure the effect on the environment of a single flow relative to a specific basic flow (Guinée 2002).

Table 3.6 Environmental indicators list

Environmental aspect	Indicator	Definition	Unit of measure
Emissions	GWP—global warming potential	The GWP indicator measures the contribution to the global warming caused by the emission of greenhouse gases in the atmosphere	kg eq. CO_2
	POCP—photochemical ozone creation potential	The POCP indicator calculates the potential creation of tropospheric ozone ("summer smog" or "photochemical oxidation") caused by the release of those gases which will become oxidants in the low atmosphere under the action of the solar radiation	kg eq. C_2H_4
	EP—eutrophication potential	The EP indicator measures the contribution to the water eutrophication (enrichment in nutritive elements) of lakes and marine waters caused by the release of polluting substances in the water	kg eq. PO_4^{3-}
	ODP—stratospheric ozone depletion potential	The ODP indicator measures the contribution to the depletion of the stratospheric ozone layer caused by gas emissions	kg eq. CFC-11
	AP—acidification potential	The AP indicator measures the contribution to the air acidification caused by gas emissions in the atmosphere	kg eq. SO_2
	TP—toxicity potential	The TP is indeed a set of six indicators that measures the relative impact of the emitted substances on specific impact categories: freshwater aquatic eco toxicity potential (FAETP), marine aquatic eco toxicity potential (MAETP), freshwater sediment eco toxicity potential (FSETP), marine sediment eco toxicity potential (MSETP), terrestrial eco toxicity potential (TETP), and human toxicity potential (HTP) due to emission to environmental compartments (air, freshwater, sea water, agricultural, and industrial soil)	kg eq. 1,4-DCB

(continued)

Table 3.6 (continued)

Environmental aspect	Indicator	Definition	Unit of measure
Use of resources	NRD—natural resources depletion	The NRD indicator measures the depletion of non-renewable abiotic natural resources	kg eq. Sb
	LU—land use	The LU indicator measures the occupation of land occurred during the whole product lifecycle	m^2 year
	WD—water depletion	The WD indicator measures the water of any quality (drinkable, industrial…) consumed during the whole lifecycle of the product. Water used in a closed loop processes are not taken into account.	m^3
	ED—energy depletion	The ED indicator measures the energy consumed during the whole lifecycle of the product distinguishing between renewable and non-renewable sources	MJ
Waste	WP—waste production	The WP indicator calculates the quantity of waste produced during the whole lifecycle of the product	kg
	PRP—product recycling potential	The PRP indicator calculates the percentage in weight of the product that could be recycled using the current best recycling techniques	%

Table 3.7 Economic indicators list

Economic aspect	Indicator	Definition	Unit of measure
Efficiency	UPVC—unitary production variable cost	The UPVC indicator measures the direct variable costs (deducting overheads and taxes) related to the manufacturing of one product unit, calculated as the average one weighted on the expected product mix	€
	PLT—production lead time	Total time required to manufacture an item, including queue time, setup time, run time, move time, inspection time, and idle time	h
	VPLT—variability of production lead time	The VPLT indicator measures how much the actual production lead times differ from the mean value as its coefficient of variation	#
	VAT—value added time	The VAT indicator measures the percentage of the production lead time spent for operations that increase the value of the product	%
	TR—throughput rate	The TR indicator measures the number of units the production system can process in a given time	h^{-1}
	CUR—capacity utilization rate	The CUR indicator measures the capability of the production system to exploit available capacity	%
Profitability	UEGP—unitary expected gross profit	The UEGP indicator measures the difference between the revenues obtained by the unitary yearly product sales (calculated on an expected volume and product mix) and the unitary related costs, before deducting overhead, payroll, taxation, and interest payments	€
	PLC—product lifecycle cost	The PLC indicator measures the total costs the customer has to afford during the product lifecycle (price plus usage, maintenance, repair, and end of life costs)	€
Investments in technologies and competences	RDII—R&D investments intensity	The RDII indicator measures the company R&D investments allocating them on the solution space	€
Risk management	Supply risk	The SR indicator is a qualitative indicator measuring the risk associated to the provision of components, modules, parts, or final products based on the component criticality and the financial reliability of the supplier providing it	–

Table 3.8 Social indicators list

Social aspect	Indicator	Definition	Unit of measure
Working conditions and workforce	II—injuries intensity	The II indicator measures the number of yearly work related injuries, diseases, and fatalities occurred in the company allocating them on the solution space	#
	SEI—safety expenditures intensity	The SEI indicator measures the company safety expenditures allocating them on the solution space	€
	EO—employment opportunity	The EO indicator measures the percentage of the new employment opportunities created by the introduction of the solution space	%
	WTI—workforce turnover intensity	The WTI indicator measures the employees leaving the company allocating them on the solution space	#
	MSO—multi skilled operators	The MSO indicator measures the percentage of the multi-skilled workers within the solution space	%
	SDII—staff development investments intensity	The SDII indicator measures the staff development investments allocating them on the solution space	€
	ID—Income distribution	The ID indicator measures the equity of the employee wage distribution within the solution space	#
	IL—income level	The IL measures, within the solution space, the average annual income per employee divided by the average income per person in the country where the company is located	#
	WH—worked hours	The WH indicator measures the number of worked hours per employee per week within the solution space	h
	CL—child labor	The CL indicator measures the percentage of supply chain members within the solution space using child labor	%
Product responsibility	PSF—product social features	The PSF measures the number of product features that aim at improving the condition of specific target groups (i.e., product for disabled, elderly, and diabetic people)	#
Local community	LS—local supply	The LS indicator measures the percentage of the purchasing expenditures made to buy items from local suppliers	%
	CCI—charitable contributions intensity	The CCI indicator measures the expenditures and charitable contributions in favor of the local community allocating them on the solution space	€

The specific emission and the specific resources consumed are translated by the characterization factors defined by the LCIA methodologies into specific equivalent impacts within the various impact environmental categories covered by the environmental indicators selected. For instance, using the LCIA methodology IPCC 2007, that is meant to calculate the global warming potential (GWP) of the emitted greenhouse gases, each kilos of CH_4 emitted for each kg of steel extracted is translated into 25 equivalent kg of CO_2 emitted for 1 kg of steel extracted.

The specific equivalent impacts of each substance emitted or resource consumed concerning the same impact category are then summed obtaining what it has been called *Impact Potential* that is meant to summarize the specific environmental impacts of the solution space activities on a impact category. To sum up, the values of the Potentials can be calculated knowing the LCI results of an activity and considering a specific LCIA methodology. The Potential values and so the indicators values are LCIA methodology dependent. The LCI results could be obtained from direct measures or from LCI databases. Some of the LCI databases (e.g., Ecoinvent) provide also the value of the Potential calculated through various LCIA methodologies.

In order to calculate the environmental category indicator value of an activity performed during the solution space lifecycle (e.g., the extraction of a raw material, the manufacturing process of a component, the transportation of the final product,…), the Potential is multiplied by the "amount" of that activity. The development of the indicators formulas through the concept of Potentials enables the automation of the indicator calculation since the LCA data are grouped in the Potentials. The definitions of the Impact Potentials used in the calculation formulas are presented in Table 3.9.

3.3.2 Selection of the LCIA Methodology

As stated in Sect. 3.3.1, the Potential values could be calculated by different LCIA methodologies. Literature provides a wide range of available LCIA methodologies that has yet been cited in Sect. 3.2.2.1: ReCiPe 2009, Eco-indicator 99 (1999), Eco-indicator 95 (1999), CML (2001a, b), BEES, EDIP (2003), Impact (2002), TRACI, EPD 2007.

The selection of the LCIA methodology to be applied in the SAM assessment model has been carried out analyzing which of the available LCIA methodologies better address the selected environmental indicators. The map of the indicator covered by the LCIA methodologies has been performed considering the LCIA methods provided by Ecoinvent in order to directly verify the availability of data needed to perform the SAM assessment. Table 3.10 maps the identified environmental indicators covered by the LCIA methodologies included in Ecoinvent; this analysis has been carried out verifying also the coherence between the unit of measure used by Ecoinvent and those described in Sect. 3.3.4. Since the SAM environmental indicators are problem oriented, the damage-oriented LCIA

Table 3.9 Impact potentials definition

Acronym	Description
GWP	Global warming potential
POCP	Photochemical ozone creation potential
EP	Eutrophication potential
ODP	Stratospheric ozone depletion potential
AP	Acidification potential
FAETP	Freshwater aquatic eco toxicity potential
MAETP	Marine aquatic eco toxicity potential
FSETP	Freshwater sediment eco toxicity potential
MSETP	Marine sediment eco toxicity potential
TETP	Terrestrial eco toxicity potential
HTP	Human toxicity potential
ADP	Abiotic depletion potential
LUP	Land-use potential
WDP	Water depletion potential
EDP	Energy depletion potential
WPP	Waste production potential
PRP	Product recycling potential

methodologies considered by Ecoinvent (i.e., IMPACT (2002), Eco-indicator 99 (1999), Ecological Scarcity (1997) and (2006), ecosystem damage potential—EDP, and EPS2000) have been excluded in the selection process.

In Table 3.10 the "*" means that the indicator is measured with a different unit of measure from those expected in the indicator definition provided in Sect. 3.3.4.

The EDIP methodologies use a different set of unit of measure for two of the SAM indicators addressed, while for the NRD indicator takes into account only the depletion of a limited set of substances. EDIP is the only LCIA method included in Ecoinvent providing the measure of the waste generated by an activity to distinguish the land filling of: bulk waste, hazardous waste, radioactive waste, and slag and ashes.

CML2001 addresses eight of the twelve SAM environmental indicators using also the same unit of measure expected by the indicator definition. Among these eight indicators, the CML method calculates POCP distinguishing different kind of Photochemical Ozone Creation equivalent emissions. In order to obtain the value of the SAM indicator, it is possible to simply sum the different CML contributions concerning the Photochemical Ozone Creation.

The cumulative energy demand methodology is the only one calculating the energy depletion. This methodology distinguishes the depletion of non-renewable energy resources [(i.e., fossil, nuclear, primary forest) and renewable energy resources (i.e., biomass, potential (in barrage water), kinetic (in wind), and solar)].

TRACI covers six of the twelve SAM environmental indicators, but using the same unit of measure expected by the indicator definition for only two of them. Moreover, the methodology analyzes only the ecotoxicity aspect of toxicity.

Table 3.10 Match between SAM indicators and ecoinvent LCIA methodologies

Environmental aspect	Indicator	Unit of measure	EDIP	EDIP 2003	CML 2001	Cumulative energy demand	TRACI	ReCiPe midpoint	Selected LCI ecoinvent
Emissions	GWP—global warming potential	kg eq. CO_2	X	X	X		X	X	
	POCP—photochemical ozone creation potential	kg eq. C_2H_4	X	X*	X		X*	X*	
	EP—eutrophication potential	kg eq. PO_4^{3-}	X*	X*	X		X*	X*	
	ODP—stratospheric ozone depletion potential	kg eq. CFC-11	X	X	X		X	X	
	AP—acidification potential	kg eq. SO_2	X	X*	X		X*	X	
	TP—toxicity potential	kg eq. 1,4-DCB	X*	X	X		X*	X	
Use of resources	NRD—natural resources depletion	kg eq. Sb	X	X	X			X	
	LU—land use	m^2 year			X			X	X
	WD—water depletion	m^3						X	X
	ED—energy depletion	kWh				X			
Waste	WP—waste production	kg	X	X					
	PRP—product recycling potential	%							

ReCiPe addresses nine of the twelve SAM environmental indicators but about the acidification it considers only the terrestrial acidification, about the NRD indicator it considers only the metal depletion and the fossil depletion, about toxicity it addresses four toxicity compartments namely human, terrestrial, freshwater, and marine and about land use it considers only agricultural and urban land occupation.

Eventually, the Selected LCI of Ecoinvent covers only two of the twelve SAM environmental indicators even though it is one of the two methodologies addressing the water depletion.

The analysis performed on the LCIA methodologies provided by Ecoinvent shows that CML2001 is the best methodology fitting the SAM environmental indicators even though, in order to cover all the selected indicators, the water depletion of the selected LCI ecoinvent and the waste production (WP) of EDIP2003 have to be added.

CML2001 is a well-established LCIA methodology developed in 1992 and updated along the years obtaining the international agreement. CML2001 methodology is a baseline characterization method, methods that are recommended to be used by Guinée (2002) as the best available LCIA models. Moreover, CML2001 satisfy the selection criteria defined by the ISO relevant standard and the work of the second SETAC-Europe (Society for Environmental Toxicology and Chemistry) Working Group on Impact Assessment. Another advantage of this method is that the characterization factors are available for free allowing the calculation of new or ad hoc Potentials if the LCIA data are not directly available from databases.

3.3.3 LCI and LCIA Databases

The calculation of the environmental indicators needs LCI or LCIA data in order to calculate the Impact Potential mentioned in Sect. 3.3.1. Since the inventory analysis is the most expensive activity of LCA and environmental assessment in general, many databases have been developed in order to gather data about the most commonly used materials and processes that are relevant to the companies. A list of the most frequently used databases by the LCA software is presented in Table 3.11.

The mentioned LCI databases provide data about flows of materials, energy, and emission for a large set of materials and processes. Most of the LCI databases are available for free and in many cases the data are provided in XML format. The use of LCI databases does not completely solve the calculation of the Impact Potentials since the characterization factors of the chosen LCIA methodology are needed too and, as stated in the previous section, they are not always available. In this perspective, the use of databases providing directly LCIA data is preferred since they directly provide the Impact Potential needed to perform the assessment.

Table 3.11 LCI and LCIA databases

Name	Authors	Notes	Cost	Link
US lifecycle inventory database	NREL—national renewable energy laboratory	LCI database Data are available in XML and Excel format	For free	http://www.nrel.gov/lci/
Ecoinvent v2.2	Swiss centre for lifecycle inventories	LCI and LCIA database Data are available online, in XML and Excel format.	With fee	http://www.ecoinvent.org/database/registration
CPM database	CPM—Chalmers University of Technology, Göteborg	LCI database. Data are available online in HTML format	For free	http://cpmdatabase.cpm.chalmers.se/
ELCD—European reference lifecycle database	JRC—Joint Research Centre, European Commission	LCI database. Data are available in XML format	For free	http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm
CRMD—canadian raw materials database	University of Waterloo	LCI database. Data are available in PDF format	For free	http://crmd.uwaterloo.ca/eng.html
PROBAS Database	UBA—German Environmental Protection Agency; Oko-Institut	LCI database. Data are available online or in PDF format	For free	http://www.probas.umweltbundesamt.de/php/index.php
GaBi database	PE International	LCI and LCIA database	With fee	http://documentation.gabi-software.com/DataSetsByCategory_EnergyCarriers.html; http://www.gabi-software.com/support/gabi/gabi-lci-documentation/data-sets-by-database-modules/professional-database/
TEAM impact and DEAM database	Ecobilan	LCI and LCIA database. It has to be verified if it is possible to pay only for the access to the database without comprising the LCA tool	With fee	https://www.ecobilan.com/uk_team05.php

(continued)

Table 3.11 (continued)

Name	Authors	Notes	Cost	Link
MATBASE	TU Delft University of Technology	It provides mechanical, physica,l and environmental data of raw materials. The provided environmental data are LCIA data calculated through the eco-indicator methodology. Data are available online or in PDF format	For free	http://www.matbase.com/index.php
IdeMat	TU Delft University of Technology	LCIA database with data calculated through the eco-indicator 99 methodology It provides also technical information: price, mechanical, and physical characteristics	With fee	http://www.idemat.nl/index.htm
LCA food database	2.-0 LCA consultants; Faculty of agricultural sciences—Aarhus universitet, DK	LCIA data on basic food products produced and consumed in Denmark Data are available online in HTML format	For free	http://www.lcafood.dk/
CML-IA	CML—Institute of Environmental Science, Leiden University	It contains the CML2001 characterization factors	For free	http://cml.leiden.edu/software/data-cmlia.html
Database registry	UNEP—lifecycle initiative	The UNEP/SETAC database registry is a global repository for finding and offering LC-related datasets	For free	http://lca-data.org:8080/web/guest

3.3.4 Expected Contribution to the Environmental Indicators

The description of the expected contributions to all the indicators calculated on the basis of the Impact Potentials (the whole environment compartment with the exception of Product Recycling Potential indicator) is provided in this section grouping the contributions into the product lifecycle concerned phases.

Extraction: equivalent impact (namely emission, use of resources or waste) caused by the extraction of raw materials constituting the product, its packaging, and the surface treatments (e.g., paint, nickel used in galvanic processes, …).

Material processing: equivalent impact caused by the material processing of the raw materials constituting the product and its packaging.

Part manufacturing: equivalent impact caused by manufacturing operations. Since production processes use auxiliary materials and produce waste materials and scrap components, the equivalent impact occurred during the extraction, the material processing, the manufacturing processes, the transportations (from the suppliers and to the EOL facilities), and the EOL treatments of auxiliary materials, waste materials, and scrap components are also taken into account.

Assembly: equivalent impact caused by assembly operations. Since assembly processes use auxiliary materials and produce scrap assemblies, the equivalent impact occurred during the extraction, the material processing, the transportations (from the suppliers and to the EOL facilities), and the EOL treatments of the auxiliary materials and scrap assemblies are also taken into account.

Product use: equivalent impact caused by the product use. They include both direct impact of the product during its use and indirect equivalent impact due to the energy consumed during the use phase. Since during the use phase consumables are used, the equivalent impact occurred during the extraction, the material processing, the manufacturing processes, the transportations (from the suppliers and to the EOL facilities), and the EOL treatments of the consumables are also taken into account.

Repair: equivalent impact occurred during the extraction, the material processing, the manufacturing processes, the transportations (from the suppliers and to the EOL facilities and customers), and the EOL treatments of the spare parts.

End of life: equivalent impact caused by end of life treatments carried out on the product and its packaging.

Transportation: equivalent impact caused by transportations of raw materials and components from suppliers, transportation of the finished product (product plus packaging) to retailers or customers, and transportations of the finished product to end of life facilities.

The total value of the environmental indicators is obtained summing the contributions of all the lifecycle phases.

3.3.5 Emissions

This section is meant to provide the calculation formulas of the environmental indicators concerning the emissions: the GWP, the Photochemical ozone creation potential (POCP), the eutrophication potential (EP), the stratospheric ozone depletion potential (ODP), the acidification potential (AP), the freshwater aquatic ecotoxicity potential (FAETP), the freshwater sediment ecotoxicity potential (FSETP), the marine aquatic ecotoxicity potential (MAETP), the marine sediment ecotoxicity potential (MSETP), the terrestrial ecotoxicity potential (TETP), and the human toxicity potential (HTP).

3.3.5.1 Global Warming Potential Indicator Calculation Formula

The GWP indicator measures the contribution to the global warming caused by the emission of greenhouse gases in the atmosphere. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of greenhouse gases and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The greenhouse gas emissions are translated into equivalent kilos of CO_2 emitted using the carbon dioxide as a reference gas. The definition of the GWP calculation formula is provided here (Table 3.12):

3.3.5.2 Photochemical Ozone Creation Potential Indicator Calculation Formula

The POCP indicator calculates the potential creation of tropospheric ozone (“summer smog” or “photochemical oxidation”) caused by the release of those gases which will become oxidants in the low atmosphere under the action of the solar radiation. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of oxidant gases and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The oxidant gases emissions are translated into equivalent kg of C_2H_4 emitted using the ethylene as a reference gas. The definition of the POCP calculation formula is provided here, by offering a substitution table that allows to derive the POCP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.13).

Table 3.12 GWP calculation formula

LC Phase	Data from design tools, data entry, and databases	Formula
	i = ith component of the final customizable product j = material type f_i = frequency of the ith component in the expected product mix (expected population of final products with their customization options) $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type j p = material processing operation l = EOL treatment q = supplier z = mean of transportation r = EOL facility	
Extraction	$GWP_{ext\ j}$[kg eq. CO_2/kg] = GWP for the extraction of material j	$GWP_{ext} = \sum_i \sum_j f_i \times V_{i,j} \times \rho_j \times\ GWP_{ext\,j}$
Material processing	$\chi_{p,i,j}$ = boolean: 1 if the material processing p is made on the material j for the ith component; otherwise 0 $GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j	$GWP_{mp} = \sum_i \sum_j \sum_p f_i \times \chi_{p,i,j} \times V_{i,j} \times \rho_j \times\ GWP_{mp\,p,j}$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Part manufacturing	SRC = average scrap rate of the components m = manufacturing operation f_m = frequency of the manufacturing operation m CS_m = specific GWP measure parameter for operation m $GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m $GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j $GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j $f_{SRC\ i,j,l}$ = frequency of the EOL treatment l performed on material j for the ith scrap component $GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z $GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z $f_{SRC\ i,j,r}$ = frequency of material j for ith scrap component treated by the EOL facility r $d_{EOL\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z w = auxiliary material $Q_{aux\ w,m}$ [kg/operation] = quantity of the auxilary material w used during the operation m $GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w $\chi_{p,w}$ = boolean: 1 if the material processing p is made on the auxiliary material w; otherwise 0 $GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w $f_{w,l}$ = frequency of the EOL treatment l performed on the auxiliary material w $GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l	$GWP_{man} = (1+SRC) \times \left(\sum_m f_m \times CS_m \times GWP_{man\ m}\right)$ $+ SRC \times \Big(\sum_i \sum_j f_i \times V_{i,j} \times \rho_j \times GWP_{ext\ j}$ $+ \sum_i \sum_j \sum_p f_i \times \chi_{p,i,j} \times V_{i,j} \times \rho_j \times GWP_{mp\ p,j}$ $+ \sum_i \sum_j \sum_l f_i \times f_{SRC\ i,j,l} \times V_{i,j} \times \rho_j \times GWP_{EOL\ j,l}$ $+ \sum_i \sum_j \sum_q \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,q} \times d_{i,j,q,z} \times GWP_{tra\ z}$ $+ \sum_i \sum_j \sum_r \sum_z f_i \times V_{i,j} \times \rho_j \times f_{SRC\ i,j,r} \times d_{EOL\ r,z} \times GWP_{tra\ z}\Big)$ $+ (1+SRC) \times \Big(\sum_m \sum_w f_m \times Q_{aux\ w,m} \times GWP_{ext\ w}$ $+ \sum_m \sum_w \sum_p f_m \times \chi_{p,w} \times Q_{aux\ w,m} \times GWP_{mp\ p,w}$ $+ \sum_m \sum_w \sum_l f_m \times f_{w,l} \times Q_{aux\ w,m} \times GWP_{EOL\ w,l}$ $+ \sum_m \sum_w \sum_q \sum_z f_m \times f_{w,q} \times Q_{aux\ w,m} \times d_{w,q,z} \times GWP_{tra\ z}$ $+ \sum_m \sum_w \sum_r \sum_z f_m \times f_{w,r} \times Q_{aux\ w,m} \times d_{EOL\ r,z} \times GWP_{tra\ z}\Big)$ $+ (1+SRC) \times \Big(\sum_m \sum_j f_m \times Q_{wm\ j,m} \times GWP_{ext\ j}$ $+ \sum_m \sum_j \sum_p f_m \times \chi_{p,j} \times Q_{wm\ j,m} \times GWP_{mp\ p,j}$ $+ \sum_m \sum_j \sum_l f_m \times f_{j,l} \times Q_{wm\ j,m} \times GWP_{EOL\ j,l}$ $+ \sum_m \sum_j \sum_q \sum_z f_m \times f_{j,q} \times Q_{wm\ j,m} \times d_{j,q,z} \times GWP_{tra\ z}$ $+ \sum_m \sum_j \sum_r \sum_z f_m \times f_{j,r} \times Q_{wm\ j,m} \times d_{EOL\ r,z} \times GWP_{tra\ z}\Big)$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
	$f_{w,q}$ = frequency of the auxiliary material *w* provided by the supplier *q* $d_{w,q,z}$ [km] = distance between supplier *q* (providing auxiliary material *w*) and the next supply chain partner covered by the mean of transportation *z* $f_{w,r}$ = frequency of the auxiliary material *w* treated by the EOL facility *r* $Q_{\mathrm{wm}\,j,m}$ [kg/operation] = quantity of the waste material *j* coming from the operation *m* $\chi_{p,j}$ = boolean: 1 if the material processing *p* is made on the material *j*; otherwise 0 $f_{j,l}$ = frequency of the EOL treatment *l* performed on the material *j* $f_{j,q}$ = frequency of the material *j* provided by the supplier *q* $d_{j,q,z}$ [km] = distance between supplier *q* (providing material *j*) and the next supply chain partner covered by the mean of transportation *z* $f_{j,r}$ = frequency of material *j* treated by the EOL facility *r*	
Assembly	SRA = average scrap rate of the assemblies *o* = assembly operation f_o = frequency of the assembly operation *o* CS_o = specific GWP measure parameter for assembly operation *o* $\mathrm{GWP}_{\mathrm{as}\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o* *a* = *a*th assembly of the final customizable product f_a = frequency of the *a*th assembly in the expected product mix $V_{a,j}$ [cm^3] = volume of the part of the *a*th assembly, made by material *j* $\mathrm{GWP}_{\mathrm{ext}\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j* $\chi_{p,a,j}$ = boolean: 1 if the material processing *p* is made on the material *j* for the *a*th assembly; otherwise 0 $\mathrm{GWP}_{\mathrm{mp}\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j* $f_{a,j,l}$ = frequency of the EOL treatment *l* performed on material *j* for the *a*th scrap assembly $\mathrm{GWP}_{\mathrm{EOL}\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l* $f_{a,j,q}$ = frequency of the material *j* for the *a*th assembly provided by supplier *q* $d_{a,j,q,z}$ [km] = distance between supplier *q* (providing material *j* for the *a*th assembly) and the next supply chain partner covered by the mean of transportation *z* $\mathrm{GWP}_{\mathrm{tra}\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$\mathrm{GWP}_{\mathrm{as}} = (1+\mathrm{SRA}) \times \left(\sum_o f_o \times \mathrm{CS}_o \times \mathrm{GWP}_{\mathrm{as}o}\right)$ $+\ \mathrm{SRA} \times \Bigg(\sum_a \sum_j f_a \times V_{a,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{ext}j}$ $+\sum_a \sum_j \sum_p f_a \times \chi_{p,a,j} \times V_{a,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{mp}p,j}$ $+\sum_a \sum_j \sum_l f_a \times f_{a,j,l} \times V_{a,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{EOL}j,l}$ $+\sum_a \sum_j \sum_q \sum_z f_a \times V_{a,j} \times \rho_j \times f_{a,j,q} \times d_{a,j,q,z} \times \mathrm{GWP}_{\mathrm{tra}z}$ $+\sum_a \sum_j \sum_r \sum_z f_a \times V_{a,j} \times \rho_j \times f_{a,j,r} \times d_{\mathrm{EOL}r,z} \times \mathrm{GWP}_{\mathrm{tra}z}\Bigg)$ $+\ (1+\mathrm{SRA}) \times \Bigg(\sum_o \sum_w f_o \times Q_{\mathrm{aux}w,o} \times \mathrm{GWP}_{\mathrm{ext}w}$ $+\sum_o \sum_w \sum_p f_o \times \chi_{p,w} \times Q_{\mathrm{aux}w,o} \times \mathrm{GWP}_{\mathrm{mp}p,w}$ $+\sum_o \sum_w \sum_l f_o \times f_{w,l} \times Q_{\mathrm{aux}w,o} \times \mathrm{GWP}_{\mathrm{EOL}w,l}$ $+\sum_o \sum_w \sum_q \sum_z f_o \times f_{w,q} \times Q_{\mathrm{aux}w,o} \times d_{w,q,z} \times \mathrm{GWP}_{\mathrm{tra}z}$ $+\sum_o \sum_w \sum_r \sum_z f_o \times f_{w,r} \times Q_{\mathrm{aux}w,o} \times d_{\mathrm{EOL}r,z} \mathrm{GWP}_{\mathrm{tra}z}\Bigg)$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
	$f_{a,j,r}$ = frequency of material j for the ath scrap assembly treated by the EOL facility r w = auxiliary material $Q_{\text{aux } w,o}$ [kg/operation] = quantity of the auxiliary material w used during the operation o $\text{GWP}_{\text{ext } w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w $\chi_{p,w}$ = boolean: 1 if the material processing p is made on the auxiliary material w; otherwise 0 $\text{GWP}_{\text{mp } p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w $f_{w,l}$ = frequency of the EOL treatment l performed on the auxiliary material w $\text{GWP}_{\text{EOL } w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l $f_{w,q}$ = frequency of the auxiliary material w provided by the supplier q $d_{w,q,z}$ [km] = distance between supplier q (providing auxiliary material w) and the next supply chain partner covered by the mean of transportation z $f_{w,r}$ = frequency of the auxiliary material w treated by the EOL facility r $d_{\text{EOL } r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Product use	c = country y = energy type f_c = frequency of the country c f_y = frequency of the energy type y used by the product E_{use} [kWh] = $P \times \mathrm{US}$ P [kW] = power dissipated in the use phase by the product US [h] = usage scenario—hours of use in the product usage $\mathrm{GWP}_{\mathrm{en}\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c $\mathrm{GWP}_{\mathrm{up}}$ [kg eq. CO_2/h] = GWP of the use phase k = kth consumable component $n_{\mathrm{cons}\ k}$ = number of consumable components k expected to be used per unit of product during the product use phase f_k = frequency of kth consumable in the expected product mix $V_{\mathrm{cons}\ k,j}$ [cm^3] = volume of the part of the kth consumable component made by the material j $\mathrm{GWP}_{\mathrm{ext}\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j $\chi_{p,k,j}$ = boolean: 1 if the material processing p is made on the material j for the kth consumable; otherwise 0 $\mathrm{GWP}_{\mathrm{mp}\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j $f_{k,j,l}$ = frequency of the EOL treatment l performed on material j for the kth consumable component $\mathrm{GWP}_{\mathrm{EOL}\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l $f_{k,j,q}$ = frequency of the material j for kth consumable component provided by the supplier q $d_{k,j,q,z}$ [km] = distance between supplier q (providing material j for kth consumable component) and the next supply chain partner covered by the mean of transportation z $\mathrm{GWP}_{\mathrm{tra}\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $f_{k,j,r}$ = frequency of the material j for kth consumable component treated by the EOL facility r	$\mathrm{GWP}_{\mathrm{use}} = \sum_c \sum_y f_c \times f_y \times E_{\mathrm{use}} \times \mathrm{GWP}_{\mathrm{en}\ y,c}$ $+\ \mathrm{GWP}_{\mathrm{up}} \times \mathrm{US}$ $+\sum_k n_{\mathrm{cons}\,k} \times \Big(\sum_j f_k \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{ext}\,j}$ $+\sum_j \sum_p f_k \times \chi_{p,k,j} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{mp}\,p,j}$ $+\sum_j \sum_l f_k \times f_{k,j,l} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{EOL}\ j,l}$ $+\sum_j \sum_q \sum_z f_k \times V_{\mathrm{cons}\,k,j} \times \rho_j \times f_{k,j,q} \times d_{k,j,q,z} \times \mathrm{GWP}_{\mathrm{tra}\ z}$ $+\sum_j \sum_z f_k \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{cust\ z} \times GWP_{tra\ z}$ $+\sum_j \sum_r \sum_z f_k \times V_{\mathrm{cons}\,k,j} \times \rho_j \times f_{k,j,r} \times d_{EOL\ r,z} \times GWP_{tra\ z} \Big)$ $+\sum_g f_g \times \mathrm{CS}_g \times \mathrm{GWP}_{\mathrm{man}g}$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
	$d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z g = manufacturing operations making the consumable components that are expected to be used per unit of product during the product use phase f_g = frequency of the manufacturing operation g CS_g = specific GWP measure parameter for manufacturing operation g $\mathrm{GWP}_{\mathrm{man}\ g}$ [kg eq. $\mathrm{CO_2}/\mathrm{CS}_g$] = GWP for manufacturing operation g	
Repair	$n_{s\ i}$ = number of substitutions of the ith component expected to occur during the product use phase $\mathrm{GWP}_{\mathrm{ext}\ j}$ [kg eq. $\mathrm{CO_2}$/kg] = GWP for the extraction of material j $\chi_{p,i,j}$ = boolean: 1 if the material processing p is made on the material j for the ith component; otherwise 0 $\mathrm{GWP}_{\mathrm{mp}\ p,j}$ [kg eq. $\mathrm{CO_2}$/kg] = GWP for the material processing p used for material j $f_{i,j,l}$ = frequency of the EOL treatment l performed on material j for the ith component $\mathrm{GWP}_{\mathrm{EOL}\ j,l}$ [kg eq. $\mathrm{CO_2}$/kg] = GWP for the EOL of material j, done with treatment l $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z $\mathrm{GWP}_{\mathrm{tra}\ z}$ [kg eq. $\mathrm{CO_2}$/(kg km)] = GWP for transportation done by the mean z $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z m = manufacturing operation $f_{s\ m}$ = frequency of the manufacturing operation m making the substitution components expected to be used per unit of product during the product use phase CS_m = specific GWP measure parameter for operation m $\mathrm{GWP}_{\mathrm{man}\ m}$ [kg eq. $\mathrm{CO_2}/\mathrm{CS}_m$] = GWP for manufacturing operation m o = assembly operation $f_{s\ o}$ = frequency of the assembly operation o making the substitution assemblies expected to be used per unit of product during the product use phase CS_o = specific GWP measure parameter for assembly operation o $\mathrm{GWP}_{\mathrm{as}\ o}$ [kg eq. $\mathrm{CO_2}/\mathrm{CS}_o$] = GWP for the assembly operation o	$\begin{aligned} \mathrm{GWP}_{\mathrm{rep}} = \sum_i n_{s\ i} \times \Bigg(& \sum_j f_i \times V_{i,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{ext}\ j} \\ & + \sum_j \sum_p f_i \times \chi_{p,i,j} \times V_{i,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{mp} p,j} \\ & + \sum_j \sum_l f_i \times f_{i,j,l} \times V_{i,j} \times \rho_j\ \mathrm{GWP}_{\mathrm{EOL} j,l} \\ & + \sum_j \sum_q \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,q} \times d_{i,j,q,z} \times \mathrm{GWP}_{\mathrm{tra} z} \\ & + \sum_j \sum_z f_i \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\ z} \times \mathrm{GWP}_{\mathrm{tra}\ z} \\ & + \sum_j \sum_r \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,r} \times d_{\mathrm{EOL}\ r,z} \times \mathrm{GWP}_{\mathrm{tra}\ z} \Bigg) \\ & + \sum_m f_{s\ m} \times \mathrm{CS}_m \times \mathrm{GWP}_{\mathrm{man}\ m} + \sum_o f_{s\ o} \times \mathrm{CS}_o \times \mathrm{GWP}_{\mathrm{as}\ o} \end{aligned}$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
EOL	$f_{i,j,l}$ = frequency of the EOL treatment l performed on material j for the ith component $\mathrm{GWP}_{\mathrm{EOL}\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$\mathrm{GWP}_{\mathrm{EOL}} = \sum_i \sum_j \sum_l f_i \times f_{i,j,l} \times V_{i,j} \times \rho_j \times \mathrm{GWP}_{\mathrm{EOL}\,j,l}$
Transportation	$f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z $\mathrm{GWP}_{\mathrm{tra}\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	$\mathrm{GWP}_{\mathrm{tra}} = \sum_i \sum_j \sum_q \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,q} \times d_{i,j,q,z} \times \mathrm{GWP}_{\mathrm{tra}\,z}$ $+ \sum_i \sum_j \sum_z f_i \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\,z} \times \mathrm{GWP}_{\mathrm{tra}\,z}$ $+ \sum_i \sum_j \sum_r \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,r} \times d_{\mathrm{EOL}\,r,z} \times \mathrm{GWP}_{\mathrm{tra}\,z}$

Table 3.13 POCP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$POCP_{ext\ j}$ [kg eq. C_2H_4/kg] = POCP for the extraction of material *j*
GWP_{ext}	$POCP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material *j*	$POCP_{mp\ p,j}$ [kg eq. C_2H_4/kg] = POCP for the material processing *p* used for material *j*
GWP_{mp}	$POCP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$POCP_{man\ m}$ [kg eq. C_2H_4/CS_m] = POCP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$POCP_{EOL\ j,l}$ [kg eq. C_2H_4/kg] = POCP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$POCP_{tra\ z}$ [kg eq. C_2H_4/(kg km)] = POCP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$POCP_{ext\ w}$ [kg eq. C_2H_4/kg] = POCP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material *w*	$POCP_{mp\ p,w}$ [kg eq. C_2H_4/kg] = POCP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$POCP_{EOL\ w,l}$ [kg eq. C_2H_4/kg] = POCP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	$POCP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$POCP_{as\ o}$ [kg eq. C_2H_4/CS_o] = POCP for the assembly operation *o*
GWP_{as}	$POCP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$POCP_{en\ y,c}$ [kg eq. C_2H_4/kWh] = POCP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$POCP_{up}$ [kg eq. C_2H_4/h] = POCP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$POCP_{man\ g}$ [kg eq. C_2H_4/CS_g] = POCP for manufacturing operation *g*
GWP_{use}	$POCP_{use}$
GWP_{rep}	$POCP_{rep}$
GWP_{EOL}	$POCP_{EOL}$
GWP_{tra}	$POCP_{tra}$

3.3.5.3 Eutrophication Potential Indicator Calculation Formula

The EP indicator measures the contribution to the water eutrophication (enrichment in nutritive elements) of lakes and marine waters caused by the release of polluting substances in the water. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of eutrophicating substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The eutrophicating substances emissions are translated into equivalent kg of PO_4^{3-} emitted using the phosphates as reference substances. The definition of the EP calculation formula is provided here, by offering a substitution table that allows to derive the EP calculus

Table 3.14 EP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$EP_{ext\ j}$ [kg eq. PO_4^{3-}/kg] = EP for the extraction of material *j*
GWP_{ext}	EP_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material *j*	$EP_{mp\ p,j}$ [kg eq. PO_4^{3-}/kg] = EP for the material processing p used for material *j*
GWP_{mp}	EP_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m	$EP_{man\ m}$ [kg eq. PO_4^{3-}/CS_m] = EP for manufacturing operation m
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$EP_{EOL\ j,l}$ [kg eq. PO_4^{3-}/kg] = EP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$EP_{tra\ z}$ [kg eq. PO_4^{3-}/(kg km)] = EP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$EP_{ext\ w}$ [kg eq. PO_4^{3-}/kg] = EP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$EP_{mp\ p,w}$ [kg eq. PO_4^{3-}/kg] = EP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$EP_{EOL\ w,l}$ [kg eq. PO_4^{3-}/kg] = EP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	EP_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$EP_{as\ o}$ [kg eq. PO_4^{3-}/CS_o] = EP for the assembly operation *o*
GWP_{as}	EP_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$EP_{en\ y,c}$ [kg eq. PO_4^{3-}/kWh] = EP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	EP_{up} [kg eq. PO_4^{3-}/h] = EP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$EP_{man\ g}$ [kg eq. PO_4^{3-}/CS_g] = EP for manufacturing operation *g*
GWP_{use}	EP_{use}
GWP_{rep}	EP_{rep}
GWP_{EOL}	EP_{EOL}
GWP_{tra}	EP_{tra}

from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.14).

3.3.5.4 Stratospheric Ozone Depletion Potential Indicator Calculation Formula

The ODP indicator measures the contribution to the depletion of the stratospheric ozone layer caused by the emission of ozone depleting gases. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of

Table 3.15 ODP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j	$ODP_{ext\ j}$ [kg eq. CFC-11/kg] = ODP for the extraction of material j
GWP_{ext}	ODP_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j	$ODP_{mp\ p,j}$ [kg eq. CFC-11/kg] = ODP for the material processing p used for material j
GWP_{mp}	ODP_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m	$ODP_{man\ m}$ [kg eq. CFC-11/CS_m] = ODP for manufacturing operation m
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$ODP_{EOL\ j,l}$ [kg eq. CFC-11/kg] = ODP for the EOL of material j, done with treatment l
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z	$ODP_{tra\ z}$ [kg eq. CFC-11/(kg km)] = ODP for transportation done by the mean z
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w	$ODP_{ext\ w}$ [kg eq. CFC-11/kg] = ODP for the extraction of the auxiliary material w
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w	$ODP_{mp\ p,w}$ [kg eq. CFC-11/kg] = ODP for the material processing p used for auxiliary material w
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l	$ODP_{EOL\ w,l}$ [kg eq. CFC-11/kg] = ODP for the EOL of auxiliary material w, done with EOL treatment l
GWP_{man}	ODP_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o	$ODP_{as\ o}$ [kg eq. CFC-11/CS_o] = ODP for the assembly operation o
GWP_{as}	ODP_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c	$ODP_{en\ y,c}$ [kg eq. CFC-11/kWh] = ODP for energy y production in country c
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	ODP_{up} [kg eq. CFC-11/h] = ODP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation g	$ODP_{man\ g}$ [kg eq. CFC-11/CS_g] = ODP for manufacturing operation g
GWP_{use}	ODP_{use}
GWP_{rep}	ODP_{rep}
GWP_{EOL}	ODP_{EOL}
GWP_{tra}	ODP_{tra}

ozone depleting gases and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The ozone depleting gases emissions are translated into equivalent kg of CFC-11 emitted using the trichlorofluoromethane as reference substance. The definition of the ODP calculation formula is provided here, by offering a substitution table that allows to derive the ODP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.15).

3.3.5.5 Acidification Potential Indicator Calculation Formula

The AP indicator measures the contribution to the acidification caused by acidification gases emitted in the atmosphere. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of acidification gases and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The acidification gases emissions are translated into equivalent kg of SO_2 emitted using the sulfur dioxide as reference substances. The definition of the EP calculation formula is provided here, by offering a substitution table that allows to derive the EP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.16).

Table 3.16 AP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$AP_{ext\ j}$ [kg eq. SO_2/kg] = AP for the extraction of material *j*
GWP_{ext}	AP_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$AP_{mp\ p,j}$ [kg eq. SO_2/kg] = AP for the material processing *p* used for material *j*
GWP_{mp}	AP_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$AP_{man\ m}$ [kg eq. SO_2/CS_m] = AP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$AP_{EOL\ j,l}$ [kg eq. SO_2/kg] = AP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$AP_{tra\ z}$ [kg eq. SO_2/(kg km)] = AP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$AP_{ext\ w}$ [kg eq. SO_2/kg] = AP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$AP_{mp\ p,w}$ [kg eq. SO_2/kg] = AP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$AP_{EOL\ w,l}$ [kg eq. SO_2/kg] = AP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	AP_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$AP_{as\ o}$ [kg eq. SO_2/CS_o] = AP for the assembly operation *o*
GWP_{as}	AP_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$AP_{en\ y,c}$ [kg eq. SO_2/kWh] = AP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	AP_{up} [kg eq. SO_2/h] = AP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$AP_{man\ g}$ [kg eq. SO_2/CS_g] = AP for manufacturing operation *g*
GWP_{use}	AP_{use}
GWP_{rAP}	AP_{rAP}
GWP_{EOL}	AP_{EOL}
GWP_{tra}	AP_{tra}

3.3.5.6 Freshwater Aquatic Eco Toxicity Potential Indicator Calculation Formula

The FAETP measures the relative impact of toxic substances on the freshwater aquatic environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the FAETP calculation formula is provided here, by offering a substitution table that allows to derive the FAETP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.17).

Table 3.17 FAETP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j	$FAETP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = FAETP for the extraction of material j
GWP_{ext}	$FAETP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j	$FAETP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = FAETP for the material processing p used for material j
GWP_{mp}	$FAETP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m	$FAETP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = FAETP for manufacturing operation m
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$FAETP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = FAETP for the EOL of material j, done with treatment l
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z	$FAETP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = FAETP for transportation done by the mean z
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w	$FAETP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = FAETP for the extraction of the auxiliary material w
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w	$FAETP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = FAETP for the material processing p used for auxiliary material w
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l	$FAETP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = FAETP for the EOL of auxiliary material w, done with EOL treatment l
GWP_{man}	$FAETP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o	$FAETP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = FAETP for the assembly operation o
GWP_{as}	$FAETP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c	$FAETP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = FAETP for energy y production in country c
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$FAETP_{up}$ [kg eq. 1,4-DCB/h] = FAETP of the use phase

(continued)

Table 3.17 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$FAETP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = FAETP for manufacturing operation *g*
GWP_{use}	$FAETP_{use}$
GWP_{rep}	$FAETP_{rep}$
GWP_{EOL}	$FAETP_{EOL}$
GWP_{tra}	$FAETP_{tra}$

3.3.5.7 Marine Aquatic Eco Toxicity Potential Indicator Calculation Formula

The MAETP measures the relative impact of toxic substances on the marine aquatic environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the MAETP calculation formula is provided here, by offering a substitution table that allows to derive the MAETP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.18).

Table 3.18 MAETP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$MAETP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = MAETP for the extraction of material *j*
GWP_{ext}	$MAETP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$MAETP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = MAETP for the material processing *p* used for material *j*
GWP_{mp}	$MAETP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$MAETP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = MAETP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$MAETP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = MAETP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$MAETP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = MAETP for transportation done by the mean *z*

(continued)

Table 3.18 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$MAETP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = MAETP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$MAETP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = MAETP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$MAETP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = MAETP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	$MAETP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$MAETP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = MAETP for the assembly operation *o*
GWP_{as}	$MAETP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$MAETP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = MAETP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$MAETP_{up}$ [kg eq. 1,4-DCB/h] = MAETP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$MAETP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = MAETP for manufacturing operation *g*
GWP_{use}	$MAETP_{use}$
GWP_{rep}	$MAETP_{rep}$
GWP_{EOL}	$MAETP_{EOL}$
GWP_{tra}	$MAETP_{tra}$

3.3.5.8 Freshwater Sediment Eco Toxicity Potential Indicator Calculation Formula

The FSETP measures the relative impact of toxic substances on the freshwater sediment environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the FSETP calculation formula is provided here, by offering a substitution table that allows to derive the FSETP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.19).

Table 3.19 FSETP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j	$FSETP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = FSETP for the extraction of material j
GWP_{ext}	$FSETP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j	$FSETP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = FSETP for the material processing p used for material j
GWP_{mp}	$FSETP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m	$FSETP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = FSETP for manufacturing operation m
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$FSETP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = FSETP for the EOL of material j, done with treatment l
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z	$FSETP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = FSETP for transportation done by the mean z
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w	$FSETP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = FSETP for the extraction of the auxiliary material w
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w	$FSETP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = FSETP for the material processing p used for auxiliary material w
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l	$FSETP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = FSETP for the EOL of auxiliary material w, done with EOL treatment l
GWP_{man}	$FSETP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o	$FSETP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = FSETP for the assembly operation o
GWP_{as}	$FSETP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c	$FSETP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = FSETP for energy y production in country c
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$FSETP_{up}$ [kg eq. 1,4-DCB/h] = FSETP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation g	$FSETP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = FSETP for manufacturing operation g
GWP_{use}	$FSETP_{use}$
GWP_{rep}	$FSETP_{rep}$
GWP_{EOL}	$FSETP_{EOL}$
GWP_{tra}	$FSETP_{tra}$

3.3.5.9 Marine Sediment Eco Toxicity Potential Indicator Calculation Formula

The MSETP measures the relative impact of toxic substances on the marine sediment environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the MSETP calculation formula is provided here, by offering a substitution table that allows to derive the MSETP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.20).

Table 3.20 MSETP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material j	$MSETP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = MSETP for the extraction of material j
GWP_{ext}	$MSETP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material j	$MSETP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = MSETP for the material processing p used for material j
GWP_{mp}	$MSETP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation m	$MSETP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = MSETP for manufacturing operation m
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$MSETP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = MSETP for the EOL of material j, done with treatment l
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z	$MSETP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = MSETP for transportation done by the mean z
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material w	$MSETP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = MSETP for the extraction of the auxiliary material w
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing p used for auxiliary material w	$MSETP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = MSETP for the material processing p used for auxiliary material w
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material w, done with EOL treatment l	$MSETP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = MSETP for the EOL of auxiliary material w, done with EOL treatment l
GWP_{man}	$MSETP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o	$MSETP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = MSETP for the assembly operation o
GWP_{as}	$MSETP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c	$MSETP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = MSETP for energy y production in country c
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$MSETP_{up}$ [kg eq. 1,4-DCB/h] = MSETP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation g	$MSETP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = MSETP for manufacturing operation g
GWP_{use}	$MSETP_{use}$
GWP_{rep}	$MSETP_{rep}$
GWP_{EOL}	$MSETP_{EOL}$
GWP_{tra}	$MSETP_{tra}$

3.3.5.10 Terrestrial Eco Toxicity Potential Indicator Calculation Formula

The TETP measures the relative impact of toxic substances on the terrestrial environment due to the emissions to environmental compartments air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the TETP calculation formula is provided here, by offering a substitution table that allows to derive the TETP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.21).

Table 3.21 TETP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$TETP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = TETP for the extraction of material *j*
GWP_{ext}	$TETP_{ext}$
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$TETP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = TETP for the material processing *p* used for material *j*
GWP_{mp}	$TETP_{mp}$
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$TETP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = TETP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$TETP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = TETP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$TETP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = TETP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$TETP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = TETP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$TETP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = TETP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$TETP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = TETP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	$TETP_{man}$
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$TETP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = TETP for the assembly operation *o*
GWP_{as}	$TETP_{as}$
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$TETP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = TETP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	$TETP_{up}$ [kg eq. 1,4-DCB/h] = TETP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$TETP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = TETP for manufacturing operation *g*
GWP_{use}	$TETP_{use}$
GWP_{rep}	$TETP_{rep}$
GWP_{EOL}	$TETP_{EOL}$
GWP_{tra}	$TETP_{tra}$

3.3.5.11 Human Toxicity Potential Indicator Calculation Formula

The HTP measures the relative impact of toxic substances on human beings related to the to the emissions in environmental compartments, namely air, freshwater, seawater, agricultural, and industrial soil. As suggested by the LCA methodology, the calculation formula addresses both the direct emission of toxic substances and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The toxic substances emissions are translated into equivalent kg of 1,4-DCB emitted using the 1,4 dichlorobenzene as reference substance. The definition of the HTP calculation formula is provided here, by offering a substitution table that allows to derive the HTP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.22).

Table 3.22 HTP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$HTP_{ext\ j}$ [kg eq. 1,4-DCB/kg] = HTP for the extraction of material *j*
GWP_{ext}	HTP_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$HTP_{mp\ p,j}$ [kg eq. 1,4-DCB/kg] = HTP for the material processing *p* used for material *j*
GWP_{mp}	HTP_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$HTP_{man\ m}$ [kg eq. 1,4-DCB/CS_m] = HTP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$HTP_{EOL\ j,l}$ [kg eq. 1,4-DCB/kg] = HTP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$HTP_{tra\ z}$ [kg eq. 1,4-DCB/(kg km)] = HTP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$HTP_{ext\ w}$ [kg eq. 1,4-DCB/kg] = HTP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$HTP_{mp\ p,w}$ [kg eq. 1,4-DCB/kg] = HTP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$HTP_{EOL\ w,l}$ [kg eq. 1,4-DCB/kg] = HTP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	HTP_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$HTP_{as\ o}$ [kg eq. 1,4-DCB/CS_o] = HTP for the assembly operation *o*
GWP_{as}	HTP_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$HTP_{en\ y,c}$ [kg eq. 1,4-DCB/kWh] = HTP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	HTP_{up} [kg eq. 1,4-DCB/h] = HTP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$HTP_{man\ g}$ [kg eq. 1,4-DCB/CS_g] = HTP for manufacturing operation *g*
GWP_{use}	HTP_{use}
GWP_{rep}	HTP_{rep}
GWP_{EOL}	HTP_{EOL}
GWP_{tra}	HTP_{tra}

3.3.6 *Use of Resources*

This section is meant to provide the calculation formulas of the environmental indicators concerning the use of resources: the natural resource depletion (NRD), the land use (LU), the water depletion (WD), the energy depletion (ED).

The description of the expected contributions to the use of resources indicators is provided in this section grouping the contributions into the product lifecycle phases concerned.

3.3.6.1 Natural Resources Depletion Indicator Calculation Formula

The NRD indicator measures the depletion of non-renewable abiotic natural resources (i.e., fossil and mineral resources) as the fraction of the resource reserve used for a single unit out of the solution space weighted by the fraction of the resource reserve that is extracted in the world in one year. The natural resources depleted are translated into equivalent depleted kilos of Sb using the antimony as a reference substance. The definition of the NRD calculation formula is provided here, by offering a substitution table that allows to derive the NRD calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.23).

Table 3.23 NRD calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$ADP_{ext\ j}$ [kg eq. Sb/kg] = ADP for the extraction of material *j*
GWP_{ext}	NRD_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$ADP_{mp\ p,j}$ [kg eq. Sb/kg] = ADP for the material processing *p* used for material *j*
GWP_{mp}	NRD_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$ADP_{man\ m}$ [kg eq. Sb/CS_m] = ADP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$ADP_{EOL\ j,l}$ [kg eq. Sb/kg] = ADP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$ADP_{tra\ z}$ [kg eq. Sb/(kg km)] = ADP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$ADP_{ext\ w}$ [kg eq. Sb/kg] = ADP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$ADP_{mp\ p,w}$ [kg eq. Sb/kg] = ADP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$ADP_{EOL\ w,l}$ [kg eq. Sb/kg] = ADP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	NRD_{man}

(continued)

Table 3.23 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$ADP_{as\ o}$ [kg eq. Sb/CS_o] = ADP for the assembly operation *o*
GWP_{as}	NRD_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$ADP_{en\ y,c}$ [kg eq. Sb/kWh] = ADP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	ADP_{up} [kg eq. Sb/h] = ADP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$ADP_{man\ g}$ [kg eq. Sb/CS_g] = ADP for manufacturing operation *g*
GWP_{use}	NRD_{use}
GWP_{rep}	NRD_{rep}
GWP_{EOL}	NRD_{EOL}
GWP_{tra}	NRD_{tra}

3.3.6.2 Land Use Indicator Calculation Formula

The LU indicator measures the land occupation caused by the production and the delivery of one unit of product belonging to the solution space. The definition of the LU calculation formula is provided here, by offering a substitution table that allows to derive the LU calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.24).

Table 3.24 LU calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$LUP_{ext\ j}$ [m^2 year/kg] = LUP for the extraction of material *j*
GWP_{ext}	LU_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$LUP_{mp\ p,j}$ [m^2 year/kg] = LUP for the material processing *p* used for material *j*
GWP_{mp}	LU_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$LUP_{man\ m}$ [m^2 year/CS_m] = LUP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$LUP_{EOL\ j,l}$ [m^2 year/kg] = LUP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$LUP_{tra\ z}$ [m^2 year/(kg km)] = LUP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$LUP_{ext\ w}$ [m^2 year/kg] = LUP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$LUP_{mp\ p,w}$ [m^2 year/kg] = LUP for the material processing *p* used for auxiliary material *w*

(continued)

Table 3.24 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$LUP_{EOL\ w,l}$ [m^2 year/kg] = LUP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	LU_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$LUP_{as\ o}$ [m^2 year/CS_o] = LUP for the assembly operation *o*
GWP_{as}	LU_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$LUP_{en\ y,c}$ [m^2 year/kWh] = LUP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	LUP_{up} [m^2 year/h] = LUP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$LUP_{man\ g}$ [m^2 year/CS_g] = LUP for manufacturing operation *g*
GWP_{use}	LU_{use}
GWP_{rep}	LU_{rep}
GWP_{EOL}	LU_{EOL}
GWP_{tra}	LU_{tra}

3.3.6.3 Water Depletion Indicator Calculation Formula

The WD indicator measures the water of any quality (drinkable, industrial, etc.) consumed during the whole lifecycle of the product. Water used in a closed loop processes are not taken into account. The definition of the WD calculation formula is provided here, by offering a substitution table that allows to derive the WD calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.25).

Table 3.25 WD calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$WDP_{ext\ j}$ [m^3/kg] = WDP for the extraction of material *j*
GWP_{ext}	WD_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$WDP_{mp\ p,j}$ [m^3/kg] = WDP for the material processing *p* used for material *j*
GWP_{mp}	WD_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$WDP_{man\ m}$ [m^3/CS_m] = WDP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$WDP_{EOL\ j,l}$ [m^3/kg] = WDP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$WDP_{tra\ z}$ [m^3/(kg km)] = WDP for transportation done by the mean *z*

(continued)

Table 3.25 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$WDP_{ext\ w}$ [m^3/kg] = WDP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$WDP_{mp\ p,w}$ [m^3/kg] = WDP for the material processing p used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$WDP_{EOL\ w,l}$ [m^3/kg] = WDP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	WD_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$WDP_{as\ o}$ [m^3/CS_o] = WDP for the assembly operation *o*
GWP_{as}	WD_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$WDP_{en\ y,c}$ [m^3/kWh] = WDP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	WDP_{up} [m^3/h] = WDP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$WDP_{man\ g}$ [m^3/CS_g] = WDP for manufacturing operation *g*
GWP_{use}	WD_{use}
GWP_{rep}	WD_{rep}
GWP_{EOL}	WD_{EOL}
GWP_{tra}	WD_{tra}

3.3.6.4 Energy Depletion Indicator Calculation Formula

The ED indicator measures the energy consumed during the whole lifecycle of the product distinguishing between renewable and non-renewable sources. The definition of the ED calculation formula is provided here, by offering a substitution table that allows to derive the ED calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.26).

Table 3.26 ED calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$EDP_{ext\ j}$ [MJ/kg] = EDP for the extraction of material *j*
GWP_{ext}	ED_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$EDP_{mp\ p,j}$ [MJ/kg] = EDP for the material processing *p* used for material *j*
GWP_{mp}	ED_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$EDP_{man\ m}$ [MJ/CS_m] = EDP for manufacturing operation *m*

(continued)

Table 3.26 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$EDP_{EOL\ j,l}$ [MJ/kg] = EDP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$EDP_{tra\ z}$ [MJ/(kg km)] = EDP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$EDP_{ext\ w}$ [MJ/kg] = EDP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$EDP_{mp\ p,w}$ [MJ/kg] = EDP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$EDP_{EOL\ w,l}$ [MJ/kg] = EDP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	ED_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$EDP_{as\ o}$ [MJ/CS_o] = EDP for the assembly operation o
GWP_{as}	ED_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$EDP_{en\ y,c}$ [MJ/kWh] = EDP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	EDP_{up} [MJ/h] = EDP of the use phase
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation *g*	$EDP_{man\ g}$ [MJ/CS_g] = EDP for manufacturing operation *g*
GWP_{use}	ED_{use}
GWP_{rep}	ED_{rep}
GWP_{EOL}	ED_{EOL}
GWP_{tra}	ED_{tra}

Moreover, in addition to the usual substitution process, it is necessary to remove an element from the use phase concerning the direct consumption that is already computed. The use phase part of the formula results in the following (Table 3.27):

Table 3.27 ED use phase calculation formula

c = country

y = energy type

f_c = frequency of the country c

f_y = frequency of the energy type y used by the product

E_{use} [kWh] = P US

P [kW] = power dissipated in the use phase by the product

US [h] = usage scenario—hours of use in the product usage

$\text{EDP}_{\text{en } y,c}$ [MJ/kWh] = EDP for energy y production in country c

EDP_{up} [MJ/h] = EDP of the use phase

k = kth consumable component

$n_{\text{cons } k}$ = number of consumable components k expected to be used per unit of product during the product use phase

f_k = frequency of kth consumable in the expected product mix

$V_{\text{cons } k,j}$ [cm^3] = volume of the part of the kth consumable component made by the material j

$\text{EDP}_{\text{ext } j}$ [MJ/kg] = EDP for the extraction of material j

$\chi_{p,k,j}$ = boolean: 1 if the material processing p is made on the material j for the kth consumable; otherwise 0

$\text{EDP}_{\text{mp } p,j}$ [MJ/kg] = EDP for the material processing p used for material j

$f_{k,j,l}$ = frequency of the EOL treatment l performed on material j for the kth consumable component

$\text{EDP}_{\text{EOL } j,l}$ [MJ/kg] = EDP for the EOL of material j, done with treatment l

$f_{k,j,q}$ = frequency of the material j for kth consumable component provided by the supplier q

$d_{k,j,q,z}$ [km] = distance between supplier q (providing material j for kth consumable component) and the next supply chain partner covered by the mean of transportation z

$\text{EDP}_{\text{tra } z}$ [MJ/(kg km)] = EDP for transportation done by the mean z

$d_{\text{cust } z}$ [km] = average distance to the customer covered by the mean of transportation z

$f_{k,j,r}$ = frequency of the material j for kth consumable component treated by the EOL facility r

$d_{\text{EOL } r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z

g = manufacturing operations making the consumable components that are expected to be used per unit of product during the product use phase

f_g = frequency of the manufacturing operation g

CS_g = specific EDP measure parameter for manufacturing operation g

$\text{EDP}_{\text{man } g}$ [MJ/CS_g] = EDP for manufacturing operation g

$$
\begin{aligned}
\text{ED}_{\text{use}} = {} & \sum_c \sum_y f_c \times f_y \times E_{\text{use}} \times \text{EDP}_{\text{en } y,c} \\
& + \text{EDP}_{\text{up}} \times \text{US} \\
& + \sum_k n_{\text{cons}k} \times \Big(\sum_j f_k \times V_{\text{cons } k,j} \times \rho_j \times \text{EDP}_{\text{ext } j} \\
& + \sum_j \sum_p f_k \times \chi_{p,k,j} \times V_{\text{cons } k,j} \times \rho_j \times \text{EDP}_{\text{mp}p,j} \\
& + \sum_j \sum_l f_k \times f_{k,j,l} \times V_{\text{cons } k,j} \times \rho_j \times \text{EDP}_{\text{EOL} j,l} \\
& + \sum_j \sum_q \sum_z f_k \times V_{\text{cons } k,j} \times \rho_j \times f_{k,j,q} \times d_{k,j,q,z} \times \text{EDP}_{\text{tra } z} \\
& + \sum_j \sum_z f_k \times V_{\text{cons } k,j} \times \rho_j \times d_{\text{cust} z} \times \text{EDP}_{\text{tra} z} \\
& + \sum_j \sum_r \sum_z f_k \times V_{\text{cons } k,j} \times \rho_j \times f_{k,j,r} \times d_{\text{EOL } r,z} \times \text{EDP}_{\text{tra } z}\Big) \\
& + \sum_g f_g \times CS_g \times \text{EDP}_{\text{man } g}
\end{aligned}
$$

3.3.7 *Waste*

This section is meant to provide the calculation formulas of the environmental indicators concerning the waste: the WP and the Product Recycling Potential (PRP).

The description of the expected contributions to the WP indicator is provided in this section grouping the contributions into the product lifecycle phases concerned.

3.3.7.1 Waste Production Indicator Calculation Formula

The WP indicator calculates the quantity of waste produced during the whole lifecycle of the product. The definition of the WP calculation formula is provided here, by offering a substitution table that allows to derive the WP calculus from the previous described GWP formula, given its similarity due to the application of the same Impact Potentials method (Table 3.28).

Table 3.28 WP calculation formula through substitution

Element found in GWP table:	To be replaced with:
$GWP_{ext\ j}$ [kg eq. CO_2/kg] = GWP for the extraction of material *j*	$WPP_{ext\ j}$ [kg/kg] = WPP for the extraction of material *j*
GWP_{ext}	WP_{ext}
$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for material *j*	$WPP_{mp\ p,j}$ [kg/kg] = WPP for the material processing *p* used for material *j*
GWP_{mp}	WP_{mp}
$GWP_{man\ m}$ [kg eq. CO_2/CS_m] = GWP for manufacturing operation *m*	$WPP_{man\ m}$ [kg/CS_m] = WPP for manufacturing operation *m*
$GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material *j*, done with treatment *l*	$WPP_{EOL\ j,l}$ [kg/kg] = WPP for the EOL of material *j*, done with treatment *l*
$GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean *z*	$WPP_{tra\ z}$ [kg/(kg km)] = WPP for transportation done by the mean *z*
$GWP_{ext\ w}$ [kg eq. CO_2/kg] = GWP for the extraction of the auxiliary material *w*	$WPP_{ext\ w}$ [kg/kg] = WPP for the extraction of the auxiliary material *w*
$GWP_{mp\ p,w}$ [kg eq. CO_2/kg] = GWP for the material processing *p* used for auxiliary material *w*	$WPP_{mp\ p,w}$ [kg/kg] = WPP for the material processing *p* used for auxiliary material *w*
$GWP_{EOL\ w,l}$ [kg eq. CO_2/kg] = GWP for the EOL of auxiliary material *w*, done with EOL treatment *l*	$WPP_{EOL\ w,l}$ [kg/kg] = WPP for the EOL of auxiliary material *w*, done with EOL treatment *l*
GWP_{man}	WP_{man}
$GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation *o*	$WPP_{as\ o}$ [kg/CS_o] = WPP for the assembly operation *o*
GWP_{as}	WP_{as}
$GWP_{en\ y,c}$ [kg eq. CO_2/kWh] = GWP for energy *y* production in country *c*	$WPP_{en\ y,c}$ [kg/kWh] = WPP for energy *y* production in country *c*
GWP_{up} [kg eq. CO_2/h] = GWP of the use phase	WPP_{up} [kg/h] = WPP of the use phase

(continued)

Table 3.28 (continued)

Element found in GWP table:	To be replaced with:
$GWP_{man\ g}$ [kg eq. CO_2/CS_g] = GWP for manufacturing operation g	$WPP_{man\ g}$ [kg/CS_g] = WPP for manufacturing operation g
GWP_{use}	WP_{use}
GWP_{rep}	WP_{rep}
GWP_{EOL}	WP_{EOL}
GWP_{tra}	WP_{tra}

3.3.7.2 Product Recycling Potential Indicator Calculation Formula

The PRP indicator calculates the percentage in weight of the product that could be recycled using the current best recycling techniques. The only lifecycle phase affecting the PRP indicator is the End of life. The definition of the PRP calculation formula is provided here and is quite different from the other environmental indicators since, for its specific nature, it does not fit in the Impact Potentials methodology approach (Table 3.29).

Table 3.29 PRP calculation formula

LC Phase	Data from design tools, data entry, and databases	Formula
EOL	i = ith component of the final customizable product j = material type r_j = recyclability potential of material j (value range $0 \div 1$) f_i = frequency of the ith components in the expected product mix (expected population of final products with their customization options) ρ_j [g/cm^3] = mass density of material type j $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j	$PRP = 100 \times \sum_i \sum_j [(r_j \times f_i \times \rho_j \times V_{ij})/(\sum_i \sum_j f_i \times \rho_j \times V_{ij})]$

3.4 Economic Indicators Calculation Formulas

In this sections the economical indicators are presented. They are subdivided into the identified contributions of each lifecycle phase of the product. For each indicator its scope of measurement, lifecycle phases contributions, and final formula are delivered.

3.4.1 Efficiency

3.4.1.1 Unitary Production Variable Cost Indicator Calculation Formula

The unitary production variable cost (UPVC) is conceived to assets the unitary production costs of the customizable product in order to evaluate the level of efficiency of the designed solution space.

For the appraisement of this indicator the whole solution space has to be taken into account: such as the components materials costs, the production system consumption of energy, the cost of labor, and the cost paid to suppliers.

Following is the description of the expected contributions to the UPVC value subdivided into the lifecycle phases.

Extraction: in the extraction phase the expected contributions to the UPVC value are from both costs paid to suppliers who perform extraction of different component materials (cumulating costs which different suppliers face in order to extract components materials of the solution space product plus the transportation cost) and costs of the same processes performed by the company itself (cost of energy consumption and operators who operates on extraction of materials of components).

Material processing: in the material processing phase the expected contributions to the UPVC value are from costs which are both paid to suppliers (cost of processing which is undertaken by supplier plus the transportation cost) and costs that the company itself undertakes in order to perform this process (costs of energy and cost of labor).

Part manufacturing: in the part manufacturing phase the expected contributions to the UPVC value are from both costs paid to suppliers who manufactured the part (purchasing costs of components from suppliers, transportation cost is also included) and from costs related to processes preformed by the company itself (cost of energy consumption and cost of operators who operates on the manufacturing of parts).

Assembly: in the assembly phase the expected contribution to the UPVC value comes from both cost paid to suppliers who assemble product variants (purchasing costs of assembly from suppliers, transportation cost is also included) and from the company itself when it performs this processes (cost of energy consumption and cost of operators who assembles product variants).

Transportation: in the transportation phase the expected contribution to the UPVC value comes from only in house production in case transportation is needed between production plants placed on different locations. In case of outsourcing phases, the purchasing cost includes the transportation costs and therefore it does not affect the transportation phase.

The total value of the UPVC indicator is obtained summing the contributions of all the lifecycle phases and its calculation formula is provided here (Table 3.30).

Table 3.30 UPVC calculation formula

LC Phase	Data from design tools, data entry, and databases	Formula
	i = ith component of the final customizable product j = material type q = supplier f_i = frequency of the ith component in the expected product mix (expected population of final products with their customization options) $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [g/cm^3] = mass density of material type j c = country y = energy type f_y = frequency of use of energy type y at the company level $\mathrm{EC}_{y,c}$ [€/KWh] = cost of energy type y in country c op = operator $\mathrm{salary}_{\mathrm{op}}$ [€/year] = average yearly salary of operator op $\mathrm{thw}_{\mathrm{op}}$ [h/year] = total number of yearly worked hour by operator op N [unit/year] = yearly produced units	
Extraction	$f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $C_{i,j,q}$ [€/kg] = cost of the extraction of material j for the ith component performed by supplier q (including transportation cost) $f_{i,j,c}$ = frequency of material j for the ith component extracted in country c $\mathrm{WC}_{i,j,c}$ = waste coefficient when processing material j for the ith component in country c $\mathrm{KC}_{i,j}$ [kWh/kg] = energy consumption per extracted kg of material j for the ith component $\mathrm{WH}_{\mathrm{ext\ op}}$ [h/year] = hours worked in one year by the operator op extracting materials j in the extraction department of the company	$\mathrm{UPVC}_{\mathrm{ext}} = \sum_i \sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times C_{i,j,q}$ $+ \sum_i \sum_j \sum_c \sum_y (1 - \sum_q f_{i,j,q}) \times f_i \times f_{i,j,c} \times f_y \times$ $(V_{i,j} \times \rho_j)/\left(1 - \mathrm{WC}_{i,j,c}\right) \times \mathrm{KC}_{i,j} \times \mathrm{EC}_{y,c}$ $+ (\sum_{\mathrm{op}} \mathrm{WH}_{\mathrm{extop}} \times \mathrm{salary}_{\mathrm{op}}/\mathrm{thw}_{\mathrm{op}})/N$

(continued)

Table 3.30 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Material processing	p = material processing operation $f_{i,j,p,q}$ = frequency of material j for the ith component processed through process p by supplier q $\mathrm{WC}_{i,j,p,c}$ = waste coefficient when processing with p material j for the ith component in country c $C_{i,j,p,q}$ [€/kg] = cost of processing material j the ith component through operation p by supplier q (including transportation cost) $f_{i,j,p,c}$ = frequency of material j for the ith component processed with p in country c $\mathrm{KC}_{i,j,p}$ [kWh/kg] = energy consumption of p per processed kg of j for the ith component $\mathrm{WH}_{\mathrm{mp\ op}}$ [h/year] = hours worked in one year by the operator op carrying out operations p in the material processing department of the company	$\mathrm{UPVC_{mp}} = \sum_i \sum_j \sum_p \sum_q f_i \times f_{i,j,p,q} \times (V_{i,j} \times \rho_j)/(1 - \mathrm{WC}_{i,j,p,c}) \times C_{i,j,p,q}$ $+\sum_i \sum_j \sum_p \sum_c \sum_y \left(1 - \sum_q f_{i,j,p,q}\right) \times f_i \times f_{i,j,p,c} \times f_y \times (V_{i,j} \times \rho_j)/(1 - \mathrm{WC}_{i,j,p,c})$ $\times \mathrm{KC}_{i,j,p} \times \mathrm{EC}_{y,c} + \left(\sum_{\mathrm{op}} \mathrm{WH_{mp\,op}} \times \mathrm{salary_{op}}/\mathrm{thw_{op}}\right)/N$
Part manufacturing	$f_{i,q}$ = frequency component i purchased from supplier q $C_{i,q}$ [€/unit] = purchasing cost of ith component provided by q (transportation cost included) m = manufacturing operation $f_{m,c}$ = frequency of operation m made in country c $\mathrm{WC}_{m,c}$ = waste coefficient of operation m in country c CS_m = specific UPVC measure parameter for operation m KC_m [kWh/CS_m] = energy needed for operation m $\mathrm{WH}_{\mathrm{man\ op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$\mathrm{UPVC_{man}} = \sum_i \sum_q f_i \times f_{i,q} \times C_{i,q}$ $+\sum_m \sum_c \sum_y f_{m,c} \times f_y \times [1/(1 - \mathrm{WC}_{m,c})] \times \mathrm{CS}_m \times \mathrm{KC}_m \times \mathrm{EC}_{y,c}$ $+ \left(\sum_{\mathrm{op}} \mathrm{WH_{man\,op}} \times \mathrm{salary_{op}}/\mathrm{thw_{op}}\right)/N$

(continued)

Table 3.30 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Assembly	a = ath assembly of the final customizable product $f_{a,q}$ = frequency of the assembly a provided by supplier q $C_{a,q}$ [€/unit] = purchasing cost of ath assembly provided by q (transportation cost included) o = assembly operation $f_{o,c}$ = frequency of the operation o made in country c $\mathrm{WC}_{o,c}$ = waste coefficient of operation o in country c CS_o = specific UPVC measure parameter for assembly operation o KC_o [kWh/CS_o] = energy needed for operation o $\mathrm{WH}_{\mathrm{as\ op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$\mathrm{UPVC}_{\mathrm{as}} = \sum_a \sum_q f_{a,q} \times C_{a,q} + \sum_o \sum_c \sum_y f_{o,c} \times f_y \times [1/(1-\mathrm{WC}_{o,c})] \times \mathrm{CS}_o \times \mathrm{KC}_o \times \mathrm{EC}_{y,c} + \left(\sum_{\mathrm{op}} \mathrm{WH}_{\mathrm{as\,op}} \times \mathrm{salary}_{\mathrm{op}}/\mathrm{thw}_{\mathrm{op}}\right)/N$
Transportation	v = company site t = transportation supplier z = mean of transportation $f_{i,j,v,t,z}$ = frequency of the material j for ith component provided by v and transported by t with mean z $d_{i,j,v,z}$ [km] = distance between company site (providing material j for ith component) and the next company site covered by the mean of transportation z $\mathrm{C}_{\mathrm{tra}\ t,z}$ [€/(kg km)] = cost of trasportation provided by t with mean z	$\mathrm{UPVC}_{\mathrm{tra}} = \sum_i \sum_j \sum_v \sum_t \sum_z f_i \times f_{i,j,v,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,v,z} \times C_{\mathrm{trat},z}$

3.4.1.2 Production Lead Time Indicator Calculation Formula

The PLT indicator measures the average time required to manufacture a product belonging to the solution space following the expected mix distribution. The PLT considers only the production activities performed in the last manufacturing step of the product which, in a mass customized context, typically coincide with the processes carried out by the company. The PLT includes the processing time, the queue time, the setup time, the move time, the idle time, and the inspection time, assessing the time passed from the start of the item production to its end. Calculation of the PLT for each product of the expected product mix is usually obtained by simulating the manufacturing system behavior.

However, a very simple formula is provided below to be used for first glance evaluation. The formula has been structured similarly to the other indicators in order to map the design activities affecting the PLT value, even though the decisions taken in the design of the product and the manufacturing system are not the only factors influencing the PLT. Some other factors as queue time and idle time are not easy to be foreseen during the design phase since they derive from a multiproduct manufacturing system.

The lifecycle phases expected to contribute to the PLT indicator are the *Extraction*, the *Material Processing* (when this phases are potentially carried out in the last production step), the *Part manufacturing*, and the *Assembly* phases (Table 3.31).

Table 3.31 PLT calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Extraction	n = product belonging to the expected product mix	$\mathrm{PLT} = \sum_n (\mathrm{EPT}_n - \mathrm{SPT}_n)/N$
Material processing	SPT_n = starting production time of the product n	
Part manufacturing	EPT_n = ending production time of the product n	
Assembly	N = yearly produced units	

3.4.1.3 Variability of Production Lead Time Indicator Calculation Formula

The variability of production lead time (VPLT) indicator measures how much the production lead time of products belonging to the expected product mix can differ from the PLT mean value. In other words, it is the coefficient of variation.

The VPLT calculation formula is provided below. The design activities affecting the VPLT value are the same of the PLT indicator and the data needed to calculate the VPLT are usually obtained through the manufacturing system simulation (Table 3.32).

Table 3.32 VPLT calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Extraction	n = product belonging to the expected product mix	$\mathrm{VPLT} = \sigma/\lvert\mu\rvert$
Material processing	$\sigma = \sqrt{(\sum_n (\mathrm{PLT}_n - \mu)^2/N)}$	
Part manufacturing	$\mu = \sum_n \mathrm{PLT}_n/N$	
Assembly	N = yearly produced units	

3.4.1.4 Value Added Time Indicator Calculation Formula

The value added time (VAT) indicator measures the average percentage of the production time spent for operations that increase the value of the product. The VAT value is calculated as the ratio of the processing time spent while performing manufacturing and assembly operations (the VAT) and the total production time that includes the processing time, the move time, the setup time, and the queue time.

As presented in the VAT calculation formula provided below, the numerator of the ratio is the sum of the processing time of all the components and assemblies constituting the expected product mix and the denominator of the formula is the sum of the processing time, the move time, the setup time, and the queue time of all the components and assemblies constituting the expected product mix. The data concerning the processing time, the move time, the setup time, and the queue time of all the components and assemblies are usually obtained through manufacturing system simulation. Similar to the PLT indicator, the formula has been structured in order to map the design activities affecting the VAT value even though the decisions taken in the design of the product and the manufacturing system are not the only factors influencing the VAT.

The lifecycle phases expected to contribute to the VAT indicator are the *Extraction*, the *Material Processing*, the *Part manufacturing*, and the *Assembly* phases though the calculated value is overall (Table 3.33).

3.4.1.5 Throughput Rate Indicator Calculation Formula

The throughput rate (TR) is defined as the average product production rate of the system. This measure is expressed as units produced per time period. The design of both the product and the production system influences the throughput rate, but the mechanics which cause the final result cannot be easily quantified during the design phase. For example, phenomena such as queues in front of production resources, effect of the scheduling, capacity of buffers cannot be deduced analytically. All these phenomena are typical of a multiproduct system with a nonlinear production flow. In order to calculate this indicator, it is thus not possible to develop a formula only through analytical means and the value has to be derived through production simulation of the expected mix.

Table 3.33 VAT calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Extraction	$i = i$th component of the final customizable product	$\mathrm{VAT} = 100 \times \left(\sum_j \sum_m \mathrm{PT}_{j,m} + \sum_j \sum_p \mathrm{PT}_{j,p} + \sum_i \sum_m \mathrm{PT}_{i,m} + \sum_a \sum_o \mathrm{PT}_{a,o} \right) / \left[\sum_j \mathrm{MT}_j + \sum_i \mathrm{MT}_i + \sum_a \mathrm{MT}_a + \sum_j \sum_m \left(\mathrm{PT}_{j,m} + \mathrm{ST}_{j,m} + \mathrm{QT}_{j,m} \right) + \sum_j \sum_p \left(\mathrm{PT}_{j,p} + \mathrm{ST}_{j,p} + \mathrm{QT}_{j,p} \right) + \sum_i \sum_m \left(\mathrm{PT}_{i,m} + \mathrm{ST}_{i,m} + \mathrm{QT}_{i,m} \right) + \sum_a \sum_o \left(\mathrm{PT}_{a,o} + \mathrm{ST}_{a,o} + \mathrm{QT}_{a,o} \right) \right]$
	$j =$ material type	
	$\mathrm{PT}_{j,m}$ [h] = processing time of the extraction process made on the material j	
	MT_j [h] = move time of the material j	
	$\mathrm{ST}_{j,m}$ [h] = setup time of the extraction process made on the material j	
	$\mathrm{QT}_{j,m}$ [h] = queue time for the material j waiting for the extraction process m	
Material processing	$p =$ material processing operation	
	$\mathrm{PT}_{j,p}$ [h] = processing time of the material processing process made on the material j	
	$\mathrm{ST}_{j,p}$ [h] = setup time of the material processing process made on the material j	
	$\mathrm{QT}_{j,p}$ [h] = queue time for the material j waiting for the material processing process m	
Part manufacturing	$m =$ manufacturing operation	
	$\mathrm{PT}_{i,m}$ [h] = processing time of the operation m made on the component i	
	MT_i [h] = move time of the component i	
	$\mathrm{ST}_{i,m}$ [h] = setup time of the operation m carried out on the component i	
	$\mathrm{QT}_{i,m}$ [h] = queue time for the component i waiting for operation m	
Assembly	$a = a$th assembly of the final customizable product	
	$o =$ assembly operation	
	$\mathrm{PT}_{a,o}$ [h] = processing time of the assembly operation o carried out on the assembly a	
	MT_a [h] = move time of the assembly a	
	$\mathrm{ST}_{a,o}$ [h] = setup time of the assembly operation o carried out on the assembly a	
	$\mathrm{QT}_{a,o}$ [h] = queue time for the assembly a waiting for the operation o	

3.4.1.6 Capacity Utilization Rate Indicator Calculation Formula

This indicator is a measure of how much the system potentialities are used and it is calculated as the ratio of the effective capacity and the ideal capacity. Effective capacity is the capacity a firm expects to achieve given the current operating constraints (product mix, methods of scheduling, maintenance and standards of quality, absenteeism, shortages, etc.). On the other hand, ideal capacity is the capacity that could be achieved when none of the above-mentioned factors influences the system. It is thus the maximum theoretical output of a system in a given period. Given these definitions it is possible to measure the two capacity values as throughput rates considering two different production scenarios.

The resulting value is a percentage that gives an idea about how the production system is used and what is the combined effect of different causes of production efficiency losses, thus providing the company with an efficiency measurement.

According to what has been explained for the TR indicator, also in this case it is possible to quantify the values only using simulation. In particular, the ideal capacity is the TR when the systems run without scraps and failures the product mix being equal, while the effective capacity is the same as the TR indicators.

The CUR calculation formula is provided here (Table 3.34).

Table 3.34 CUR calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Extraction Material processing	TR = throughput rate calculated considering failures and scrap generation	$\text{CUR} = \text{TR}/\text{TR}_i \times 100$
Part manufacturing Assembly	TR_i = ideal throughput rate calculated without considering failures and scrap generation	

3.4.2 *Profitability*

3.4.2.1 Unitary Expected Gross Profit Indicator Calculation Formula

The unitary expected gross profit (UEGP) is conceived to assess the level of profitability of the designed product solution space. This indicator measures the difference between the unitary revenues obtained by the yearly product sales (calculated on the expected volume and product mix) and the unitary related costs, before deducting administrative and selling expenses, taxation, and interest payments.

Since the UEGP calculation uses the UPVC indicator, the design activities affecting the UEGP are the same of the UPVC and the same is to the expected contribution of the impacts over the lifecycle phases (see Sect. 3.4.1.1). The UEGP calculation formula is provided here (Table 3.35).

Table 3.35 UEGP calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Extraction	Pr [€] = unitary selling price	$\mathrm{UEGP} = \mathrm{Pr} - [\mathrm{UPVC} + (\mathrm{Pr} \times N/S_c) \times (\mathrm{OH}/N)]$
Material processing	UPVC [€] = unitary production variable cost	
Part manufacturing	S_c [€] = expected annual turnover for the company	
Assembly	OH = overhead (indirect production costs at company level: amortization, insurance, rents, …)	
	N = yearly produced units	

3.4.2.2 Product Lifecycle Cost Indicator Calculation Formula

The product lifecycle cost (PLC) aims to assess the level of profitability of the designed product solution space by taking into account the whole set of costs the customer has to face during the product lifecycle. This indicator utilizes the expected product price, maintenance costs, repair costs, and end of life costs.

The expected contributions to the PLC value are here subdivided into the product lifecycle phases.

Product use: In the product use phase, the expected contributions to the PLC value are the cost of energy which the product will dissipate and the consumables it will consume during its use phase.

Repair: In repair phase the expected contributions to the PLC value are the cost of spare parts (only those which are not included in warranty or for which warranty has expired) and the cost of technical assistance services which are expected to be required by the product.

End of life: In end of life phase, the expected contributions to the PLC value are costs of product disposal.

The total value of the PLC indicator is obtained summing the contributions of all the lifecycle phases and its calculation formula is provided in Table 3.36.

3.4.3 Investment in Technologies and Competencies

3.4.3.1 Research and Development Investment Intensity Indicator Calculation Formula

The research and development investment intensity (RDII) indicator measures the research and development investments made by the company and its suppliers, allocating these investments on the solution space and along the whole lifecycle of the product. The R&D investment allows the business of company and supply chain members to last and evolve in a long-term perspective.

The RDII calculation formula is presented in Table 3.37. For each lifecycle phase the first contribution described is about the company, while the next ones are

Table 3.36 PLC calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
Product use	Pr [€] = unitary selling price c = country y = energy type f_c = frequency of the country c f_y = frequency of the energy type y used by the product E_{use} [kWh] = P US P [kW] = power dissipated in the use phase by the product US [h] = usage scenario—hours of use in the product usage $\text{EC}_{y,c}$ [€/KWh] = cost of energy type y in country c k = kth consumable component $n_{\text{cons}\ k}$ = number of consumable components k expected to be used per unit of product during the product use phase f_k = frequency of kth consumable in the expected product mix $\text{CC}_{\text{cons}\ k}$ [€] = cost of consumable k	$\text{PLC}_{\text{use}} = \text{Pr} + \sum_c \sum_y f_c \times f_y \times E_{\text{use}} \times \text{EC}_{y,c} + \sum_k n_{\text{cons}\,k} \times f_k \times \text{CC}_{\text{cons}\,k}$
Repair	i = ith component of the final customizable product q = supplier $n_{s\ i}$ = number of substitutions of the ith component expected to occur during the product use phase f_i = frequency of the ith component in the expected product mix (expected population of final products with their customization options) $f_{\text{rep}\ i,q}$ = frequency of the ith component for repair purchased by the customer from supplier q $p_{q,i}$ = price of component i purchased by supplier q L_q [€/h] = hourly cost of labor per service provision of supplier q SH_i = service hour per hour of use [%]	$\text{PLC}_{\text{rep}} = \sum_i \sum_q n_{s\,i} \times f_i \times f_{\text{rep}\,i,q} \times p_{q,i} + \sum_i \sum_q f_i \times f_{q,i} \times L_q \times \text{SH}_i \times \text{US}$
EOL	C_{EOL} [€] = average unitary cost of the EOL treatments of the expected product mix	$\text{PLC}_{\text{EOL}} = C_{\text{EOL}}$

Table 3.37 RDII calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
	S_{ss} [€] = expected sales turnover of the solution space S_c [€] = expected total sales turnover of the company N = yearly produced units i = ith component of the final customizable product j = material type q = supplier f_i = frequency of the ith component in the expected product mix (expected population of final products with their customization options) $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type I RDI_q [€] = average yearly R&D investments made by the supplier q ST_q [€] = sales turnover of supplier q r = EOL facility t = transportation supplier z = mean of transportation	
Extraction	$\mathrm{RDI}_{\mathrm{ext}}$ [€] = average yearly R&D investments made by the company in extraction activities $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $C_{i,j,q}$ [€/kg] = cost of the raw material j for the ith component paid to supplier q	$\mathrm{RDII}_{\mathrm{ext}} = \mathrm{RDI}_{\mathrm{ext}} \times (S_{ss}/S_c)/N + \sum_i \sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_q \times \left(C_{i,j,q}/\mathrm{ST}_q\right)$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Material Processing	$\mathrm{RDI}_{\mathrm{mp}}$ [€] = average yearly R&D investments made by the company in material processing activities p = material processing operation $f_{i,j,p,q}$ = frequency of the material processing p, used for material j for the ith component, provided by the supplier q $C_{i,j,p,q}$ [€/kg] = cost of the material processing p, made on the material j for the ith component, paid to the supplier q	$\mathrm{RDII}_{\mathrm{mp}} = \mathrm{RDI}_{\mathrm{mp}} \times (\mathrm{S}_{\mathrm{ss}}/S_c)/N$ $+\sum_i \sum_j \sum_p \sum_q f_i \times V_{i,j} \times \rho_j \times f_{i,j,p,q} \times \mathrm{RDI}_q \times \left(C_{i,j,p,q}/\mathrm{ST}_q\right)$
Part manufacturing	$\mathrm{RDI}_{\mathrm{man}}$ [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company $f_{i,q}$ = frequency of the ith component provided by supplier q $C_{i,q}$ [€] = cost of the ith component paid to the supplier q m = manufacturing operation w = auxiliary material f_m = frequency of the manufacturing operation m $f_{w,q}$ = frequency of the auxiliary material w provided by supplier q $Q_{\mathrm{aux}\ w,m}$ [kg/operation] = quantity of the auxilary material w used during the operation m $C_{w,q}$ [€/kg] = cost of the auxiliary material w paid to the supplier q $f_{w,p,q}$ = frequency of the material processing p, carried out on the auxiliary material w, provided by supplier q	$\mathrm{RDII}_{\mathrm{man}} = \mathrm{RDI}_{\mathrm{man}} \times (S_{\mathrm{ss}}/S_c)/N$ $+\sum_i \sum_q f_i \times f_{i,q} \times \mathrm{RDI}_q \times \left(C_{i,q}/\mathrm{ST}_q\right)$ $+\sum_m \sum_w \sum_q f_m \times f_{w,q} \times Q_{\mathrm{aux}\ w,m} \times \mathrm{RDI}_q \times \left(C_{w,q}/\mathrm{ST}_q\right)$ $+\sum_m \sum_w \sum_q f_m \times f_{w,p,q} \times Q_{\mathrm{aux}\ w,m} \times \mathrm{RDI}_q \times \left(C_{w,p,q}/\mathrm{ST}_q\right)$ $+\sum_m \sum_w \sum_r f_m \times f_{w,r} \times Q_{\mathrm{aux}\ w,m} \times \mathrm{RDI}_r \times \left(C_{\mathrm{EOL}\ w,r}/\mathrm{ST}_r\right)$ $+\sum_m \sum_w \sum_q \sum_t \sum_z f_m \times f_{w,q} \times f_{w,t,z} \times Q_{\mathrm{aux}\ w,m} \times d_{w,q,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ w,t,z}/\mathrm{ST}_t\right)$ $+\sum_m \sum_w \sum_r \sum_t \sum_z f_m \times f_{w,r} \times f_{w,t,z} \times Q_{\mathrm{aux}\ w,m} \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ w,t,z}/\mathrm{ST}_t\right)$ $+\sum_m \sum_j \sum_q f_m \times f_{j,q} \times Q_{\mathrm{wm}\ j,m} \times \mathrm{RDI}_q \times \left(C_{j,q}/\mathrm{ST}_q\right)$ $+\sum_m \sum_j \sum_q f_m \times f_{j,p,q} \times Q_{\mathrm{wm}\ j,m} \times \mathrm{RDI}_q \times \left(C_{j,p,q}/\mathrm{ST}_q\right)$ $+\sum_m \sum_j \sum_r f_m \times f_{j,r} \times Q_{\mathrm{wm}\ j,m} \times \mathrm{RDI}_r \times \left(C_{\mathrm{EOL}\ j,r}/\mathrm{ST}_r\right)$ $+\sum_m \sum_j \sum_q \sum_t \sum_z f_m \times f_{j,q} \times f_{j,t,z} \times Q_{\mathrm{wm}\ j,m} \times d_{j,q,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ j,t,z}/\mathrm{ST}_t\right)$ $+\sum_m \sum_j \sum_q \sum_t \sum_z f_m \times f_{j,r} \times f_{j,t,z} \times Q_{\mathrm{wm}\ j,m} \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ j,t,z}/\mathrm{ST}_t\right)$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
	$C_{w,p,q}$ [€/kg] = cost of the material processing p, made on the auxiliary material w, paid to the supplier q $f_{w,r}$ = frequency of the EOL treatment performed on material w provided by the EOL facility r RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments $C_{\mathrm{EOL}\ w,r}$ [€/kg] = cost of the EOL treatments made on material w paid to the EOL facility r ST_r [€] = sales turnover of EOL facility r $f_{w,t,z}$ = frequency of the transportation provided by the supplier t transporting w by means of transportation z $d_{w,q,z}$ [km] = distance between supplier q (providing auxiliary material w) and the next supply chain partner covered by the mean of transportation z RDI_t [€] = average yearly R&D investments made by the transportation supplier t $C_{\mathrm{tra}\ w,t,z}$ [€/(kg km)] = cost of the transportation of w by means z paid to the transportation supplier t ST_t [€] = sales turnover of transportation supplier t $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z $f_{j,q}$ = frequency of the material j provided by the supplier q $Q_{\mathrm{wm}\ j,m}$ [kg/operation] = quantity of the waste material j coming from the operation m $C_{j,q}$ [€/kg] = cost of the raw material j paid to supplier q $f_{j,p,q}$ = frequency of the material processing p, carried out on material j, provided by supplier q $C_{j,p,q}$ [€/kg] = cost of the material processing p made on the material j paid to the supplier q $f_{j,r}$ = frequency of material j treated by the EOL facility r $C_{\mathrm{EOL}\ j,r}$ [€/kg] = cost of the EOL treatments made on material j paid to the EOL facility r $f_{j,t,z}$ = frequency of the transportation provided by the supplier t transporting j by means of transportation z $d_{j,q,z}$ [km] = distance between supplier q (providing material j) and the next supply chain partner covered by the mean of transportation z $C_{\mathrm{tra}\ j,t,z}$ [€/(kg km)] = cost of the transportation of j by means z paid to the transportation supplier t	

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Assembly	$\mathrm{RDI}_{\mathrm{as}}$ [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company a = ath assembly of the final customizable product f_a = frequency of the ath assembly in the expected product mix $f_{a,q}$ = frequency of the ath assembly provided by supplier q $C_{a,q}$ [€] = cost of the ath assembly paid to the supplier q o = assembly operation w = auxiliary material f_o = frequency of the assembly operation o $f_{w,q}$ = frequency of the auxiliary material w provided by supplier q $f_{w,t,z}$ = frequency of the transportation provided by the supplier t transporting w by means of transportation z $Q_{\mathrm{aux}\ w,o}$ [kg/operation] = quantity of the auxiliary material w used during the operation o $d_{w,q,z}$ [km] = distance between supplier q (providing auxiliary material w) and the next supply chain partner covered by the mean of transportation z RDI_t [€] = average yearly R&D investments made by the transportation supplier t $C_{\mathrm{tra}\ w,t,z}$ [€/(kg km)] = cost of the transportation of w by means z paid to the transportation supplier t ST_t [€] = sales turnover of transportation supplier t $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	$\mathrm{RDII}_{\mathrm{as}} = \mathrm{RDI}_{\mathrm{as}} \times (S_{\mathrm{ss}}/S_c)/N$ $+ \sum_a \sum_q f_a \times f_{a,q} \times \mathrm{RDI}_q \times \left(C_{a,q}/\mathrm{ST}_q\right)$ $+ \sum_o \sum_w \sum_q f_o \times f_{w,q} \times Q_{\mathrm{aux}\ w,o} \times \mathrm{RDI}_q \times \left(C_{w,q}/\mathrm{ST}_q\right)$ $+ \sum_o \sum_w \sum_q f_o \times f_{w,p,q} \times Q_{\mathrm{aux}\ w,o} \times \mathrm{RDI}_q \times \left(C_{w,p,q}/\mathrm{ST}_q\right)$ $+ \sum_o \sum_w \sum_r f_o \times f_{w,r} \times Q_{\mathrm{aux}\ w,o} \times \mathrm{RDI}_r \times \left(C_{\mathrm{EOL}\ w,r}/\mathrm{ST}_r\right)$ $+ \sum_o \sum_w \sum_q \sum_t \sum_z f_o \times f_{w,q} \times f_{w,t,z} \times Q_{\mathrm{aux}\ w,o} \times d_{w,q,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ w,t,z}/\mathrm{ST}_t\right)$ $+ \sum_o \sum_w \sum_r \sum_t \sum_z f_o \times f_{w,r} \times f_{w,t,z} \times Q_{\mathrm{aux}\ w,o} \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ w,t,z}/\mathrm{ST}_t\right)$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Product use	$\mathrm{RDI}_{\mathrm{use}}$ [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company k = kth consumable component $n_{\mathrm{cons}\,k}$ = number of consumable components k expected to be used per unit of product during the product use phase f_k = frequency of kth consumable in the expected product mix $f_{k,j,q}$ = frequency of the material j for kth consumable component provided by the supplier q $V_{\mathrm{cons}\,k,j}$ [cm^3] = volume of the part of the kth consumable component made by the material j $C_{k,j,q}$ [€/kg] = cost of the raw material j for the kth component paid to supplier q $f_{k,j,p,q}$ = frequency of the material processing p, used for material j for the kth component, provided by the supplier q $C_{k,j,p,q}$ [€/kg] = cost of the material processing p, made on the material j for the kth component, paid to the supplier q $f_{k,q}$ = frequency of the kth component provided by supplier q $C_{k,q}$ [€] = cost of the kth component paid to the supplier q $f_{k,j,r}$ = frequency of the material j for kth consumable component treated by the EOL facility r RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments $C_{\mathrm{EOL}\;k,j,r}$ [€/kg] = cost of the EOL treatments made on material j for the kth component paid to the EOL facility r ST_r [€] = sales turnover of EOL facility r $f_{k,j,t,z}$ = frequency of the transportation provided by the supplier t, transporting j for the kth component by means of transportation z	$\mathrm{RDII}_{\mathrm{use}} = \mathrm{RDI}_{\mathrm{use}} \times (S_{\mathrm{ss}}/S_c)/N$ $+\sum_k n_{\mathrm{cons}\,k} \times (\sum_j \sum_q f_k \times f_{k,j,q} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{k,j,q}/\mathrm{ST}_q)$ $+\sum_j \sum_p \sum_q f_k \times f_{k,j,p,q} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{k,j,p,q}/\mathrm{ST}_q)$ $+\sum_q f_{k,q} \times \mathrm{RDI}_q \times (C_{k,q}/\mathrm{ST}_q)$ $+\sum_j \sum_r f_k \times f_{k,j,r} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_r \times (C_{\mathrm{EOL}\,k,j,r}/\mathrm{ST}_r)$ $+\sum_j \sum_q \sum_t \sum_z f_k \times f_{k,j,q} \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{k,j,q,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_t \sum_z f_k \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{\mathrm{cust}\,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_r \sum_t \sum_z f_k \times f_{k,j,r} \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{\mathrm{EOL}\,r,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t))$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
	$d_{k,j,q,z}$ [km] = distance between supplier q (providing material j for kth component) and the next supply chain partner covered by the mean of transportation z RDI_t [€] = average yearly R&D investments made by the transportation supplier t ST_t [€] = sales turnover of transportation supplier t $C_{\mathrm{tra}\ k,j,t,z}$ [€/(kg km)] = cost of the transportation of j for kth component by means z paid to the transportation supplier t $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	
Repair	$\mathrm{RDI}_{\mathrm{rep}}$ [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company $n_{s\ i}$ = number of substitutions of the ith component expected to occur during the product use phase $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $C_{i,j,q}$ [€/kg] = cost of the raw material j for the ith component paid to supplier q p = material processing operation $f_{i,j,p,q}$ = frequency of the material processing p, used for material j for the ith component, provided by the supplier q $C_{i,j,p,q}$ [€/kg] = cost of the material processing p, made on the material j for the ith component, paid to the supplier q $f_{i,q}$ = frequency of the ith component provided by supplier q $C_{i,q}$ [€] = cost of the ith component paid to the supplier q $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments $C_{\mathrm{EOL}\ i,j,r}$ [€/kg] = cost of the EOL treatments made on material j for the ith component paid to the EOL facility r ST_r [€] = sales turnover of EOL facility r $f_{i,j,t,z}$ = frequency of the transportation provided by the supplier t, transporting j for the ith component by means of transportation z	$\mathrm{RDII}_{\mathrm{rep}} = \mathrm{RDI}_{\mathrm{rep}} \times (S_{\mathrm{ss}}/S_c)/N$ $+\sum_i n_{s\,i} \times (\sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{i,j,q}/\mathrm{ST}_q)$ $+\sum_j \sum_p \sum_q f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{i,j,p,q}/\mathrm{ST}_q)$ $+\sum_q f_i \times f_{i,q} \times \mathrm{RDI}_q \times (C_{i,q}/\mathrm{ST}_q)$ $+\sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_r \times (C_{\mathrm{EOL}\ i,j,r}/\mathrm{ST}_r)$ $+\sum_j \sum_q \sum_t \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_t \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\ z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_r \sum_t \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t))$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
	$d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z RDI_t [€] = average yearly R&D investments made by the transportation supplier t ST_t [€] = sales turnover of transportation supplier t $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $C_{\mathrm{tra}\ i,j,t,z}$ [€/(kg × km)] = cost of the transportation of j for ith component by means z paid to the transportation supplier t $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	
EOL	$\mathrm{RDI}_{\mathrm{EOL}}$ [€] = average yearly R&D investments made by the company in EOL treatments of the product $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments $C_{\mathrm{EOL}\ i,j,r}$ [€/kg] = cost of the EOL treatments made on material j for the ith component paid to the EOL facility r ST_r [€] = sales turnover of EOL facility r	$\mathrm{RDII}_{\mathrm{EOL}} = \mathrm{RDI}_{\mathrm{EOL}} \times (S_{\mathrm{ss}}/S_c)/N$ $+ \sum_i \sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_r \times \left(C_{\mathrm{EOL}\ i,j,r}/\mathrm{ST}_r\right)$
Transportation	$\mathrm{RDI}_{\mathrm{tra}\ z}$ [€] = average yearly R&D investments made by the company in transportation activities $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $f_{i,j,t,z}$ = frequency of the transportation provided by the supplier t, transporting j for the ith component by means of transportation z $d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z RDI_t [€] = average yearly R&D investments made by the transportation supplier t $C_{\mathrm{tra}\ i,j,t,z}$ [€/(kg × km)] = cost of the transportation of j for ith component by means z paid to the transportation supplier t ST_t [€] = sales turnover of transportation supplier t $d_{\mathrm{cust}\ z}$ [km] = average distance to the customer covered by the mean of transportation z $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r $d_{\mathrm{EOL}\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	$\mathrm{RDII}_{\mathrm{tra}} = \mathrm{RDI}_{\mathrm{tra}\ z} \times (S_{\mathrm{ss}}/S_c)/N$ $+ \sum_i \sum_j \sum_q \sum_t \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right)$ $+ \sum_i \sum_j \sum_t \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\ z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right)$ $+ \sum_i \sum_j \sum_r \sum_t \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right)$

about the suppliers. In each lifecycle phase, the investments made by the company for that specific phase are allocated to the solution space and divided by the number of product expected to be produced in the product mix in order to obtain a unitary value. The suppliers' contributions are indeed already unitary and allocated to the solution space. In each lifecycle phase, the R&D investments made by each supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. Then the contribution of each item is summed considering its frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the R&D investments allocated to each item provided could be obtained through the calculation provided in Table 3.37 or through data coming from database that could be developed in the future.

The expected contributions to the RDII indicators are presented in the following for each lifecycle phase.

Extraction: Average yearly unitary R&D investments made by the company in extraction activities allocated on the solution space and the average yearly R&D investments made by the suppliers allocated on the provided raw materials.

Material processing: Average yearly unitary R&D investments made by the company in material processing activities allocated on the solution space and the average yearly R&D investments made by the suppliers allocated on the material processing provided.

Part manufacturing: Average yearly unitary R&D investments made by the company in manufacturing activities allocated on the solution space including, when these activities are directly carried out by the company, the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials produced by the manufacturing activities; average yearly R&D investments made by the suppliers allocated on the components provided. Average yearly R&D investments made by the suppliers in the extraction, the material processing, the EOL, and the transportation allocated on the provided auxiliary and waste materials.

Assembly: Average yearly unitary R&D investments made by the company in assembly activities allocated on the solution space including, when these activities are directly carried out by the company, the extraction, the material processing, the EOL, and the transportation of auxiliary materials produced by the manufacturing activities; average yearly R&D investments made by the suppliers allocated on the assembly provided. Average yearly R&D investments made by the suppliers in the extraction, the material processing, the EOL, and the transportation allocated on the provided auxiliary materials.

Product use: Average yearly unitary R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) allocated on the solution space including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company. Average yearly R&D investments made by the suppliers in the extraction, the material processing, the manufacturing, the EOL, and the transportations allocated on the provided consumables.

Repair: Average yearly unitary R&D investments made by the company in repair activities allocated on the solution space including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company. Average yearly R&D investments made by the suppliers in the extraction, the material processing, the manufacturing, the assembly, the EOL, and the transportation allocated on the provided spare parts.

End of life: Average yearly unitary R&D investments made by the company in end of life treatments of the product allocated on the solution space and average yearly R&D investments made by the EOL facilities allocated on the provided EOL treatments.

Transportation: Average yearly unitary R&D investments made by the company in transportation activities allocated on the solution space. Average yearly R&D investments made by the suppliers allocated on the transportation provided. In this phase are considered all the transportation carried out on components, assemblies, and final products: transportations between the company sites, transportations from the suppliers, transportations to customers and retailers, transportations to EOL facilities.

The total value of the RDII indicator is obtained summing the contributions of all the lifecycle phases and its calculation formula is provided in Table 3.37.

3.4.4 Risk Management

3.4.4.1 Supply Risk Indicator Calculation Formula

The supply risk (SR) indicator is a quantitative indicator based on qualitative evaluations measuring the risk associated to the provision of items (raw materials, components, modules, parts, or final products) or services by the suppliers belonging to the supply chain defined by the solution space. This indicator is based on the two different factors:

- the provided resource criticality which is a qualitative measure of the item availability on the market, evaluated considering the number of possible alternative suppliers, and the ease in changing supplier, evaluated considering the setup time of a new supplier;
- the supplier risk which is a qualitative measure of the financial reliability of the supplier that provides the item.

Each lifecycle phase is characterized by a specific criticality depending on the item or service provided (e.g., material, components, assembly, etc.):

Extraction: in this phase the risk related to the purchasing of raw materials constituting the product, its surface treatments, and its packaging is assessed. The material criticality is here evaluated.

Material processing: in this phase the risk related to the purchasing of material processing carried out on the raw materials constituting the product, its surface treatments, and its packaging is assessed. The material processing criticality is here evaluated.

Part manufacturing: in this phase the risk related to the purchasing of components and auxiliary materials is assessed. The component criticality, the auxiliary material criticality, and the material processing concerning auxiliary materials criticality are here evaluated.

Assembly: in this phase the risk related to the purchasing of assemblies and auxiliary materials is assessed. The assembly criticality, the auxiliary material criticality and the material processing concerning auxiliary materials criticality are here evaluated.

The total value of the SR indicator is obtained by combining the contributions of all the lifecycle phases, whose calculation formulas are provided in Table 3.38, through the following formula:

$$\mathrm{SR} = 1 - \left[(1 - \mathrm{SR}_{\mathrm{ext}}) \times \left(1 - \mathrm{SR}_{\mathrm{mp}}\right) \times \left(1 - \mathrm{SR}_{\mathrm{pm}}\right) \times (1 - \mathrm{SR}_{\mathrm{as}})\right]$$

3.5 Social Indicators Calculation Formulas

Since the social pillar of sustainability did not get as much attention as environmental and economic pillars, the development of social indicators formulas starts almost from scratch for the majority of the indicators. This section is meant to provide for each indicator the scope of measurement, the general description of the formula and, whenever possible, the contributions to the indicator value grouped into the product lifecycle phases. The calculation formulas and the description of the acronyms, indexes, and terms used in the formula are also provided.

3.5.1 Working Condition and Workforce

3.5.1.1 Injury Intensity Indicator Calculation Formula

This indicator is meant to evaluate the average number of injuries per produced unit within the solution space considering the contribution of all actors involved in the production in different lifecycle phases.

For each lifecycle phase there are two contributions: the first is due to the part of activities carried out by the company, while the next one considers the contribution from suppliers who carry out part of activities belonging to the same

Table 3.38 SR calculation formula

LC phase	Data from design tools, data entry, and databases	Formula
	s_{targ} = supply chain member receiving the transported resource s_{source} = supply chain member providing the transported resource	
Extraction	b_{ext} = resource transported within the supply chain in the extraction phase $\mathrm{RC}_{b^{\mathrm{ext}}}$ = criticality of acquiring the resource b_{ext} on the market (value ranges between 0 and 1 where 0 means that the resource is a standard one widely available on the market and 1 means that the resource is a critical one and cannot be found on the market) $\mathrm{SR}_{(\mathrm{b}^{\mathrm{ext}},s^{\mathrm{source}},s^{\mathrm{targ}})}$ = risk related to the supply of the resource b_{ext} provided by the supply chain member s_{source} to the supply chain member s_{targ} (value ranges between 0 and 1 where 0 means that the financial reliability of the supplier s_{source} is very high while 1 means that it is almost non-existent) $\mathrm{SR}_{(b^{\mathrm{ext}},s^{\mathrm{source}},s^{\mathrm{targ}})}$ = boolean: 1 if the resource b_{ext} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{\mathrm{ext}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{ext} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$\mathrm{SR}_{\mathrm{ext}} = 1 - \Pi_{(b^{\mathrm{ext}},\, s^{\mathrm{targ}})}[1 - \mathrm{RC}_{b^{\mathrm{ext}}} \times \Pi_{(b^{\mathrm{ext}},\, s^{\mathrm{source}},\, s^{\mathrm{targ}})}(\mathrm{SR}_{(b^{\mathrm{ext}},s^{\mathrm{source}},\, s^{\mathrm{targ}})})^{\chi_{b^{\mathrm{ext}},\, s^{\mathrm{source}},\, s^{\mathrm{targ}}}}]^{\chi_{b^{\mathrm{ext}},\, s^{\mathrm{targ}}}}$
Material Processing	b_{mp} = resource transported within the supply chain in the material processing phase $\mathrm{RC}_{b^{\mathrm{mp}}}$ = criticality of acquiring the resource b_{mp} on the market (value ranges between 0 and 1 where 0 means that the resource is a standard one widely available on the market and 1 means that the resource is a critical one and cannot be found on the market) $\mathrm{SR}_{(b^{\mathrm{mp}},s^{\mathrm{source}},s^{\mathrm{targ}})}$ = risk related to the supply of the resource b_{mp} provided by the supply chain member s_{source} to the supply chain member s_{targ} (value ranges between 0 and 1 where 0 means that the financial reliability of the supplier s_{source} is very high while 1 means that it is almost non-existent) $\chi_{b^{\mathrm{mp}},s^{\mathrm{source}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{mp} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{\mathrm{b}^{\mathrm{mp}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{mp} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$\mathrm{SR}_{\mathrm{mp}} = 1 - \Pi_{(b^{\mathrm{mp}},\, s^{\mathrm{targ}})}[1 - \mathrm{RC}_{b^{\mathrm{mp}}} \times \Pi_{(b^{\mathrm{mp}},\, s^{\mathrm{source}},\, s^{\mathrm{targ}})} (\mathrm{SR}_{(b^{\mathrm{mp}},\, s^{\mathrm{source}},\, s^{\mathrm{targ}})})^{\chi_{b^{\mathrm{mp}},\, s^{\mathrm{source}},\, s^{\mathrm{targ}}}}]^{\chi_{b^{\mathrm{mp}},\, s^{\mathrm{targ}}}}$

(continued)

Table 3.38 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Part Manufacturing	b_{pm} = resource transported within the supply chain in the part manufacturing phase $\mathrm{RC}_{b^{\mathrm{pm}}}$ = criticality of acquiring the resource b_{pm} on the market (value ranges between 0 and 1 where 0 means that the resource is a standard one widely available on the market and 1 means that the resource is a critical one and cannot be found on the market) $\mathrm{SR}_{(b^{\mathrm{pm}},s^{\mathrm{source}},s^{\mathrm{targ}})}$ = risk related to the supply of the resource b_{pm} provided by the supply chain member s_{source} to the supply chain member s_{targ} (value ranges between 0 and 1 where 0 means that the financial reliability of the supplier s_{source} is very high while 1 means that it is almost non-existent) $\chi_{b^{\mathrm{pm}},s^{\mathrm{source}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{pm} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{\mathrm{pm}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{pm} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$\mathrm{SR}_{\mathrm{pm}} = 1 - \Pi_{(b^{\mathrm{pm}},s^{\mathrm{targ}})}[1 - \mathrm{RC}_{b^{\mathrm{pm}}} \times \Pi_{(b^{\mathrm{pm}},s^{\mathrm{source}},s^{\mathrm{targ}})} (\mathrm{SR}_{(b^{\mathrm{pm}},s^{\mathrm{source}},s^{\mathrm{targ}})})^{\chi_{b^{\mathrm{pm}},s^{\mathrm{source}},s^{\mathrm{targ}}}}]^{\chi_{b^{\mathrm{pm}},s^{\mathrm{targ}}}}$
Assembly	b_{as} = resource transported within the supply chain in the assembly phase $\mathrm{RC}_{b^{\mathrm{as}}}$ = criticality of acquiring the resource b_{as} on the market (value ranges between 0 and 1 where 0 means that the resource is a standard one widely available on the market and 1 means that the resource is a critical one and cannot be found on the market) $\mathrm{SR}_{(b^{\mathrm{as}},s^{\mathrm{source}},s^{\mathrm{targ}})}$ = risk related to the supply of the resource b_{as} provided by the supply chain member s_{source} to the supply chain member s_{targ} (value ranges between 0 and 1 where 0 means that the financial reliability of the supplier s_{source} is very high while 1 means that it is almost non-existent) $\chi_{b^{\mathrm{as}},s^{\mathrm{source}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{as} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{\mathrm{as}},s^{\mathrm{targ}}}$ = boolean: 1 if the resource b_{as} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$\mathrm{SR}_{\mathrm{as}} = 1 - \Pi_{(b^{\mathrm{as}},s^{\mathrm{targ}})}[1 - \mathrm{RC}_{b^{\mathrm{as}}} \times \Pi_{(b^{\mathrm{as}},s^{\mathrm{source}},s^{\mathrm{targ}})} (\mathrm{SR}_{(b^{\mathrm{as}},s^{\mathrm{source}},s^{\mathrm{targ}})})^{\chi_{b^{\mathrm{as}},s^{\mathrm{source}},s^{\mathrm{targ}}}}]^{\chi_{b^{\mathrm{as}},s^{\mathrm{targ}}}}$

phase. Since the number of injuries is usually measured at the company level, in order to allocate the number of injuries to the solution space, the turnover is used as allocation driver. In each lifecycle phase, the injuries occurred in each supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. For the company, the number of injuries is multiplied for the ratio of the turnover generated by the solution space and the total turnover of the company. The value due to the company is then divided by the yearly production volume to get the unitary value (the suppliers' contributions are indeed already unitary and allocated to the solution space). Then the contributions of each item are summed considering their frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the injuries allocated to each item can be provided directly in the calculation formula of Table 3.39 or, in the future, retrieved from database whenever available.

The expected contributions to the injury intensity (II) indicator are presented below. The II indicator is the first of a subset of the social indicators related to the intensity of different issues (including also Safety Expenditure Intensity, WTI, Staff Development Investments Intensity, and Charitable Contributions Intensity) and therefore the following considerations can be extended to those indicators.

Extraction: average yearly unitary injuries occurred in the company during the extraction activities allocated on the solution space and the average yearly injuries occurred in the suppliers allocated on the provided raw materials.

Material processing: average yearly unitary injuries occurred in the company during material processing activities allocated on the solution space and the average yearly injuries occurred in the suppliers allocated on the material processing provided.

Part manufacturing: average yearly unitary injuries occurred in the company during manufacturing activities allocated on the solution space including, when these activities are directly carried out by the company, the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials produced by the manufacturing activities; average yearly injuries occurred in the suppliers allocated on the components provided; average yearly injuries occurred in the suppliers during the extraction, the material processing, the EOL, and the transportation allocated on the provided auxiliary and waste materials.

Assembly: average yearly unitary injuries occurred in the company during assembly activities allocated on the solution space including, when these activities are directly carried out by the company, the extraction, the material processing, the EOL, and the transportation of auxiliary materials needed by the assembly activities; average yearly injuries occurred in the suppliers allocated on the assembly provided; average yearly injuries occurred in the suppliers during the extraction, the material processing, the EOL, and the transportation allocated on the provided auxiliary materials.

Product use: average yearly unitary injuries occurred in the company during the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company; average yearly injuries occurred in the suppliers during the extraction,

Table 3.39 II calculation formula through substitution

Element found in RDII table:	To be replaced with:
$\mathrm{RDI}_{\mathrm{ext}}$ [€] = average yearly R&D investments made by the company in extraction activities	$\mathrm{NI}_{\mathrm{ext}}$ [#] = average yearly number of injuries occurred in the company in extraction activities
$\mathrm{RDII}_{\mathrm{ext}}$	$\mathrm{II}_{\mathrm{ext}}$
$\mathrm{RDI}_{\mathrm{mp}}$ [€] = average yearly R&D investments made by the company in material processing activities	$\mathrm{NI}_{\mathrm{mp}}$ [#] = average yearly number of injuries occurred in the company in material processing activities
$\mathrm{RDII}_{\mathrm{mp}}$	$\mathrm{II}_{\mathrm{mp}}$
$\mathrm{RDI}_{\mathrm{man}}$ [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company	$\mathrm{NI}_{\mathrm{man}}$ [#] = average yearly number of injuries occurred in the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL and the transportation of auxiliary and waste materials when these activities are directly carried out by the company
RDI_q [€] = average yearly R&D investments made by the supplier q	NI_q [#] = average yearly number of injuries occurred at the supplier q
RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments	NI_r [#] = average yearly number of injuries occurred in the EOL facility r in EOL treatments
RDI_t [€] = average yearly R&D investments made by the transportation supplier t	NI_t [#] = average yearly number of injuries occurred at the transportation supplier t
$\mathrm{RDII}_{\mathrm{man}}$	$\mathrm{II}_{\mathrm{man}}$
$\mathrm{RDI}_{\mathrm{as}}$ [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company	$\mathrm{NI}_{\mathrm{as}}$ [#] = average yearly number of injuries occurred in the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company
$\mathrm{RDII}_{\mathrm{as}}$	$\mathrm{II}_{\mathrm{as}}$

(continued)

Table 3.39 (continued)

Element found in RDII table:	To be replaced with:
RDI_{use} [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company	NI_{use} [#] = average yearly number of injuries occurred in the company during the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company
$RDII_{use}$	II_{use}
RDI_{rep} [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company	NI_{rep} [#] = average yearly number of injuries occurred in the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company
$RDII_{rep}$	II_{rep}
RDI_{EOL} [€] = average yearly R&D investments made by the company in EOL treatments of the product	NI_{EOL} [#] = average yearly number of injuries occurred in the company in EOL treatments of the product
$RDII_{EOL}$	II_{EOL}
$RDI_{tra\ z}$ [€] = average yearly R&D investments made by the company in transportation activities	$NI_{tra\ z}$ [#] = average yearly number of injuries occurred in the company in transportation activities
$RDII_{tra}$	II_{tra}

the material processing, the manufacturing, the EOL, and the transportations allocated on the provided consumables.

Repair: average yearly unitary injuries occurred in the company during repair activities allocated on the solution space including the injuries occurred during the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company; average yearly injuries occurred in the suppliers during the extraction, the material processing, the manufacturing, the assembly, the EOL, and the transportation allocated on the provided spare parts.

End of life: average yearly unitary injuries occurred in the company during end of life treatments of the product allocated on the solution space; average yearly injuries occurred in the EOL facilities allocated on the provided EOL treatments.

Transportation: average yearly unitary injuries occurred in the company during transportation activities allocated on the solution space; average yearly injuries occurred in the suppliers allocated on the transportation provided. In this phase, all the transportations carried out on components, assemblies, and final products are considered: transportations between the company sites, transportations from the suppliers, transportations to customers and retailers, transportations to EOL facilities.

The total value of the II indicator is obtained summing the contributions of all the lifecycle phases. The definition of the II calculation formula is provided here, by offering a substitution table that allows to derive the II calculus from the previous described RDII formula, given its similarity due to the application of the same intensity method.

3.5.1.2 Safety Expenditure Intensity (II) Indicator Calculation Formula

This indicator is meant to measure the average unitary expense in safety issues considering the contribution of all actors involved in the production in different lifecycle phases.

For each lifecycle phase, the first contribution described is about the company, while the next ones are about the suppliers. In each lifecycle phase, the safety expenditures made by the company for that specific phase are allocated to the solution space and divided by the number of product expected to be produced in the product mix in order to obtain a unitary value. The allocation driver is the ratio of the turnover generated by the solution space and the total turnover of the company. The suppliers' contributions are indeed already unitary and allocated to the solution space. In each lifecycle phase, the safety expenditures made by each supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. Then the contributions of each item are summed considering its frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the safety expenditures allocated to each item can be provided directly in the calculation formula of Table 3.40 or, in the future, retrieved from database whenever available.

Table 3.40 SEI calculation formula through substitution

Element found in RDII table:	To be replaced with:
$\mathrm{RDI}_{\mathrm{ext}}$ [€] = average yearly R&D investments made by the company in extraction activities	$\mathrm{SE}_{\mathrm{ext}}$ [€] = average yearly safety expenditures made by the company in extraction activities
$\mathrm{RDII}_{\mathrm{ext}}$	$\mathrm{SEI}_{\mathrm{ext}}$
$\mathrm{RDI}_{\mathrm{mp}}$ [€] = average yearly R&D investments made by the company in material processing activities	$\mathrm{SE}_{\mathrm{mp}}$ [€] = average yearly safety expenditures made by the company in material processing activities
$\mathrm{RDII}_{\mathrm{mp}}$	$\mathrm{SEI}_{\mathrm{mp}}$
$\mathrm{RDI}_{\mathrm{man}}$ [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company	$\mathrm{SE}_{\mathrm{man}}$ [€] = average yearly safety expenditures made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company
RDI_q [€] = average yearly R&D investments made by the supplier q	SE_q [€] = average yearly safety expenditures made by the supplier q
RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments	SE_r [€] = average yearly safety expenditures made by the EOL facility r in EOL treatments
RDI_t [€] = average yearly R&D investments made by the transportation supplier t	SE_t [€] = average yearly safety expenditures made by the transportation supplier t
$\mathrm{RDII}_{\mathrm{man}}$	$\mathrm{SEI}_{\mathrm{man}}$
$\mathrm{RDI}_{\mathrm{as}}$ [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company	$\mathrm{SE}_{\mathrm{as}}$ [€] = average yearly safety expenditures made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company
$\mathrm{RDII}_{\mathrm{as}}$	$\mathrm{SEI}_{\mathrm{as}}$
$\mathrm{RDI}_{\mathrm{use}}$ [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company	$\mathrm{SE}_{\mathrm{use}}$ [€] = average yearly safety expenditure made by the company for manufacturing consumables

(continued)

Table 3.40 (continued)

Element found in RDII table:	To be replaced with:
$RDII_{use}$	SEI_{use}
RDI_{rep} [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company	SE_{rep} [€] = average yearly safety expenditures made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company
$RDII_{rep}$	SEI_{rep}
RDI_{EOL} [€] = average yearly R&D investments made by the company in EOL treatments of the product	SE_{EOL} [€] = average yearly safety expenditures made by the company in EOL treatments of the product
$RDII_{EOL}$	SEI_{EOL}
$RDI_{tra\ z}$ [€] = average yearly R&D investments made by the company in transportation activities	$SE_{tra\ z}$ [€] = average yearly safety expenditures made by the company in transportation activities
$RDII_{tra}$	SEI_{tra}

Table 3.41 EO calculation formula

Data from design tools, data entry, and databases	Formula
EO_{SS} = new employment opportunities created by the introduction of the solution space E_{SS} = total number of employees within the solution space	$EO = EO_{SS}/E_{SS} \times 100$

The expected contributions to the SEI indicators are the same as for the II indicator as described in Sect. 3.5.1.1. The definition of the SEI calculation formula is provided here, by offering a substitution table that allows to derive the SEI calculus from the previous described RDII formula, given its similarity due to the application of the same intensity method.

3.5.1.3 Employment Opportunity Indicator Calculation Formula

The employment opportunity (EO) indicator measures the percentage of the new employment opportunities created by the introduction of the solution space considering the contributions of the company only. The EO calculation formula is provided here (Table 3.41).

3.5.1.4 Workforce Turnover Intensity Indicator Calculation Formula

Social sustainability is intended to track stakeholders and one of them is workforce. Evaluation of the level of workforce satisfaction with their job results into development of an indicator called WTI. This indicator targets to evaluate rate of solution space workforces who leave the company considering all the supply chain actors (company and suppliers) along the product lifecycle.

For each lifecycle phase, the first contribution described is about the company, while the next ones are about the suppliers. In each lifecycle phase the number of employees working in that specific phase that are leaving the company are allocated to the solution space and divided by the number of product expected to be produced in the product mix in order to obtain a unitary value. The allocation driver is the ratio of the turnover generated by the solution space and the total turnover of the company. The suppliers' contributions are indeed already unitary and allocated to the solution space. In each lifecycle phase, the employees leaving the supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. Then the contributions of each item are summed considering its frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the employees leaving the supplier allocated to each item can be provided directly in the calculation formula of Table 3.42 or, in the future, retrieved from database whenever available.

Table 3.42 WTI calculation formula through substitution

Element found in RDII table:	To be replaced with:
RDI_{ext} [€] = average yearly R&D investments made by the company in extraction activities	WT_{ext} [#] = average yearly number of employees working in extraction activities leaving the company
$RDII_{ext}$	WTI_{ext}
RDI_{mp} [€] = average yearly R&D investments made by the company in material processing activities	WT_{mp} [#] = average yearly number of employees working in material processing activities leaving the company
$RDII_{mp}$	WTI_{mp}
RDI_{man} [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company	WT_{man} [#] = average yearly number of employees leaving the company that are working in manufacturing activities and in extraction, material processing, EOL, and transportation of auxiliary and waste materials
RDI_q [€] = average yearly R&D investments made by the supplier q	WT_q [#] = average yearly number of employees leaving the supplier q
RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments	WT_r [#] = average yearly number of employees leaving the EOL facility r
RDI_t [€] = average yearly R&D investments made by the transportation supplier t	WT_t [#] = average yearly number of injuries occurred at the transportation supplier t
$RDII_{man}$	WTI_{man}
RDI_{as} [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company	WT_{as} [#] = average yearly number of employees leaving the company that are working in assembly activities and in extraction, material processing, EOL, and transportations of auxiliary materials
$RDII_{as}$	WTI_{as}
RDI_{use} [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company	WT_{use} [#] = average yearly number of employees leaving the company that are working in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables

(continued)

Table 3.42 (continued)

Element found in RDII table:	To be replaced with:
$RDII_{use}$	WTI_{use}
RDI_{rep} [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company	WT_{rep} [#] = average yearly number of employees leaving the company that are working in repair activities and in extraction, material processing, manufacturing, EOL, and transportations of spare parts
$RDII_{rep}$	WTI_{rep}
RDI_{EOL} [€] = average yearly R&D investments made by the company in EOL treatments of the product	WT_{EOL} [#] = average yearly number of employees leaving the company that are working in EOL treatments of the product
$RDII_{EOL}$	WTI_{EOL}
$RDI_{tra\ z}$ [€] = average yearly R&D investments made by the company in transportation activities	$WT_{tra\ z}$ [#] = average yearly number of employees working in transportation activities
$RDII_{tra}$	WTI_{tra}

The expected contributions to the WTI indicators are the same as for the II indicator as described in Sect. 3.5.1.1. The definition of the WTI calculation formula is provided here, by offering a substitution table that allows to derive the WTI calculus from the previous described RDII formula, given its similarity due to the application of the same intensity method.

3.5.1.5 Multi-Skilled Operators Indicator Calculation Formula

This indicator is used as a proxy to measure how flexible the workforce is calculating the ratio of multi-skilled operators working within the solution space and the total number of operators working within the solution space. An operator is multi-skilled when he/she is able to perform more than one operation. In case the operator works in different department, he/she is considered only once in the department where he/she spends most of the time and he/she is considered to be multi-skilled even though in this department he/she is able to perform only one operation. The workforce flexibility is a plus in a mass customized environment since it allows operators to be moved in different areas of the production system depending on the workload of a specific moment that could be different in different areas as a consequence of the multiproduct context. This indicator is the sum of the values calculated for each production phase (extraction, material processing, manufacturing, assembly) as explained in more detail in what follows.

This section is meant to provide the description of the expected contributions to the MSO value from the different lifecycle phases.

Extraction: in the extraction phase the MSO is calculated as the ratio of the number of operators who are able to perform more than one extraction operation and the total number of operators working in the extraction department of the company.

Material processing: in the material processing phase the MSO is calculated as the ratio of the number of operators who are able to perform more than one material processing activity and the total number of operators working in the material processing department of the company.

Part Manufacturing: in the manufacturing phase the MSO is calculated as the ratio of the number of operators who are able to perform more than one manufacturing operation.

Assembly: in the assembly phase the MSO is calculated as the ratio of the number of operators who are able to perform more than one assembly operation.

The MSO calculation formula is provided here (Table 3.43).

Table 3.43 MSO calculation formula

LC Phase	Data from design tools, data entry, and databases	Formula
	op = operator	
	OP = total number of operators working in the company within the solution space	
Extraction	$OPX_{ext\ op}$ = binary variable whose value is 1 if operator op, working in the extraction department, is able to perform more than one extraction activities; 0 otherwise	$MSO_{ext} = \sum_{op} OPX_{ext\ op}/OP$
Material processing	$OPX_{mp\ op}$ = binary variable whose value is 1 if operator op, working in the material processing department, is able to perform more than one material processig activity; 0 otherwise	$MSO_{mp} = \sum_{op} OPX_{mp\ op}/OP$
Part manufacturing	$OPX_{man\ op}$ = binary variable whose value is 1 if operator op, working in the part manufacturing department, is able to perform more than one manufacturing operation; 0 otherwise	$MSO_{man} = \sum_{op} OPX_{man\ op}/OP$
Assembly	$OPX_{as\ op}$ = binary variable whose value is 1 if operator op, working in the assembly department, is able to perform more than one assembly operation; 0 otherwise	$MSO_{as} = \sum_{op} OPX_{as\ op}/OP$
Repair	$OPX_{rep\ op}$ = binary variable whose value is 1 if operator op, working in the repair department, is able to perform more than one repair operation; 0 otherwise	$MSO_{rep} = \sum_{op} OPX_{rep\ op}/OP$
EOL	$OPX_{EOL\ op}$ = binary variable whose value is 1 if operator op, working in the EOL department, is able to perform more than one EOL operation; 0 otherwise	$MSO_{EOL} = \sum_{op} OPX_{EOL\ op}/OP$

3.5.1.6 Staff Development Investment Intensity Indicator Calculation Formula

The staff development investment intensity (SDII) indicator measures the staff development investments made by the company and its suppliers for each unit of product, allocating these investments on the solution space and along the whole lifecycle of the product. The staff development investments are meant to train up labors and employees in order to enhance the workforce competencies.

For each lifecycle phase, the first contribution described is about the company, while the next ones are about the suppliers. In each lifecycle phase, the investments made by the company for that specific phase are allocated to the solution space and divided by the number of product expected to be produced in the product mix in order to obtain a unitary value. The allocation driver is the ratio of the turnover generated by the solution space and the total turnover of the company. The suppliers' contributions are indeed already unitary and allocated to the solution space. In each lifecycle phase, the staff development investments made by each supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. Then the contributions of each item are summed considering its frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the staff development investments allocated to each item can be provided directly in the calculation formula of Table 3.44 or, in the future, retrieved from database whenever available.

The expected contributions to the SDII indicators are the same as for the II indicator as described in Sect. 3.5.1.1. The definition of the SDII calculation formula is provided here, by offering a substitution table that allows to derive the SDII calculus from the previous described RDII formula, given its similarity due to the application of the same intensity method.

3.5.1.7 Income Level Indicator Calculation Formula

The income level (IL) measures are meant to compare the employees income of the solution space with an average yearly income per person taken as reference considering the weighted contribution of the company and its suppliers (the supply chain members) along the whole lifecycle of the product. For each supply chain member, the IL is measured as the ratio of the average yearly employee income and the average yearly income per person in the country where the supply chain member is placed. The employees included in this evaluation are from labors to middle management.

For each lifecycle phase, the IL of each supply chain member contributing to this phase is assessed. Then the contribution of each supply chain member is weighted: the suppliers' contribution through the ratio of the unitary costs paid to the supplier and the sum of the unitary purchasing expenditures and the unitary variable cost incurred by the company; the company contribution through the ratio of the unitary variable costs afforded by the company and the sum of the unitary

Table 3.44 SDII calculation formula through substitution

Element found in RDII table:	To be replaced with:
RDI_{ext} [€] = average yearly R&D investments made by the company in extraction activities	SDI_{ext} [€] = average yearly staff development investments made by the company in extraction activities
$RDII_{ext}$	$SDII_{ext}$
RDI_{mp} [€] = average yearly R&D investments made by the company in material processing activities	SDI_{mp} [€] = average yearly staff development investments made by the company in material processing activities
$RDII_{mp}$	$SDII_{mp}$
RDI_{man} [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company	SDI_{man} [€] = average yearly staff development investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company
RDI_q [€] = average yearly R&D investments made by the supplier q	SDI_q [€] = average yearly staff development investments made by the supplier q
RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments	SDI_r [€] = average yearly staff development investments made by the EOL facility r in EOL treatments
RDI_t [€] = average yearly R&D investments made by the transportation supplier t	SDI_t [€] = average yearly staff development investments made by the transportation supplier t
$RDII_{man}$	$SDII_{man}$
RDI_{as} [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL and the transportations of auxiliary materials when these activities are directly carried out by the company	SDI_{as} [€] = average yearly staff development investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL and the transportations of auxiliary materials when these activities are directly carried out by the company
$RDII_{as}$	$SDII_{as}$

(continued)

Table 3.44 (continued)

Element found in RDII table:	To be replaced with:
RDI_{use} [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company	SDI_{use} [€] = average yearly staff development investments made by the company in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company
$RDII_{use}$	$SDII_{use}$
RDI_{rep} [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company	SDI_{rep} [€] = average yearly staff development investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company
$RDII_{rep}$	$SDII_{rep}$
RDI_{EOL} [€] = average yearly R&D investments made by the company in EOL treatments of the product	SDI_{EOL} [€] = average yearly staff development investments made by the company in EOL treatments of the product
$RDII_{EOL}$	$SDII_{EOL}$
$RDI_{tra\ z}$ [€] = average yearly R&D investments made by the company in transportation activities	$SDI_{tra\ z}$ [€] = average yearly staff development investments made by the company in transportation activities
$RDII_{tra}$	$SDII_{tra}$

purchasing expenditures and the unitary variable cost incurred by the company. The weighted contributions are then summed along the product lifecycle phases in order to obtain the total value of the IL indicator.

The expected contributions to the IL value are grouped in the following into the product lifecycle phases.

Extraction: weighted IL of company and suppliers performing extraction activities.

Material processing: weighted IL of company and suppliers performing material processing activities.

Part manufacturing: weighted IL of company and suppliers performing manufacturing activities.

Assembly: weighted IL of company and suppliers performing assembly activities.

Use: weighted IL of company and suppliers manufacturing consumables.

Repair: weighted IL of company and suppliers performing repair activities.

End of life: weighted IL of company and suppliers performing end of life treatments.

Transportation: weighted IL of company and suppliers performing transportations. Since the costs paid to the suppliers in the other lifecycle phases usually include the transportation costs, here are considered the transportation costs paid to transportation suppliers for inter sites movements and the unitary variable costs of transportation directly afforded by the company.

The total value of the IL indicator is obtained summing the contributions of all the lifecycle phases according to the calculation formula provided here. Moreover, the calculation formulas of a subset of social indicators (namely Income Distribution, Worked Hours, Child Labor, and Local Supply) can be easily derived through substitution using the IL as reference (Table 3.45).

3.5.1.8 Income Distribution Indicator Calculation Formula

The income distribution (ID) indicator measures the equity of the employee wage distribution within the solution space considering the weighted contribution of the company and its suppliers (the supply chain members) along the whole lifecycle of the product. For each supply chain member, the ID measures the ratio of the income of the top 10 % employees and the income of the bottom 10 % employees. The employees included in this evaluation are from labor to middle management.

For each lifecycle phase, the ID of each supply chain member contributing to this phase is assessed. Then the contribution of each supply chain member is weighted by means of the ratio of the unitary cost paid to the supplier and the sum of the unitary purchasing expenditures and the unitary variable cost of the solution space; the company contribution through the ratio of the unitary variable costs afforded by the company and the sum of the unitary purchasing expenditures and the unitary variable cost of the solution space. The weighted contributions are then

Table 3.45 IL calculation formula

LC Phase	Data from design tools, data entry, and databases	Formula
	s = supply chain member (all the suppliers q + company) IL_s [€] = average income of the supply chain member's employees IL_{avg} [€] = average income of employees in the country where s is operating PE_{SS} [€] = purchasing expenditures made in the solution space N = yearly produced units UVC_{SS} [€] = unitary variable costs of the expected product mix $(UVC_{SS} = UVC_{ext} + UVC_{mp} + UVC_{man} + UVC_{as} + UVC_{use} + UVC_{rep} + UVC_{EOL} + UVC_{tra})$ q = supplier i = ith component of the final customizable product j = material type f_i = frequency of the ith component in the expected product mix (expected population of final products with their customization options) c = country y = energy type f_y = frequency of use of energy type y at the company level $EC_{y,c}$ [€/KWh] = cost of energy type y in country c op = operator $salary_{op}$ [€/year] = average yearly salary of operator op thw_{op} [h/year] = total number of yearly worked hour by operator op	

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Extraction	$w_{\text{ext }s}$ = weight of the supply chain member performing material extraction $c_{\text{ext }s}$ [€] = unitary cost of the extraction processes $c_{\text{ext }q}$ [€] = unitary cost of the extraction processes paid to q UVC_{ext} [€] = unitary variable cost faced by the company for extraction activities $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type j $C_{i,j,q}$ [€/kg] = cost of the raw material j for the ith component paid to supplier q $f_{i,j,c}$ = frequency of material j for the ith component extracted in country c $\text{WC}_{i,j,c}$ = waste coefficient when processing material j for the ith component in country c $\text{KC}_{i,j}$ [kWh/kg] = energy consumption per extracted kg of material j for the ith component $\text{WH}_{\text{ext op}}$ [h/year] = hours worked in one year by the operator op extracting materials j in the extraction department of the company	$\text{IL}_{\text{ext}} = \sum_s w_{\text{ext}\,s} \times \text{IL}_s/\text{IL}_{\text{avg}}$ where: $w_{\text{ext }s} = c_{\text{ext }s}/(\text{PE}_{\text{SS}}/N + \text{UVC}_{\text{SS}})$ $c_{\text{ext }s} = c_{\text{ext }q}$ if $s = q$ $c_{\text{ext }s} = \text{UVC}_{\text{ext}}$ if s = company $c_{\text{ext }q} = \sum_i \sum_j f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times C_{i,j,q}$ $\text{UVC}_{\text{ext}} = \sum_i \sum_j \sum_c \sum_y (1 - \sum_q f_{i,j,q}) \times f_i \times f_{i,j,c} \times f_y \times (V_{i,j} \times \rho_j)/(1 - \text{WC}_{i,j,c})$ $\times\ \text{KC}_{i,j} \times \text{EC}_{y,c} + (\sum_{\text{op}} \text{WH}_{\text{ext op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Material Processing	$w_{\mathrm{mp}\ s}$ = weight of the supply chain member performing material processing $c_{\mathrm{mp}\ s}$ [€] = unitary cost of the material processing $c_{\mathrm{mp}\ q}$ [€] = unitary cost of the material processing paid to q $\mathrm{UVC}_{\mathrm{mp}}$ [€] = unitary variable cost faced by the company for material processing p = material processing operation $f_{i,j,p,q}$ = frequency of the material processing p, used for material j for the ith component, provided by the supplier q $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type j $C_{i,j,p,q}$ [€/kg] = cost of the material processing p, made on the material j for the ith component, paid to the supplier q $f_{i,j,p,c}$ = frequency of material j for the ith component processed with p in country c $\mathrm{WC}_{i,j,p,c}$ = waste coefficient when processing with p material j for the ith component in country c $\mathrm{KC}_{i,j,p}$ [kWh/kg] = energy consumption of p per processed kg of j for the ith component $\mathrm{WH}_{\mathrm{mp}\ \mathrm{op}}$ [h/year] = hours worked in one year by the operator op carrying out operations p in the material processing department of the company	$\mathrm{IL}_{\mathrm{mp}} = \sum_s w_{\mathrm{mp}\ s} \times \mathrm{IL}_s/\mathrm{IL}_{\mathrm{avg}}$ where : $w_{\mathrm{mp}\ s} = c_{\mathrm{mp}\ s}/(\mathrm{PE}_{\mathrm{SS}}/N + \mathrm{UVC}_{\mathrm{SS}})$ $c_{\mathrm{mp}\ s} = c_{\mathrm{mp}\ q}$ if $s = qc_{\mathrm{mp}\ s} = \mathrm{UVC}_{\mathrm{mp}}$ if s = company $c_{\mathrm{mp}\ q} = \sum_i \sum_j \sum_p f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times C_{i,j,p,q}$ $\mathrm{UVC}_{\mathrm{mp}} = \sum_i \sum_j \sum_p \sum_c \sum_y (1 - \sum_q f_{i,j,p,q}) \times f_i \times f_{i,j,p,c} \times f_y \times (V_{i,j} \times \rho_j)/(1 - \mathrm{WC}_{i,j,p,c})$ $\times\ \mathrm{KC}_{i,j,p} \times \mathrm{EC}_{y,c} + (\sum_{\mathrm{op}} \mathrm{WH}_{\mathrm{mp\,op}} \times \mathrm{salary}_{\mathrm{op}}/\mathrm{thw}_{\mathrm{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Part Manufacturing	$w_{\text{man } s}$ = weight of the supply chain member performing part manufacturing $c_{\text{man } s}$ [€] = unitary cost of the manufacturing processes $c_{\text{man } q}$ [€] = unitary cost of the ith component paid to q UVC_{man} [€] = unitary variable cost faced by the company for part manufacturing $f_{i,q}$ = frequency of the ith component provided by supplier q $C_{i,q}$ [€] = cost of the ith component paid to the supplier q m = manufacturing operation $f_{m,c}$ = frequency of operation m made in country c $\text{WC}_{m,c}$ = waste coefficient of operation m in country c CS_m = specific UVC measure parameter for operation m KC_m [kWh/CS_m] = energy needed for operation m $\text{WH}_{\text{man op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$\text{IL}_{\text{man}} = \sum_s w_{\text{man } s} \times \text{IL}_s/\text{IL}_{\text{avg}}$ where : $w_{\text{man } s} = c_{\text{man } s}/(\text{PE}_{\text{SS}}/N + \text{UVC}_{\text{SS}})$ $c_{\text{man } s} = c_{\text{man } q}$ if $s = q$ $c_{\text{man } s} = \text{UVC}_{\text{man}}$ if $s = \text{company}$ $c_{\text{man } q} = \sum_i f_i \times f_{i,q} \times C_{i,q}$ $\text{UVC}_{\text{man}} = \sum_m \sum_c \sum_y f_{m,c} \times f_y \times \left[1/\left(1 - \text{WC}_{m,c}\right)\right] \times \text{CS}_m \times \text{KC}_m \times \text{EC}_{y,c}$ $+ (\sum_{\text{op}} \text{WH}_{\text{man op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$
Assembly	$w_{\text{as } s}$ = weight of the supply chain member performing assembly $c_{\text{as } s}$ [€] = unitary cost of the assembly processes $c_{\text{as } q}$ [€] = unitary cost of the ath assembly paid to q UVC_{as} [€] = unitary variable cost faced by the company for assembly operations a = ath assembly of the final customizable product f_a = frequency of the ath assembly in the expected product mix $f_{a,q}$ = frequency of the ath assembly provided by supplier q $C_{a,q}$ = cost of the ath assembly paid to the supplier q o = assembly operation $f_{o,c}$ = frequency of the operation o made in country c $\text{WC}_{o,c}$ = waste coefficient of operation o in country c CS_o = specific UVC measure parameter for assembly operation o KC_o [kWh/CS_o] = energy needed for operation o $\text{WH}_{\text{as op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$\text{IL}_{\text{as}} = \sum_s w_{\text{as } s} \times \text{IL}_s/\text{IL}_{\text{avg}}$ where : $w_{\text{as } s} = c_{\text{as } s}/(\text{PE}_{\text{SS}}/N + \text{UVC}_{\text{SS}})$ $c_{\text{as } s} = c_{\text{as } q}$ if $s = q$ $c_{\text{as } s} = \text{UVC}_{\text{as}}$ if $s = \text{company}$ $c_{\text{as } q} = \sum_a f_a \times f_{a,q} \times C_{a,q}$ $\text{UVC}_{\text{as}} = \sum_o \sum_c \sum_y f_{o,c} \times f_y \times \left[1/\left(1 - \text{WC}_{o,c}\right)\right]$ $\times \text{CS}_o \times \text{KC}_o \times \text{EC}_{y,c} + (\sum_{\text{op}} \text{WH}_{\text{as op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Product use	$w_{k\ s}$ = weight of the supply chain member manufacturing consumables $c_{k\ s}$ [€] = unitary cost of the kth consumable $c_{k\ q}$ [€] = unitary cost of the kth consumable paid to q $\mathrm{UVC_{use}}$ [€] = unitary variable cost faced by the company for consumables production k = kth consumable component $n_{\mathrm{cons}\ k}$ = number of consumable components k expected to be used per unit of product during the product use phase f_k = frequency of kth consumable in the expected product mix $f_{k,j,q}$ = frequency of the material j for kth consumable component provided by the supplier q $V_{\mathrm{cons}\ k,j}$ [cm^3] = volume of the part of the kth consumable component made by the material j ρ_j [kg/cm^3] = mass density of material type j $C_{k,j,q}$ [€/kg] = cost of the raw material j for the kth component paid to supplier q g = manufacturing operations making the consumable components that are expected to be used per unit of product during the product use phase $f_{g,c}$ = frequency of the manufacturing operation g made in country c $\mathrm{WC}_{g,c}$ = waste coefficient of operation g in country CS_g = specific GWP measure parameter for manufacturing operation g KC_g [kWh/CS_g] = energy needed for operation g $\mathrm{WH_{mank\ op}}$ [h/year] = hours worked in one year by the operator op carrying out operations g in the part manufacturing department of the company	$\mathrm{IL_{use}} = \sum_s w_{k\,s} \times \mathrm{IL}_s/\mathrm{IL_{avg}}$ where : $w_{k\,s} = c_{k\,s}/(\mathrm{PE_{SS}}/N + \mathrm{UVC_{SS}})$ $c_{k\,s} = c_{k\,q}$ if $s = \mathrm{q}c_{k\,s} = \mathrm{UVC_{use}}$ if $s = \mathrm{company}$ $c_{k\,q} = \sum_k n_{\mathrm{cons}\,k} \times f_k \times f_{k,j,q} \times V_{\mathrm{cons}\ k,j} \times \rho_j \times C_{k,j,q}$ $\mathrm{UVC_{use}} = \sum_g \sum_c \sum_y f_{g,c} \times f_y \times \left[1/\left(1 - \mathrm{WC}_{g,c}\right)\right] \times \mathrm{CS}_g \times \mathrm{KC}_g \times \mathrm{EC}_{y,c}$ $+ (\sum_{\mathrm{op}} \mathrm{WH_{mank\ op}} \times \mathrm{salary_{op}}/\mathrm{thw_{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Repair	$w_{\text{rep }s}$ = weight of the supply chain member performing repair $c_{\text{rep }s}$ [€] = unitary cost of the repair activities and components $c_{\text{rep }q}$ [€] = unitary cost of the repair activities and components paid to q UVC_{rep} [€] = unitary variable cost faced by the company for repair the products $n_{s\ i}$ = number of substitutions of the ith component expected to occur during the product use phase $f_{i,q}$ = frequency of the ith component provided by supplier q $C_{i,q}$ [€] = cost of the ith component paid to the supplier q m = manufacturing operation $f_{s\ m,c}$ = frequency of the manufacturing operation m in country c, making the substitution components expected to be used per unit of product during the product use phase $\text{WC}_{m,c}$ = waste coefficient of operation m in country c CS_m = specific UVC measure parameter for operation m KC_m [kWh/CS_m] = energy needed for operation m $\text{WH}_{\text{manr op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m making the substitution components expected to be used per unit of product during the product use phase	$\text{IL}_{\text{rep}} = \sum_s w_{\text{rep }s} \times \text{IL}_s/\text{IL}_{\text{avg}}$ where : $w_{\text{rep }s} = c_{\text{rep }s}/(\text{PE}_{\text{SS}}/N + \text{UVC}_{\text{SS}})$ $c_{\text{rep }s} = c_{\text{rep }q}$ if $s = q$ $c_{\text{rep }s} = \text{UVC}_{\text{rep}}$ if $s =$ company $c_{\text{rep }q} = \sum_i n_{s\ i} \times f_i \times f_{i,q} \times C_{i,q}$ $\text{UVC}_{\text{rep}} = \sum_m \sum_c \sum_y f_{s\ m,c} \times f_y \times [1/(1 - \text{WC}_{m,c})] \times \text{CS}_m \times \text{KC}_m \times \text{EC}_{y,c}$ $+ (\sum_{\text{op}} \text{WH}_{\text{manr op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
EOL	$w_{\mathrm{EOL}\ s}$ = weight of the supply chain member performing EOL of the product $c_{\mathrm{EOL}\ s}$ [€] = unitary cost of the EOL treatments $c_{\mathrm{EOL}\ q}$ [€] = unitary cost of the EOL treatments paid to q $\mathrm{UVC}_{\mathrm{EOL}}$ [€] = unitary variable cost faced by the company for EOL of the products r = EOL facility $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type j $C_{\mathrm{EOL}\ i,j,r}$ [€/kg] = cost of the EOL treatments made on material j for the ith component paid to the EOL facility r l = EOL treatment $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $f_{i,j,c}$ = frequency of material j for the ith component extracted in country c $\mathrm{WC}_{i,j,c}$ = waste coefficient when processing material j for the ith component in country c $\mathrm{KC}_{i,j}$ [kWh/kg] = energy consumption per extracted kg of material j for the ith component $\mathrm{KC}_{i,j,l}$ [kWh/kg] = energy consumption of the EOL treatment l carried out on material j for the ith component $\mathrm{WH}_{\mathrm{EOL\ op}}$ [h/year] = hours worked in one year by the operator op treating j in the EOL department of the company	$\mathrm{IL}_{\mathrm{EOL}} = \sum_s w_{\mathrm{EOL}\ s} \times \mathrm{IL}_s / \mathrm{IL}_{\mathrm{avg}}$ where : $w_{\mathrm{EOL}\ s} = c_{\mathrm{EOL}\ s} / (\mathrm{PE}_{\mathrm{SS}}/N + \mathrm{UVC}_{\mathrm{SS}})$ $c_{\mathrm{EOL}\ s} = c_{\mathrm{EOL}\ q}$ if $s = q$ $c_{\mathrm{EOL}\ s} = \mathrm{UVC}_{\mathrm{EOL}}$ if $s =$ company $c_{\mathrm{EOL}\ q} = \sum_i \sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times C_{\mathrm{EOL}\ i,j,r}$ $\mathrm{UVC}_{\mathrm{EOL}} = \sum_i \sum_j \sum_l \sum_c \sum_y (1 - \sum_q f_{i,j,q}) \times f_i \times f_{i,j,c} \times f_y$ $\times\ (V_{i,j} \times \rho_j)/\left(1 - \mathrm{WC}_{i,j,c}\right) \times \mathrm{KC}_{i,j,l} \times \mathrm{EC}_{y,c} + (\sum_{\mathrm{op}} \mathrm{WH}_{\mathrm{EOL\ op}} \times \mathrm{salary}_{\mathrm{op}}/\mathrm{thw}_{\mathrm{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
Transportation	$w_{\text{tra }s}$ = weight of the supply chain member performing transportations $c_{\text{tra }s}$ [€] = unitary cost of transportations t = transportation supplier $c_{\text{tra }t}$ [€] = unitary cost of transportations paid to supplier t UVC_{tra} [€] = unitary variable cost faced by the company for transportations z = mean of transportation $f_{i,j,q}$ = frequency of the material j for the ith component provided by supplier q $f_{i,j,t,z}$ = frequency of the transportation provided by the supplier t, transporting j for the ith component by means of transportation z $V_{i,j}$ [cm^3] = volume of the portion of the ith component made by the material type j ρ_j [kg/cm^3] = mass density of material type j $d_{i,j,q,z}$ [km] = distance between supplier q (providing material j for ith component) and the next supply chain partner covered by the mean of transportation z $C_{\text{tra }i,j,t,z}$ [€/(kg km)] = cost of the transportation of j for ith component by means z paid to the transportation supplier t $d_{\text{cust }z}$ [km] = average distance to the customer covered by the mean of transportation z r = EOL facility $f_{i,j,r}$ = frequency of material j for ith component treated by the EOL facility r $d_{\text{EOL }r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z $C_{\text{tra }i,j,z}$ [€/(kg km)] = cost of the transportation of j for ith component by means z directly faced by the company $\text{WH}_{\text{tra op}}$ [h/year] = hours worked in one year by the operator op in transportation activities	$\text{IL}_{\text{tra}} = \sum_s w_{\text{tra }s} \times \text{IL}_s/\text{IL}_{\text{avg}}$ where : $w_{\text{tra }s} = c_{\text{tra }s}/(\text{PE}_{\text{SS}}/N + \text{UVC}_{\text{SS}})$ $c_{\text{tra }s} = c_{\text{tra }t}$ if $s = t$ $c_{\text{tra }s} = \text{UVC}_{\text{tra}}$ if $s = \text{company}$ $c_{\text{tra }t} = \sum_i \sum_j \sum_q \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times C_{\text{tra }i,j,t,z}$ $+ \sum_i \sum_j \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{cust }z} \times C_{\text{tra }i,j,t,z}$ $+ \sum_i \sum_j \sum_r \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{EOL }r,z} \times C_{\text{tra }i,j,t,z}$ $\text{UVC}_{\text{tra}} = \sum_i \sum_j \sum_z f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times C_{\text{tra }i,j,z}$ $+ \sum_i \sum_j \sum_z f_i \times V_{i,j} \times \rho_j \times d_{\text{cust }z} \times C_{\text{tra }i,j,z}$ $+ \sum_i \sum_j \sum_r \sum_z f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times d_{\text{EOL }r,z} \times C_{\text{tra }i,j,z}$ $+ (\sum_{\text{op}} \text{WH}_{\text{tra op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$

ummed along the product lifecycle phases in order to obtain the total value of the ID indicator.

The expected contributions to the ID indicators are the same as for the IL indicator as described in Sect. 3.5.1.7. The definition of the ID calculation formula is provided here, by offering a substitution table that allows to derive the ID calculus from the previous described IL formula, given its similarity due to the application of the same calculation method (Table 3.46).

Table 3.46 ID calculation formula through substitution

Element found in IL table:	To be replaced with:
IL_s [€] = average income of the supply chain member's employees	IT_s [€] = average income of the top 10 % employees of the supply chain member
IL_{avg} [€] = average income of employees in the country where s is operating	IB_s [€] = average income of the bottom 10 % employees of the supply member s
IL_{ext}	ID_{ext}
IL_{mp}	ID_{mp}
IL_{man}	ID_{man}
IL_{as}	ID_{as}
IL_{use}	ID_{use}
IL_{rep}	ID_{rep}
IL_{EOL}	ID_{EOL}
IL_{tra}	ID_{tra}

3.5.1.9 Worked Hours Indicator Calculation Formula

The worked hours (WH) indicator measures the number of worked hours per employee per week considering the weighted contribution of the company and its suppliers (the supply chain members) along the whole lifecycle of the product. The employees included in this evaluation are from labor to middle management.

For each lifecycle phase, the WH of each supply chain member contributing to this phase is assessed. Then the contribution of each supply chain member is weighted: the suppliers' contribution through the ratio of the unitary costs paid to the supplier and the sum of the unitary purchasing expenditures and the unitary variable cost incurred by the company; the company contribution through the ratio of the unitary variable costs afforded by the company and the sum of the unitary purchasing expenditures and the unitary variable cost of incurred by the company. The weighted contributions are then summed along the product lifecycle phases in order to obtain the total value of the WH indicator.

The expected contributions to the WH indicators are the same as for the IL indicator as described in Sect. 3.5.1.7. The definition of the WH calculation formula is provided here, by offering a substitution table that allows to derive the WH

Table 3.47 WH calculation formula through substitution

Element found in IL table:	To be replaced with:
IL_s [€]/IL_{avg} [€] = average income of the supply chain member's employees divided by average income of employees in the country where s is operating	WH_s [h] = average weekly worked hour per employee (labor plus employees including middle management) of the supply chain member s
IL_{ext}	WH_{ext}
IL_{mp}	WH_{mp}
IL_{man}	WH_{man}
IL_{as}	WH_{as}
IL_{use}	WH_{use}
IL_{rep}	WH_{rep}
IL_{EOL}	WH_{EOL}
IL_{tra}	WH_{tra}

calculus from the previous described IL formula, given its similarity due to the application of the same calculation method (Table 3.47).

3.5.1.10 Child Labor Indicator Calculation Formula

The child labor (CL) indicator measures the use of child labor within the solution space considering the weighted contribution of the company and its suppliers (the supply chain members) along the whole lifecycle of the product.

For each lifecycle phase, the use of child labor by each supply chain member contributing to this phase is assessed considering if the supply chain member uses or not children in its activity, neglecting the number of children used. Then the contribution of each supply chain member (indeed a 1 if it uses child labor, otherwise 0) is weighted: the suppliers' contribution through the ratio of the unitary costs paid to the supplier and the sum of the unitary purchasing expenditures and the unitary variable cost of the solution space; the company contribution through the ratio of the unitary variable costs afforded by the company and the sum of the unitary purchasing expenditures and the unitary variable cost of the solution space. The weighted contributions are then summed along the product lifecycle phases in order to obtain the total value of the CL indicator, obtaining a value included from 0 (no one is using children in its activity) to 1 (all supply chain members use children).

The expected contributions to the CL indicators are the same as for the IL indicator as described in Sect. 3.5.1.7. The definition of the CL calculation formula is provided here, by offering a substitution table that allows to derive the CL calculus from the previous described IL formula, given its similarity due to the application of the same calculation method (Table 3.48).

Table 3.48 CL calculation formula through substitution

Element found in IL table:	To be replaced with:
IL_s [€]/IL_{avg} [€] = average income of the supply chain member's employees divided by average income of employees in the country where s is operating	$\chi_{CL\ s}$ = boolean that is equal to 1 if s uses child labor, 0 otherwise
IL_{ext}	CL_{ext}
IL_{mp}	CL_{mp}
IL_{man}	CL_{man}
IL_{as}	CL_{as}
IL_{use}	CL_{use}
IL_{rep}	CL_{rep}
IL_{EOL}	CL_{EOL}
IL_{tra}	CL_{tra}

3.5.2 Product Responsibility

3.5.2.1 Product Social Features Indicator Calculation Formula

The product social features (PSF) indicator measures the number of product features that aim at improving the condition of specific target groups (e.g., product for disabled, elderly, and diabetic people).

Since PSF merely measures the number of social features, a formula is not required. The design activities affecting the PSF indicator are those happening during the design phase through the formalization of customers requirements and relative selection of those features to be customized toward specific groups. To this end also social sustainability may result empowered by the application of mass customization options. No contributions are expected from the product lifecycle phases since the number of social features is determined at design level.

3.5.3 Local Community

3.5.3.1 Charitable Contribution Intensity Indicator Calculation Formula

The charitable contribution intensity (CCI) indicator is meant to measure the expenditure in charities within the solution space along the product lifecycles.

For each lifecycle phase, the first contribution described is about the company, while the next ones are about the suppliers. In each lifecycle phase, the charity expenditures made by the company department operating in that specific phase are allocated to the solution space and divided by the number of product expected to be produced in the product mix in order to obtain a unitary value. The allocation driver is the ratio of the turnover generated by the solution space and the total

Table 3.49 CCI calculation formula through substitution

Element found in RDII table:	To be replaced with:
RDI_{ext} [€] = average yearly R&D investments made by the company in extraction activities	CC_{ext} [€] = average yearly charitable contributions made by the extraction division of the company
$RDII_{ext}$	CCI_{ext}
RDI_{mp} [€] = average yearly R&D investments made by the company in material processing activities	CC_{mp} [€] = average yearly charitable contributions made by the material processing division of the company
$RDII_{mp}$	CCI_{mp}
RDI_{man} [€] = average yearly R&D investments made by the company in manufacturing activities including the investment made in the extraction, the material processing, the EOL, and the transportation of auxiliary and waste materials when these activities are directly carried out by the company	CC_{man} [€] = average yearly charitable contributions made by the manufacturing division of the company
RDI_q [€] = average yearly R&D investments made by the supplier q	CC_q [€] = average yearly charitable contributions made by the supplier q
RDI_r [€] = average yearly R&D investments made by the EOL facility r in EOL treatments	CC_r [€] = average yearly charitable contributions made by the EOL facility r
RDI_t [€] = average yearly R&D investments made by the transportation supplier t	CC_t [€] = average yearly charitable contributions made by the transportation supplier t
$RDII_{man}$	CCI_{man}
RDI_{as} [€] = average yearly R&D investments made by the company in assembly activities including the investment made in the extraction, the material processing, the EOL, and the transportations of auxiliary materials when these activities are directly carried out by the company	CC_{as} [€] = average yearly charitable contributions made by the assembly division of the company
$RDII_{as}$	CCI_{as}
RDI_{use} [€] = average yearly R&D investments made by the company in product features (e.g., a new material, the power dissipated during its functioning) including the R&D investments in the extraction, the material processing, the manufacturing, the EOL, and the transportations of consumables when these activities are directly carried out by the company	CC_{use} [€] = average yearly charitable contributions made by the company division producing consumables

(continued)

Table 3.49 (continued)

Element found in RDII table:	To be replaced with:
$RDII_{use}$	CCI_{use}
RDI_{rep} [€] = average yearly R&D investments made by the company in repair activities including the investments made in the extraction, the material processing, the manufacturing, the EOL, and the transportations of spare parts when these activities are directly carried out by the company	CC_{rep} [€] = average yearly charitable contributions made by the repair division of the company
$RDII_{rep}$	CCI_{rep}
RDI_{EOL} [€] = average yearly R&D investments made by the company in EOL treatments of the product	CC_{EOL} [€] = average yearly charitable contributions made by the EOL division of the company
$RDII_{EOL}$	CCI_{EOL}
$RDI_{tra\ z}$ [€] = average yearly R&D investments made by the company in transportation activities	$CC_{tra\ z}$ [€] = average yearly charitable contributions made by the transportation division of the company
$RDII_{tra}$	CCI_{tra}

Table 3.50 LS calculation formula through substitution

Element found in IL table:	To be replaced with:
s = supply chain member (all the suppliers q + company)	q = supplier
IL_s [€]/$\mathrm{IL}_{\mathrm{avg}}$ [€] = average income of the supply chain member's employees divided by average income of employees in the country where s is operating	$\chi_{\mathrm{LS}\,q}$ = boolean that is equal to 1 if s uses child labor, 0 otherwise
$\mathrm{IL}_{\mathrm{ext}}$	$\mathrm{LS}_{\mathrm{ext}}$
$w_{\mathrm{ext}\ s}$ = weight of the supply chain member performing material extraction	$w_{\mathrm{ext}\,q}$ =weight of supplier q performing material extraction $\left(w_{\mathrm{ext}\,q} = c_{\mathrm{ext}\,q}/(\mathrm{PE}_{\mathrm{SS}}/N)\right)$
$c_{\mathrm{ext}\ s}$ [€] = unitary cost of the extraction processes	$c_{\mathrm{ext}\,q}$[€] =unitary cost of the extraction processes paid to q $\left(c_{\mathrm{ext}\,q} = \sum_i \sum_j f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times C_{i,j,q}\right)$
$\mathrm{IL}_{\mathrm{mp}}$	$\mathrm{LS}_{\mathrm{mp}}$
$w_{\mathrm{mp}\ s}$ = weight of the supply chain member performing material processing	$w_{\mathrm{mp}\,q}$ =weight of supplier q performing material processing $\left(w_{\mathrm{mp}\,q} = c_{\mathrm{mp}\,q}/(\mathrm{PE}_{\mathrm{SS}}/N)\right)$
$c_{\mathrm{mp}\ s}$ [€] = unitary cost of the material processing processes	$c_{\mathrm{mp}\,q}$[€] =unitary cost of the material processing processes paid to q $\left(c_{\mathrm{mp}\,q} = \sum_i \sum_j \sum_p f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times C_{i,j,p,q}\right)$
$\mathrm{IL}_{\mathrm{man}}$	$\mathrm{LS}_{\mathrm{man}}$
$w_{\mathrm{man}\ s}$ = weight of the supply chain member providing components	$w_{\mathrm{man}\,q}$ =weight of supplier q providing components $\left(w_{\mathrm{man}\,q} = c_{\mathrm{man}\,q}/(\mathrm{PE}_{\mathrm{SS}}/N)\right)$
$c_{\mathrm{man}\ s}$ [€] = unitary cost of the ith component processes	$c_{\mathrm{man}\,q}$[€] =unitary cost of the ith component processes paid to q $\left(c_{\mathrm{man}\,q} = \sum_i f_i \times f_{i,q} \times C_{i,q}\right)$
$\mathrm{IL}_{\mathrm{as}}$	$\mathrm{LS}_{\mathrm{as}}$

(continued)

Table 3.50 (continued)

Element found in IL table:	To be replaced with:
$w_{\text{as}\ s}$ = weight of the supply chain member providing assemblies	$w_{\text{as}\ q}$ =weight of supplier q providing assemblies $\left(w_{\text{as}\ q} = c_{\text{as}\ q}/(\text{PE}_{\text{SS}}/N)\right)$
$c_{\text{as}\ s}$ [€] = unitary cost of the ath assembly processes	$c_{\text{as}\ q}$[€] =unitary cost of the ath assembly processes paid to q $\left(c_{\text{as}\ q} = \sum_{a} f_a \times f_{a,q} \times C_{a,q}\right)$
IL_{use}	LS_{use}
$w_{\text{use}\ s}$ = weight of the supply chain member providing consumables	$w_{k\ q}$ =weight of supplier q providing consumables $\left(w_{k\ q} = c_{k\ q}/(\text{PE}_{\text{SS}}/N)\right)$
$c_{\text{use}\ s}$ [€] = unitary cost of the kth consumable processes	$c_{k\ q}$[€] =unitary cost of the kth consumable paid to q $\left(c_{k\ q} = \sum_{k} n_{\text{cons}\ k} \times f_k \times f_{k,j,q} \times V_{\text{cons}\ k,j} \times \rho_j \times C_{k,j,q}\right)$
IL_{rep}	LS_{rep}
$w_{\text{rep}\ s}$ = weight of the supply chain member providing components for repair	$w_{\text{rep}\ q}$ =weight of supplier q providing components for repair $\left(w_{\text{rep}\ q} = c_{\text{rep}\ q}/(\text{PE}_{\text{SS}}/N)\right)$
$c_{\text{rep}\ s}$ [€] = unitary cost of the repair activities and components processes	$c_{\text{rep}\ q}$[€] =unitary cost of the repair activities and components paid to q $\left(c_{\text{rep}\ q} = \sum_{i} n_{s\ i} \times f_i \times f_{i,q} \times C_{i,q}\right)$
IL_{EOL}	LS_{EOL}
$w_{\text{EOL}\ s}$ = weight of the supply chain member performing EOL of the product	$w_{\text{EOL}\ q}$ =weight of supplier q performing EOL of the product $\left(w_{\text{EOL}\ q} = c_{\text{EOL}\ q}/(\text{PE}_{\text{SS}}/N)\right)$

(continued)

Table 3.50 (continued)

Element found in IL table:	To be replaced with:
$c_{\text{EOL}\ s}$ [€] = unitary cost of the EOL treatments	$c_{\text{EOL}\ q}$[€] =unitary cost of the EOL treatments paid to q $\left(c_{\text{EOL}\ q} = \sum_i \sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times C_{\text{EOL}\ i,j,r}\right)$
IL_{tra}	LS_{tra}
$w_{\text{tra}\ s}$ = weight of the supply chain member performing transportations	$w_{\text{tra}\ t}$ =weight of supplier t performing transportations $\left(w_{\text{tra}\ q} = c_{\text{tra}\ q}/(\text{PE}_{\text{SS}}/N)\right)$
$c_{\text{tra}\ s}$ [€] = unitary cost of the transportations	$c_{\text{tra}\ t}$[€] =unitary cost of the transportations paid to q $\left(c_{\text{tra}\ t} = \sum_i \sum_j \sum_q \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times C_{\text{tra}\ i,j,t,z}\right.$ $+ \sum_i \sum_j \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{cust}\ z} \times C_{\text{tra}\ i,j,t,z}$ $\left.+ \sum_i \sum_j \sum_r \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{EOL}\ r,z} \times C_{\text{tra}\ i,j,t,z}\right)$

turnover of the company. The suppliers' contributions are indeed already unitary and allocated to the solution space. In each lifecycle phase, the charity expenditures made by each supplier are weighted through the ratio of the cost of the item or service provided and the sales turnover of the supplier. Then the contributions of each item are summed considering its frequency within the solution space. The suppliers' contributions are structured so that the terms concerning the charity expenditures allocated to each item can be provided directly in the calculation formula of Table 3.49 or, in the future, retrieved from database whenever available.

The expected contributions to the CCI indicators are the same as for the II indicator as described in Sect. 3.5.1.1. The definition of the CCI calculation formula is provided here, by offering a substitution table that allows to derive the CCI calculus from the previous described RDII formula, given its similarity due to the application of the same intensity method.

3.5.3.2 Local Supply Indicator Calculation Formula

The local supply (LS) indicator measures the percentage of the purchasing expenditures related to items supplied from local suppliers considering the weighted contribution of the suppliers along the whole lifecycle of the product.

For each lifecycle phase each supplier is identified as local or not. Then the contribution of supplier (indeed a 1 if the supplier is local, 0 otherwise) is weighted through the ratio of the unitary costs paid to the supplier and the unitary purchasing expenditures. The weighted contributions are then summed along the product lifecycle phases in order to obtain the total value of the LS indicator, that is a value included from 0 (no suppliers are local) to 1 (all suppliers are local).

The expected contributions to the LS indicators are the same as for the IL indicator as described in Sect. 3.5.1.7. The definition of the LS calculation formula is provided here, by offering a substitution table that allows to derive the LS calculus from the previous described IL formula, given its similarity due to the application of the same calculation method (Table 3.50).

3.6 Conclusions and Next Steps

This chapter addresses the development of the SAM assessment model. We start from its literature foundations through the definition of each single indicator along with its calculation formula.

With the development of this assessment model, a crucial cornerstone toward the concrete implementation of the Sustainable Mass Customization paradigm has been met. In fact, SAM deals with the issue of concretizing the effects of the decisions taken at design level down into numbers.

Selection of the indicators was focused on obtaining a homogeneous and balanced set of reliable indicators that measures the overall impact of all the entities involved in the product lifecycle on the three sustainability aspects. Such an ambitious target was never set in the existing literature so far and is meant to promote a real possibility to evaluate the performances of the Stable Solution Space for the companies as well as communicating in a transparent and reliable way the achieved improvements to customers.

Bibliography

Azapagic A, Perdan S (2000) Indicators of sustainable development for industry: a general framework. IChemE 78(4): 243–261

Bare J, Norris G, Pennington D, McKone T (2003) TRACI: the tool for the reduction and assessment of chemical and other environmental impacts. J Ind Ecol 6(3–4):49–78

BEES online documentation. Retrieved from http://www.nist.gov/el/economics/BEESSoftware.cfm/registration.html

Benoît C, Bernard M (eds) (2009) Guidelines for social life cycle assessment of products. UNEP, Paris

Brent AC (2004) A life cycle impact assessment procedure with resource groups as areas of protection. Int J Life Cycle Assess 9(3):172–179

Centre of Environmental Science (CML) and University of Technology (TUD/TB), Fuels and Raw Material Bureau (Bureau B&G), University of Amsterdam (UVA), IVAM-Environmental Research (IVAM-ER), & Netherlands Organization for Applied Scientific Research (TNO) (2001a). Life cycle assessment: an operational guide to the ISO standards - part 1: LCA in perspective [online]. Available from: http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

Centre of Environmental Science (CML) and University of Technology (TUD/TB), Fuels and Raw Material Bureau (Bureau B&G), University of Amsterdam (UVA), IVAM-Environmental Research (IVAM-ER), & Netherlands Organization for Applied Scientific Research (TNO) (2001b). Life cycle assessment: an operational guide to the ISO standard—Part 2a: Guide [online]. Available from: http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html

Corbiere NT, Blanc I, Erkman S (2011) Towards a global criteria based framework for the sustainability assessment of bioethanol supply chains application to the Swiss dilemma: Is local produced bioethanol more sustainable than bioethanol imported from brazil. Ecol Ind 11(5):1447–1458

Dow Jones Sustainability World Index (DJSI) Guide Book (2010) Retrieved from http://www.sustainability-index.com/

Dreyer L (2009). Inclusion of social aspects in life cycle assessment of products development of a methodology for social life cycle assessment, PhD Thesis, DTU Management Engineering, Denmark

Dreyer L, Hauschild Z, Schierbeck J (2010a) Characterization of social impacts in LCA part 1: Development of indicators for labour rights. Int J Life Cycle Assess 15(3):247–259

Dreyer L, Hauschild Z, Schierbeck J (2010b) Characterization of social impacts in LCA part 2: implementation in six company case studies 15(4): 385–402

Eco-indicator 95 Report (1999) Retrieved from http://www.pre-sustainability.com/content/reports

Eco-indicator 99 Report (1999) Retrieved from http://www.pre-sustainability.com/content/reports

Ecoinvent Overview and Methodology (2007) Retrieved from http://www.ecoinvent.org/home/

Ecoinvent Code of Practice (2009) Retrieved from http://www.ecoinvent.org/home/

Ecoinvent Implementation of LCIA Methods (2010) Retrieved from http://www.ecoinvent.org/home/

Ecoinvent Technical Documentation of the Ecoinvent Database (2003) Retrieved from http://www.ecoinvent.org/home/

EIME Indicators Manual (2009) Retrieved from http://codde.fr/

EPD Program (2007) Retrieved from http://www.environdec.com/

Fiksel J (1996) Design for environment. McGraw Hill, New York

FTSE4Good Index Series—Inclusion Criteria. Retrieved from http://www.ftse.com/Indices/FTSE4Good_Index_Series/index.jsp

Global Reporting Initiative (2002) Sustainability reporting guidelines. Global Reporting Initiative, Boston

Global Reporting Initiative (2000–2011) Sustainability reporting guidelines G3.1

Global Reporting Initiative (GRI) (2006) Sustainability Reporting Guidelines V3.0. GRI, Amsterdam, Netherlands

Global Reporting Initiative (GRI) (2006) The sustainability reporting guidelines. Retrieved from http://www.globalreporting.org/Home

Guinèe JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, Weidema BP (2001) Life cycle assessment; An operational guide to the ISO standards. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, The Netherlands

Guinée JB (2002) Handbook on life cycle assessment. Springer, Berlin

Gungor A, Gupta SM (1999) Issues in environmentally conscious manufacturing and product recovery: a survey. Comput Ind Eng 36:811–853

Hang Y, Qu M, & Zhao F (2011) Economical and environmental assessment of an optimized solar cooling system for a medium-sized benchmark office building in Los Angeles, California. To appear 36(2):648–658

Hauschild M, Potting J (2005) Spatial differentiation in life cycle impact assessment—the EDIP2003 methodology. In: Environmental news of the Danish ministry of environment, p 80

Introduction to GreenSCOR. Retrieved from http://supply-chain.org/

Jensen AA, Remmen A (eds) (2006) Background report for a UNEP guide to life cycle management—a bridge to sustainable products. UNEP, Paris

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8(6):324–330

Jorgensen A, Le Bocq A, Nazarkina L, Hauschild M (2008) Methodologies for social life cycle assessment. Int J Life Cycle Assess 13(2):96–103

Krajnc D, Glavic P (2003) Indicators of sustainable production. Clean Tech Environ Policy 5:279–288

Kruse S, Flysjö A, Kasperczyk N, Scholz AJ (2009) Socioeconomic indicators as a complement to life cycle assessment—an application to salmon production systems. Int J Life Cycle Assess 14(1):8–18

Mascle C, Zhao HP (2008) Integrating environmental consciousness in product/process development based on life-cycle thinking. Int J Prod Econ 112(1): 5–17

ReCiPe Report (2009) Retrieved from http://www.pre-sustainability.com/content/reports

Solidworks sustainability indexes. Retrieved from http://www.solidworks.com/sustainability/

Veleva V, Ellenbecker M (2001) Indicators of sustainable production: framework and methodology. J Cleaner Prod 9:519–549

Verein Deutscher Ingenieure (VDI 1997) Cumulative energy demand—terms, definitions, methods of calculation. VDI-Richtlinien 4600. Düsseldorf, Germany

WCED: World Commission on Environment and Development (1987) Our common future. Oxford University Press, Oxford

Wright M, Allen D, Clift R, Sas H (1997) Measuring corporate environmental performance: the ICI environmental burden system. J Ind Ecol 1(4):117–127

Chapter 4
Assessment of Sustainable MC Production in a Selected Test Case

4.1 Introduction

In the previous chapters, we have provided means to answer a set of fundamental questions: how can a mass customization implementation be set up? What kind of production system is needed? What channels are the most suitable for tracking the targeted customer segment? How will this solution perform as far as sustainability is concerned?

Here we present a real test case, where actual data are retrieved and handled in practical terms in order to perform both the solution space generation (through the instantiation of the MCIT template) and the sustainability assessment of the designed solution.

This chapter therefore offers to the reader an actual contextualization of the MCIT template and SAM model, thus promoting a conscious application of the proposed methodologies to his own business cases.

4.2 MCIT: An Instantiation in Kitchen Furniture

When starting the process of defining the solution space for a mass customized product, a company management needs to take into account many relevant aspects concerning both internal strengths and weaknesses and external characteristics of the market, where it is going to position the product.

Here we will start the analysis of our case study in the kitchen furniture by applying the Mass Customization Implementation Template in order to map all its interesting features and to show how to build a viable business model and the skeleton of the solution space.

The result, as applied in the company we will refer to as Tertium for privacy reasons, is presented in Fig. 4.1 though, as always, the journey is more important than the destination. So, let us see how the blocks of the MCIT have been populated.

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_4,

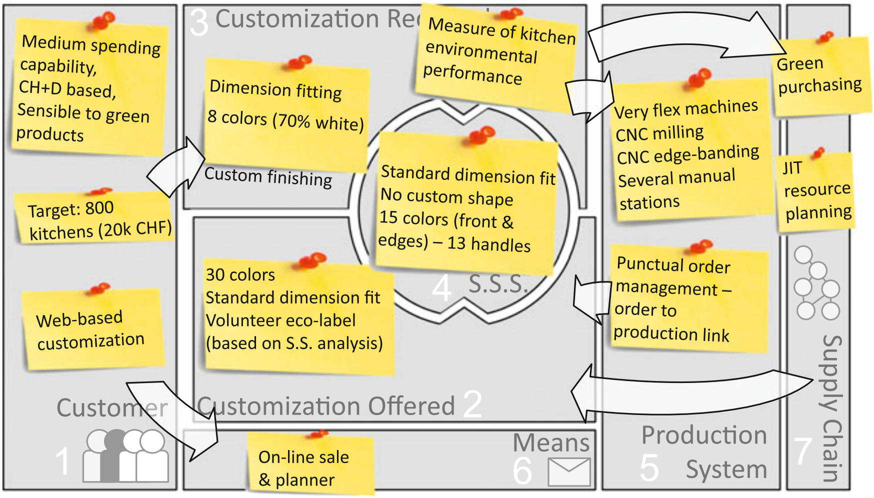


Fig. 4.1 Mass customization implementation template instantiated in the Tertium test case

The block order followed in the approach to the template has been driven by the peculiarities of the implemented strategy in the specific case in order to reflect somehow the way the business model has been conceived. As mentioned, there's no specific block to start from within the MCIT.

4.2.1 Customer

In order to understand where the company wants to position its new mass customized line, it is useful to take one step back and take a look at the current business the company is running. Tertium is active in the production of high-end customized kitchens, with a strong attention to the single customer requirements which often lead to engineered-to-order solutions. In this capability to satisfy almost any request coming from the customer lies the key company strength.

Its main market resides in the Tessin Canton in Switzerland, though the company sells also in the rest of the country through a network of multi-brand dealers.

Nonetheless, following a contraction of sold volumes due to the global demand crisis and to the growth of European competitors set by the unfavorable shift occurred to the currency change between Euro and Swiss Franc, the company has decided to differentiate its offer and breach into new markets.

That brings to the first question, *what is the target market?* The opportunity to use its flexible production means and expertise in the customization market to create a more mass-oriented offer has seemed natural. So the journey we are about to tell is about the structuring of a stable solution space out of what we can call an industrial craft production.

The identification of the target market is thus driven by this starting point whose aim is to create a parallel line of more standardized products which still hold the same high-quality standards but limit the customization choices and options to a predefined set.

Through market analysis it has been possible to determine that, due to closeness of taste in style, Swiss and German customers interested in a customized offer with a medium-to-high spending capability (20,000 CHF allocated for buying a kitchen) are the reference target for a customized offer coming from a producer like Tertium. Moreover, a clear aptitude for environmental responsible products has been elicited as a distinctive trait of this market segment.

The second question is about the *expected sales volume* this new offer is likely to be providing to the company. The performed analysis pointed out that a target of 800 kitchens per year at the end of the warm-up period (estimated in three years) is a feasible goal. This expansion in the sold volume is in line with the company expectations and would allow to saturate its capabilities.

What is the expected degree of customer satisfaction in relation with balance Price/Personalization? The 20,000 CHF has been verified against the average market price for kitchens belonging to the same cluster whose cost has been estimated in 16,000 CHF. Thanks to the market analysis, the 25 % increase in price has been evaluated as reasonable premium that customers would be willing to pay for the possibility to both participate in the co-design experience of their kitchen and to get a product that better fits their specific needs in the terms we will see in the next section.

This leads us to the next question that is the level of *satisfaction with involvement in design?* A significant part of the new customized offer stands in the possibility granted to the customer to interact and play with the design of his customized kitchen. The web-based configuration of the product that many competitors have already implemented becomes then not only a tool that supports the sale phase in the absence of dedicated retailers (this is the case of the German market that is new to the company) but also a way to make aware and attract new customers to the Tertium's offer.

4.2.2 Customization Required

Going ahead in our case study, the most important features that the target customers, identified in Sect. 4.2.1, require are the following:

- *Dimension fitting*, that is the possibility to significantly customize the dimension of the kitchen elements in order to both create a unique instance of the product and more relevantly to fit the furniture dimensions with the specific measures of the room where it is placed.
- The market analysis on the aesthetic preferences of the customers have highlighted that approximately *8 colors* are usually chosen among which the white color is chosen 70 % of the times. However, a requirement of *personalized finishing* of the kitchen elements has also been elicited from the market.

- Eventually, it has been resolved that the aptitude toward environmentally responsible production and delivery of products requires from the customer a *measurable proof of the environmental sustainability* of the proposed offer.

4.2.3 Production System

The required customization, defined in the previous section, leads us to analyze how the current production system of the company copes with it and how it needs *to evolve toward specific Customization technologies.*

Despite this could look like a simple case where only a downsize of the company capabilities is required (Tertium already produces highly personalized kitchens), still a step-up in the order management is mandatory for the success of the implementation. In fact, the current process of order data acquisition and transmission from the retailers to the company and down to production lacks completely the required rigor and structure. To this purpose, the implementation of an integrated software suite including critical nodes as ERP, the online configurator, design tools, etc., has been defined as a main priority and is currently ongoing in the company.

To the contrary, no actual change has been required to the equipments within the production system that already accounts flexible cutting, milling and drilling machines, and advanced edging machines for both gluing and laser edging operations.

These changes will imply that *skills and attitude of the current human operators adapt* to the new way of managing the order, though the only affected employees are:

- the already existing retailers who will need to be trained in the use of the configurator;
- the designers, who will need to cope their design strategies with the mass customization paradigm for defining stable solutions.

4.2.4 Supply Chain

The second block that is strongly influenced by the customization offered is the supply chain one, where we get to ask ourselves if *the supply chain cope with the erraticism in terms of variations and volumes imposed by my MC implementation*. The market analysis already brings to us a valid starting point for this reasoning that is the evaluation of customers' preferences in terms of colors. In fact one of the key decisions for the implementation of mass customized furniture production is the position of the decoupling point. The storage, in the company warehouses of vast amounts of semi-finished, is a situation that should be by nature avoided especially when these are large chipboards in a multitude of different colors. Therefore, except for the white color that covers 70 % of the request, the Just in Time resource planning needs to be implemented for a proper cost containment and efficiency of the flexible production. This nonetheless appears to be a strength of the legacy production system of the company since it is already experienced in producing even higher personalization-level kitchens and thus has already incorporated this concepts in their business.

Concerning the *impact of this flexibility on costs*, if correctly implemented following the above-mentioned criteria, the new mass customized offer should have little effect on it. In fact, when compared to an similar system producing standard kitchens, what we can observe is the introduction of more unpredictable color options that the proposed approach can easily handle and of the sustainability assessment which can be made almost transparent in terms of costs. What remains difficult to translate in economic terms is the likely delay of the order lead time due to the handling of a complex though flexible system dealing with Lot Size One orders.

Eventually, in order to meet its customers requirement of green products, Tertium chooses to incorporate in procurement sustainability considerations alongside the conventional criteria of price and quality. Sustainable procurement is used by companies that meet their needs for goods not on a pure cost-benefit analysis, but with a view to maximizing net sustainability benefits for the wider world. By applying this approach Tertium shifts part of the liability of being sustainable to suppliers with long history and experience in green products, also capable to produce reliable data on their wares.

4.2.5 Customization Offered

The study of the capabilities of the production system allows to produce a first instance of *what degree of customization can it offer and if any extension is needed*. The following features can be defined:

- *Standard dimension fitting*, meaning that, within this mass customized offer, the company is capable to allow only the choosing of element dimension with a varying, even with a remarkable granularity but not continuous, width. The obtainment of different heights for the columns will be granted through the modularity of the components while depth is fixed.
- The upper limit of color choice is set by the capability of the edging machine to handle different colors without requiring additional setups and by the availability of corresponding chipboards at local suppliers that have been chosen in order to ease the implementation of the Just in Time strategy. By combining these elements, *30 colors* is set as the reference limit.

- Eventually, the *sustainability profile* of the offer resulting from the implementation of the Sustainability Assessment presented in Chap. 3 at the company, becomes an element of the customized proposal aimed at coping with the customer requirements.

4.2.6 Stable Solution Space

At this point, it is possible to combine the elements so far analyzed in order to sketch what will then become the stable solution space of the new customized offer. This will be treated in detail in Sect. 4.3.1, where all the choices and options will be listed. Here it is enough to remind that a compromise between request and offer must be done without, on one hand, neglecting any important requirement and, on the other hand, altering significantly the associated costs (it can be done obviously when needed, yet this requires an iteration of the process to tune the whole business model).

4.2.7 Means

The final block of the MCIT to be here filled deals with the reshaping of the interaction with the customer. *Rising awareness on the product* is the foremost goal for this business since it is supposed to attract customers belonging to market segments that are currently not targeted by the company. What is more, this has to be carried out without relying on the usual channels, since the business is meant to be expanded abroad where no company dealers are available, thus leading us to the second question: *how and where does the co-design take place?* The conceived answer is to move on the net the co-design phase by implementing a valid online configurator capable to let the customer know, interact, personalize, and order his own kitchen. Also the sustainability issue is included in the configurator so that, by actively playing with the customization choices and relative impact, the customer can judge the reliability of the proposed measures.

The last question of this block about the *increase in delivery costs* scarcely affects the studied business, since already kitchens need to be directly delivered to the final customer. The only increase, estimated in 5 %, occurs in the delivery of products to Germany.

4.3 Sustainability Assessment of a Kitchen Solution Space

This section will stage a practical application of the sustainability assessment model to a selected test case, related to the production of mass customized kitchens presented in Sect. 4.2. The goal is to guide the reader in a step-by-step process aimed at clarifying the use of the complex formulas shown in Chap. 3.

The complete assessment of a solution space describing a complex product such as a mass customized kitchen (and the related production system and supply chain) would require several complex and articulated calculation steps, exceeding the purpose of this section. Therefore, we will limit the analysis to a significant subset of the considered product, to be chosen so that it represents both a relevant proxy of the issues that can arise when considering the full kitchen and a valid demonstrator of the main characteristics of the proposed assessment model (and its capability to be applied on mass-customized solution spaces).

Out of the 35 indicators presented, we will focus here on the calculation of the global warming potential (GWP) related to the solution space, as it is a good representative of the methodologies used not only in the environmental compartment but also in the economic and social ones.

4.3.1 The Solution Space

The first step is the modeling of the solution space that is the description of all the possible configurations of the product, the production processes that can make them and the supply chain supporting both production and delivering of the product. In the following sections we will go through these three aspects separately for the sake of clarity although it is plain that, in reality, they are concurrently designed and so they appear to be intrinsically interrelated.

4.3.1.1 Product, Where also the Forecast of the Product Mix is Defined

As anticipated in the Introduction of this chapter, the product that we are going to consider in this exercise is a subset of all the possible configurations of a customizable kitchen. Within these reasonable boundaries, the goal is to understand how we can produce a synthetic representation of the bill of material for a customizable product. In fact, the mass customization approach aims at proposing many different (dependent or independent) options to the customer during the co-design phase. This reflects directly on the complexity of describing the product in its potential configuration and so before it is instantiated in one single entity personalized for a specific customer. Nonetheless, since the sustainability assessment takes place during the design phase and not during the co-design, a way to have a holistic description of the product is needed.

Let's consider, as an example, what seems to be a simple case of customized product: a running shoe. Usually, the customer can apply many modifications starting from the standard design. He can choose the color of many parts like the upper, the insole, the laces, etc.; he can define the cushioning level of the sole for adapting it to its weight and running style; sometimes he can even apply his own logo or name and, obviously, he can choose the best fitting shoe size.

It is easy to understand how the number of choices can rapidly explode even for a simple product like a shoe and, for each choice, the number of possible options can be relevant as well (that is, for example, the case of colorizing parts when usually a wide palette is offered to the customer).

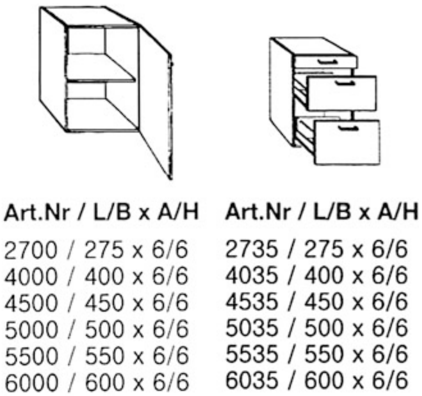
This brings to the impossibility to handle customization by pursuing the description of all the possible configurations in a brute force approach. However, even the opposite approach, that is considering the list of all possible components in the customizable offer without relating them to the choices, is a failing one. In fact, if we are to consider sustainability level in a mass customization environment we need to cope from the very beginning with its peculiarities. To this end, two things are required: (1) a holistic and structured bill of material of the product that allows to relate customer choices with product components and (2) a meaningful forecast of the product mix to be applied on it.

In this way, it is possible to weight the choices of the customers—as a whole, not considered as single entities—on the final burden set to the sustainability compartments.

In our example, we will extract from all the possible components that can constitute a customizable kitchen, two cabinets as shown in the figure below. The first one has a single front door and one shelf on the inside. The other one has three drawers, each one with a different height (1/6, 2/6, 3/6) (Fig. 4.2).

Both cabinets can be customized in many of their features. To each one of these customization opportunities, we will link a unique identifier as in the following list:

- *elementType*: it represents the choice between the two different cabinets and so it can assume the value 6,000, referring to the cabinet with the front door or 6,035 referring to the cabinet with drawers;
- *width*: both cabinets come with the same height (6/6 that corresponds to 762 mm) and depth (570 mm) but they can be customized in their width according to the available values of 275, 400, 450, 500, 550, and 600 mm;



Art.Nr / L/B x A/H	Art.Nr / L/B x A/H
2700 / 275 x 6/6	2735 / 275 x 6/6
4000 / 400 x 6/6	4035 / 400 x 6/6
4500 / 450 x 6/6	4535 / 450 x 6/6
5000 / 500 x 6/6	5035 / 500 x 6/6
5500 / 550 x 6/6	5535 / 550 x 6/6
6000 / 600 x 6/6	6035 / 600 x 6/6

Fig. 4.2 Cabinets 6,000 and 6,035

- *frontColor*: to both the front door of cabinet 6,000 and the drawers front of cabinet 6,035 can be applied 15 different colors;
- *frontEdgeColor*: to the edge of front doors or drawers fronts the same 15 colors as for the option above can be applied that do not have to match mandatorily with the color of the relative fronts;
- *internalEdgeColor*: also the visible edge of the cabinet box is offered in the four different colors that are *white*, *black*, *anthracite*, and *aluminum silver*;
- *handleType*: both the front door of cabinet 6,000 and the drawers front of cabinet 6,035 can be equipped with one among a choice of 13 different handle types;
- *sideHasColor*: eventually there is the possibility to have one or both sides of the cabinet painted the same color as applied to the front usually when the cabinet is the last of the row or standalone and so its sides are visible (the accepted values are therefore *right*, *left*, *null*, *both*).

These will be the reference choices granted to the customer for this example, with the forecasts shown in Table 4.1. As stated before, upon these choices a forecast of the product mix that will be sold needs to be defined in order to, let's say, balance the weighted version of the customizable product to be assessed. To this purpose, many strategies can be put in place depending on the level of maturity of the considered solution space. In this example, the data shown in the table below have been extracted from last year orders of the company since the product is an established one.

After having defined the customization choices and the forecast occurrence of each of their options, it is necessary to link them to the structured bill of material of the product. This has been done in an ad hoc environment that allows to handle all the necessary building blocks for this representation.

The bill of material of our sample product is shown in Fig. 4.3 where different symbols refer to the above-mentioned building blocks:

- square: represents the product—our kitchen—and it is the root node of the structure;
- three circles: are the assemblies that constitute the product and are positioned in an intermediate point within the structure;
- circles: represent the components constituting the product and are therefore the leaves of the structure;
- hexagons: give the possibility to follow different paths along the structure depending on a customization choice whose options values are drawn on the arrows linked to them;
- pentagons: are the so-called multipliers, every element placed below them appears in the bill of material as many times as the reported multiplier value. This value can, in turn, be driven by a customization choice;
- arrows: draw the dependencies between the elements thus creating the hierarchical structure of the bill of material.

It can be observed that this kind of modeling language allows for reuse of common parts of the product description. This happens also in our example for the

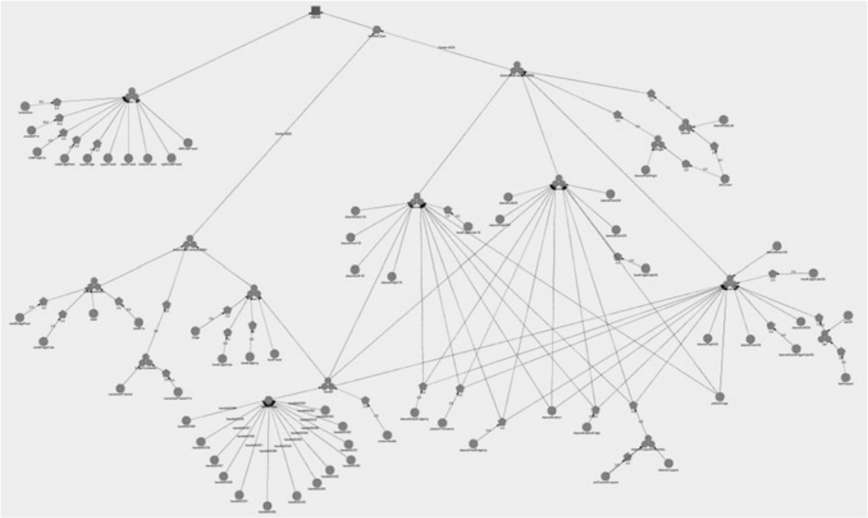


Fig. 4.3 Representation of the bill of material for the customizable product

part related to the cabinet box that is shared both by cabinet 6,000 and 6,035. If we zoom in the upper part of the bill of material, as shown in Fig. 4.4, we can see, on the left side, the panels and the other components needed to assembly the box whereas, on the right side, the distinctive components of the two different cabinets are positioned under the choice that drives them.

4.3.1.2 Production System, Where the Manufacturing Operations Frequency Is Presented

The modeling of the production system is the second step to be carried out and it is aimed at listing the operations needed to manufacture components and assemblies

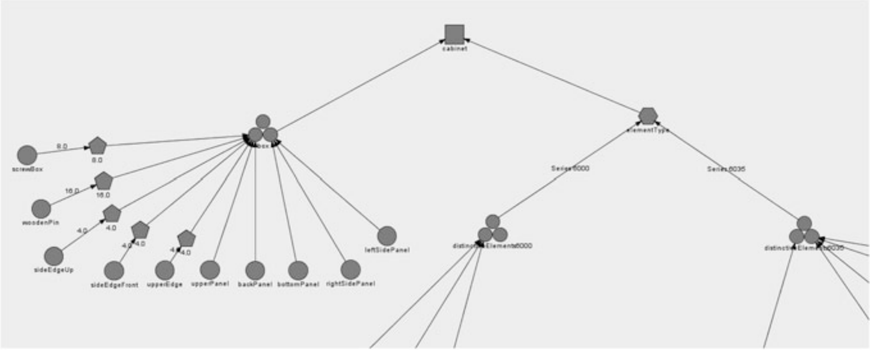


Fig. 4.4 Shared parts of the bill of material

of the product. Again, the interest is on the implication that the mass customization approach brings to the process. In fact, the personalization will require each time different components and/or different operations for making them.

Accordingly, our model of the production system has to be at the same time holistic, so that it can describe how any instance of the customizable product is produced, but also synthetic so that it doesn't overgrow with the increasing number of potential products. To this end, we can exploit the forecast of the product mix done at product level in order to generate the frequency of occurrence of the manufacturing operation per unit of product.

Let us see this with an example where we consider the element *leftSidePanel* which represents the left side of the cabinet box. Its production requires operations listed in Table 4.2.

As it can be observed, the first three operations and the last one are common to both cabinets 6,000 and 6,035 and thus their manufacturing frequency is simply how many times the operation is performed. To the contrary, if we look, for instance, at *drillingLeftSideShelf*, its manufacturing frequency is weighted by the percentage of occurrence as defined by the product mix forecast:

$$f_m = 6\,\text{holes} \cdot 0.6 = 3.6$$

This is the value that will be used in the calculation of the sustainability assessment for multiplying the operation impact.

The here defined operations will be later on aggregated in processes that are the basis for the definition of the supply chain blocks as it will be presented in the next section.

4.3.1.3 Supply Chain, Where Also a First Glance at Frequency of Resources Is Given

Eventually, the supply chain that supports the production and distribution of the product needs to be defined as many impacts on sustainability are related to the transportation of resources between the supply chain actors. In Fig. 4.5, the supply chain for our example is depicted. Although the example has been developed in collaboration with a real company on real data, we will use fake names to preserve the privacy of the involved companies.

The kitchen producer, that we will call Tertium, is surrounded by its suppliers. For each one a process is defined, according to what described in the previous section. This allows to determine the input and output needed by each supply chain actor which needs to be provided through the transportation represented by the arrows shown in the figure.

Let us make an example. Tertium, our kitchen producer, is in charge of the final assembly of the cabinets, a process that is identified as *cabinetManufacturing*. This process requires as input the resources listed in Table 4.2.

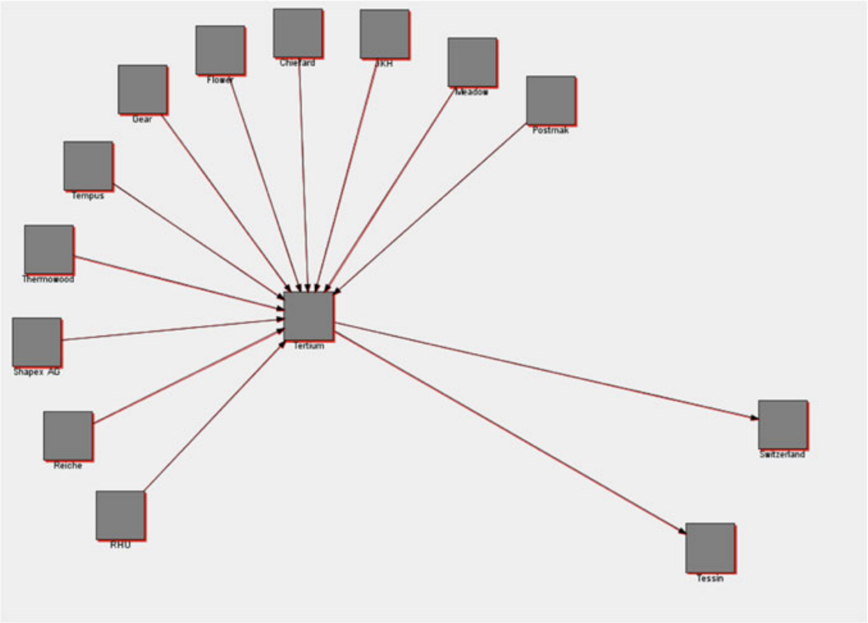


Fig. 4.5 Representation of the supply chain

If we focus on the handle resource, this is provided by JKH that is responsible for a process called *handleProduction* which delivers as output the needed resource in all its possible variants. In order to complete the transport description we need to add the distance between JKH and Tertium that is 51 km and the type of transport mean used, in this case by lorry.

We can also see how its occurrence in the final product depends on the applied customization. In fact cabinet 6,000 requires only one handle to be assembled on the front door whereas cabinet 6,035 requires three, one for each drawer. This allows to make a first consideration on the impact of product mix on the resources occurrence in the weighted product to be assessed. In fact we know, from Table 4.1, that cabinet 6,000 appears in the final product 60 % of the times and cabinet 6,035 in the remaining ones. This means that the number of handles in the product is:

$$\mathit{handle\,frequency} = 1 \cdot 0.6 + 3 \cdot 0.4 = 1.8$$

This applies in turn to the choice of the handle type. Going back again to Table 4.1, we can focus on the handle 00389 which is chosen 23.7 % of the times. For the purpose of the sustainability assessment, the resources (components, raw and auxiliary materials, etc.) needed to produce it will appear with the following frequency:

$$\mathit{handle}\ 00389\,\mathit{frequency} = \mathit{handle\,frequency} \cdot 0.237 = 0.426$$

Table 4.1 Forecast of the product mix on the customizable offer

Customization choice	Option	Sale percentage (%)
Element Type	6,000	60
	6,035	40
Width	275	5
	400	5
	450	5
	500	5
	550	40
	600	40
FrontColor	168 White	71.4
	228 Porcelain	4.2
	229 Light gray	3.2
	230 Dakar	1.2
	235 Mud	0.7
	236 Reed	0
	239 Pistachio green	0.5
	240 Denim	0.8
	242 Camel	0.3
	243 Lava	2.0
	246 Stone	1.1
	247 Brick	0.9
	162 Aluminum silver	2.4
	163 Graphite	2.4
	167 Lakeland acacia	8.9
FrontEdgeColor	168 White	71.4
	228 Porcelain	4.2
	229 Light gray	3.2
	230 Dakar	1.2
	235 Mud	0.7
	236 Reed	0
	239 Pistachio green	0.5
	240 Denim	0.8
	242 Camel	0.3
	243 Lava	2.0
	246 Stone	1.1
	247 Brick	0.9
	162 Aluminum silver	2.4
	163 Graphite	2.4
	167 Lakeland acacia	8.9
InteralEdgeColor	White	95
	Black	2
	Anthracite	1
	Aluminum silver	2

(continued)

Table 4.1 (continued)

Customization choice	Option	Sale percentage (%)
HandleType	00395	1.3
	00394	4.1
	00393	0.7
	00391	3.7
	00392	8.2
	00390	7
	00307	1.7
	00308	0.6
	00309	2.5
	00339	4.8
	00337	11.9
	00389	23.7
	00345	29.9
SideHasColor	Right	1
	Left	1
	Null	98
	Both	0

This allows to define for each transportation the quantity of transported resources per unit of product.

The carried out analysis needs to be extended also to the downstream supply chain by defining the markets where the product is going to be sold. In our example, these are the Tessin Canton of Switzerland, selected since a relevant portion of the sales is there located, and the rest of the country for which an average distance is defined (250 km). The modeling of these parts of the supply chain follows the same rules applied to the upstream. In this case, the process *cabinetManufacturing* produces as output the cabinet which is absorbed by the two defined markets according to the share of sales (20 % for Tessin, 80 % for rest of Switzerland).

4.3.2 Calculation of the Global Warming Potential

This section reports upon the assessment of the Global Warming Potential calculated on the solution space described in Sect. 4.3.1.

4.3.2.1 Extraction and Material Processing phases

The first phase that we encounter for the GWP calculation is the “extraction” followed by “material processing” which we will deal with together given the strong analogies they present. In Chap. 3 we have defined the extraction phase as

Table 4.2 Operations for the manufacturing of the left side panel

Operation	f_m	Explanation
DrillingLeftSide	8	Creates 8 holes for connecting the upper and bottom panels (pins)
MillingLeftSide	1	Creates a groove where the back panel is inserted
DrillingLeftSideScrew	4	Creates 4 holes for connecting the upper and bottom panels (screws)
DrillingLeftSideShelf	3.6	Creates 6 holes for supporting the internal shelf of cabinet 6,000
DrillingLeftSideRail	4.8	Creates 12 holes for fixing the drawers rails to the box
DrillingLeftSideHingeConnection	2.4	Creates 4 holes for fixing the hinge to the box
CuttingLeftSide	1	Represents the cutting operations needed to obtain the panel in the proper dimension

the one responsible for the "extraction of raw materials constituting the product, its packaging, and the surface treatments". Similarly, the material processing phase will address "material processing of the raw materials constituting the product and its packaging".

As it can be seen in the formula presented in Sect. 3.3.5.1, the impact of these phases depends solely on the weight of the components and the materials constituting them. The LCA databases present a wide set of materials for which $\mathrm{GWP}_{\mathrm{ext}\,j}$ is provided. An alternative, that we adopted in some future section of this calculus, is to rely on certified data coming from the components supplier. For instance, we can follow the calculation of the GWP related to extraction and material processing of the front panel of cabinet 6,000. The supplier declared value for the malamine faced chipboard used is −1.1560 kg CO_2/kg of extracted and processed material. The minus sign is due to the fact that, during the tree growth, CO_2 is absorbed and stored into the wood that has been planted specifically for the production of wooden goods like our panels.

Again, the impact of customization on the formula is a key point. Below, in Table 4.3, are listed the data needed for assessing the impact on the GWP produced by the front panel extraction and material processing. Each row in the table is related to a different value of the cabinet width. For the purpose of assessment this is translated in the definition of six different components (i.e. the panel in its six dimensions). How these components weight in the final formula is defined by the frequency f_i, which is shown in the second to last column. The values there are a combination of the frequency of occurrence of the front panel (60 % of the total product instances since it is not needed for cabinet 6,035) and the frequency of occurrence of each width. For instance, given a width of 275, the frequency results:

$$f_i = 0.6\ (\text{cabinet 6000 frequency}) \cdot 0.05(\text{width 275 frequency}) = 0.03$$

Following the GWP formula, the contribution of each version of the *frontPanel* component is summed to obtain the total value of −3.597 kg CO_2 that is the total amount of CO_2 absorbed (pay attention to the minus sign!) for the extraction and

Table 4.3 Input resources for the *cabinetManufacturing* process

Input resource	Quantity
ABSedge	Depending on product mix
BackPanel	1
bar	Depending on product mix
Boxpanel	0.25
DrawerBackPanel	Depending on product mix
DrawerBottom	Depending on product mix
DrawerLeft1/6	Depending on product mix
DrawerLeft2/6	Depending on product mix
DrawerLeft3/6	Depending on product mix
DrawerRight1/6	Depending on product mix
DrawerRight2/6	Depending on product mix
DrawerRight3/6	Depending on product mix
DrawerSupportAssembly	Depending on product mix
Handle	Depending on product mix
Hinge	Depending on product mix
HingeConnector	Depending on product mix
PanelForFront	Depending on product mix
PlasticPinDrawer	Depending on product mix
PodiumLogo	Depending on product mix
PPedge	Depending on product mix
RailLeft	Depending on product mix
RailRight	Depending on product mix
ScrewBox	8
Shelf	Depending on product mix
ShelfPin	Depending on product mix
WoodenPin	16

material processing of the average front panel needed for one unit of product. The impact of the two lifecycle phases cannot be separated for this component as the input data come aggregated. This is something that happens very often when making assessment in real life, though it doesn't really spoil the worth of the results.

Even within the same assessment the granularity of the input data coming from database and other sources could vary that is what happens when we pass to the drawers rails, for instance. Here the datasets available for the steel they are made of are split in the two phases. The first dataset, coming from the Ecoinvent database, considers the extraction of low-alloyed steel at plant with an emission of 1.756 kg CO_2 per kg of extracted ore. A second dataset describes the sheet rolling operation causing an emission of 0.361 kg CO_2 per kg of processed steel. The total amount, for the extraction of the material needed for the rails, is thus calculated as follows:

$$\begin{aligned} \mathrm{GWP}_{\mathrm{ext}} &= \sum_j f_i \cdot V_{i,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{ext}j} = 2.4 \cdot 0.942\,\mathrm{kg} \cdot 1.756\,\mathrm{kg\ CO_2/kg} \\ &= 3.970\ \mathrm{kg\ CO_2} \end{aligned}$$

Similarly, the impact of the material processing is:

$$\begin{aligned}\mathrm{GWP}_{\mathrm{mp}} &= \sum_j \sum_p f_i \cdot \chi_{p,i,j} \cdot V_{i,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{mp}p,j} \\ &= 2.4 \cdot 0.942\ \mathrm{kg} \cdot 0.361\ \mathrm{kg\ CO_2/kg} = 0.816\,\mathrm{kg\ CO_2}\end{aligned}$$

A brief note for the curious reader about the calculation of the rail frequency. The value 2.4 is obtained by multiplying the 6 rails (3 left and 3 right) needed for the cabinet version with drawers with its occurrence in the product mix that is 40 %.

4.3.2.2 Part Manufacturing Phase

In this phase we will calculate the GWP related to the manufacturing operations that produce the components needed for our kitchen. Moreover, we will consider the impact of the generated scraps and operation wastes as well as the impact of all the auxiliary materials used in the manufacturing operations.

Let us recall, given its complexity, the formula for the impact of the part manufacturing phase and start some reasoning on it (for the definition of the terms below, please refer to Sect. 3.3.5.1). First thing we can do is to split the $\mathrm{GWP}_{\mathrm{man}}$ in its four subsets:

1.

$$(1 + \mathrm{SRC}) \cdot \left(\sum_m f_m \cdot CS_m \cdot \mathrm{GWP}_{\mathrm{man}m} \right)$$

2.

$$\mathrm{SRC} \cdot \left(\begin{array}{ll} \sum\limits_i \sum\limits_j f_i \cdot V_{i,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{ext}j} & + \sum\limits_i \sum\limits_j \sum\limits_p f_i \cdot \chi_{p,i,j} \cdot V_{i,j} \cdot \rho_j \cdot \mathrm{GWP}_{mp\,p,j} \\ & + \sum\limits_i \sum\limits_j \sum\limits_l f_i \cdot f_{\mathrm{SRC}i,j,l} \cdot V_{i,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{EOL}j,l} \\ & + \sum\limits_i \sum\limits_j \sum\limits_q \sum\limits_z f_i \cdot V_{i,j} \cdot \rho_j \cdot f_{i,j,q} \cdot d_{i,j,q,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\ & + \sum\limits_i \sum\limits_j \sum\limits_r \sum\limits_z f_i \cdot V_{i,j} \cdot \rho_j \cdot f_{\mathrm{SRC}\,i,j,r} \cdot d_{\mathrm{EOL}r,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \end{array} \right)$$

3.

$$(1 + \mathrm{SRC}) \cdot \left(\begin{array}{ll} \sum\limits_m \sum\limits_w f_m \cdot Q_{\mathrm{aux}w,m} \cdot \mathrm{GWP}_{\mathrm{ext}w} & + \sum\limits_m \sum\limits_w \sum\limits_p f_m \cdot \chi_{p,w} \cdot Q_{\mathrm{aux}w,m} \cdot \mathrm{GWP}_{mp\,p,w} \\ & + \sum\limits_m \sum\limits_w \sum\limits_l f_m \cdot f_{w,l} \cdot Q_{\mathrm{aux}w,m} \cdot \mathrm{GWP}_{\mathrm{EOL}w,l} \\ & + \sum\limits_m \sum\limits_w \sum\limits_q \sum\limits_z f_m \cdot f_{w,q} \cdot Q_{\mathrm{aux}w,m} \cdot d_{w,q,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\ & + \sum\limits_m \sum\limits_w \sum\limits_r \sum\limits_z f_m \cdot f_{w,r} \cdot Q_{\mathrm{aux}w,m} \cdot d_{\mathrm{EOL}r,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \end{array} \right)$$

4.

$$(1+\mathrm{SRC})\cdot\left(\begin{array}{ll}\sum_m\sum_j f_m\cdot Q_{wmj,m}\cdot \mathrm{GWP}_{\mathrm{ext}j} & +\sum_m\sum_j\sum_p f_m\cdot \chi_{p,j}\cdot Q_{wmj,m}\cdot \mathrm{GWP}_{mp\,p,j}\\ & +\sum_m\sum_j\sum_l f_m\cdot f_{j,l}\cdot Q_{wmj,m}\cdot \mathrm{GWP}_{\mathrm{EOL}j,l}\\ & +\sum_m\sum_j\sum_q\sum_z f_m\cdot f_{j,q}\cdot Q_{wmj,m}\cdot d_{j,q,z}\cdot \mathrm{GWP}_{\mathrm{tra}z}\\ & +\sum_m\sum_j\sum_r\sum_z f_m\cdot f_{j,r}\cdot Q_{wmj,m}\cdot d_{\mathrm{EOL}r,z}\cdot \mathrm{GWP}_{\mathrm{tra}z}\end{array}\right)$$

Let us also choose a reference example for our analysis that is the left side panel already studied in Sect. 4.3.1.2. A first consideration we can do regards the scrap rate term (SRC). In the kitchen industry, given the high level of automation it is very rare that the manufactured panels and cabinets need to be eliminated. Therefore, after an analysis made with our kitchen producer, it has been confirmed that the scrap rate can be assumed to be zero. This implies that the second term of $\mathrm{GWP}_{\mathrm{man}}$, that relates on all the lifecycle impact of scrapped items, automatically disappear. Moreover, the other terms are simplified since the $(1 + \mathrm{SRC})$ multiplier becomes simply 1.

A second term that we won't have to calculate is the third one, given the nature of the used datasets that include the auxiliary material impact within the operation description.

Eventually, also the end of life of the product, its waste and auxiliary materials won't be considered due to the lack of information available at company level on this issue. The formula of the $\mathrm{GWP}_{\mathrm{man}}$, for our left side panel, thus becomes:

1.

$$(1)\cdot\left(\sum_m f_m\cdot CS_m\cdot \mathrm{GWP}_{\mathrm{mam}\,m}\right)$$

2.

$$(1)\cdot\left(\begin{array}{ll}\sum_m\sum_j f_m\cdot Q_{wmj,m}\cdot \mathrm{GWP}_{\mathrm{ext}j} & +\sum_m\sum_j\sum_p f_m\cdot \chi_{p,j}\cdot Q_{wmj,m}\cdot \mathrm{GWP}_{mp\,p,j}\\ & +\sum_m\sum_j\sum_q\sum_z f_m\cdot f_{j,q}\cdot Q_{wmj,m}\cdot d_{j,q,z}\cdot \mathrm{GWP}_{\mathrm{tra}z}\end{array}\right)$$

That is the sum of four contributions related to impact of:

- the manufacturing operations;
- extraction of the operations waste materials;
- material processing of the operations waste materials;
- transportation of the operations waste materials.

Starting from the first one, the manufacturing operations that produce the left side panel are the ones listed in Table 4.4 where we already calculated the frequencies $\mathrm{f_m}$ for each one. In Table 4.5 are added the missing terms that are CS_m, specific GWP measure parameter for operation m, and $\mathrm{GWP}_{\mathrm{man}\ m}$, GWP for manufacturing operation m.

Let us take the *millingLeftSide* operation and see how the data have been calculated so as to clarify the calculation process. The frequency f_m of the operation has already been calculated in Sect. 4.3.1.2 and its value is 1 since it always appears whatever cabinet is produced. The $\mathrm{GPW}_{\mathrm{man}\ m}$ for the manufacturing operation has been retrieved from Ecoinvent where it is defined in kg $\mathrm{CO_2}$ emitted per kg of removed material with a value of 3.5876. The last parameter is the specific GWP measure CS_m that, in this case, quantifies the weight of the removed material through the milling operation whose scope is to create a groove for housing the back panel. This groove has a depth of 6 mm, a width of 3.5 mm, and runs along the 762 mm of length of the panel. By multiplying the obtained volume of 0.016 $\mathrm{dm^3}$ per the material density of 0.67 $\mathrm{kg/dm^3}$, we get the CS_m value of $10.720 \cdot 10^{-3}$ kg of removed material.

Finally for the milling of the left side panel, we obtain:

$$\begin{aligned}\mathrm{GWP}_{\mathrm{man(millingLeftSide},\,m)} &= f_m \cdot CS_m \cdot \mathrm{GWP}_{\mathrm{man}m}\\ &= 1 \cdot 10.720 \cdot 10^{-3}\mathrm{kg} \cdot 3.5876\ \mathrm{kg\ CO_2/\ kg}\\ &= 0.038\ \mathrm{kg\ CO_2}\end{aligned}$$

by applying the sum to all the operations on the left side panel we obtain:

$$\begin{aligned}\mathrm{GWP}_{man\,(\mathrm{leftSidePanel},\,m)} &= \sum_{m\mathrm{leftSidePanel}} f_m \cdot CS_m \cdot \mathrm{GWP}_{\mathrm{man}m}\\ &= 0.010 + 0.038 + 0.006 + 0.001 + 0.006 + 0.005\\ &\quad + 0.001\\ &= 0.067\ \mathrm{kg\ CO_2}\end{aligned}$$

Now we can proceed with the other terms related to the extraction, material processing, and transportation of the waste materials. In our example, the wastes are generated as a consequence of the cutting of panels out of larger semifinished whose dimensions are 2,800 × 2,050 mm. The optimization of the cutting process

Table 4.4 Data required for calculation of $\mathrm{GWP_{ext}}$ and GPW_{mp} of the front panel

Component	Cabinet width	ρ_j (kg/ $\mathrm{dm^3}$)	Thickness (mm)	Height (mm)	Width (mm)	$V_{i,j}$ ($\mathrm{dm^3}$)	f_i	$\mathrm{GWP_{ext}} + \mathrm{GPW_{mp}}$ (kg $\mathrm{CO_2}$)
FrontPanel	275	0.67	19	758	271	3.903	0.03	−0.090
	400	0.67	19	758	396	5.703	0.03	−0.133
	450	0.67	19	758	446	6.423	0.03	−0.149
	500	0.67	19	758	496	7.143	0.03	−0.166
	550	0.67	19	758	546	7.863	0.24	−1.462
	600	0.67	19	758	596	8.584	0.24	−1.596

Table 4.5 Calculation of GWP_{man} for the left side panel manufacturing operations

Operation	f_m	CS_m (kg)	$GWP_{man\ m}$ (kg CO_2/kg)	GWP_{man} (kg CO_2)
DrillingLeftSide	8	0.360 · 10¯3 kg	3.6274	0.010
MillingLeftSide	1	10.720 · 10^{-3} kg	3.5876	0.038
DrillingLeftSideScrew	4	0.412 · 10^{-3} kg	3.6274	0.006
DrillingLeftSideShelf	3.6	0.079 · 10^{-3} kg	3.6274	0.001
DrillingLeftSideRail	4.8	0.360 · 10^{-3} kg	3.6274	0.006
DrillingLeftSideHingeConnection	2.4	0.579 · 10^{-3} kg	3.6274	0.005
CuttingLeftSide	1	1.5 m	0.000552	0.001

allows to reduce the percentage of discarded material to 10 %. This means that the impact of the above-mentioned phases needs to be accordingly increased. In terms of GWP formula, this results in the term:

$$\sum_m \sum_j f_m \cdot Q_{\text{wm}j,m} \cdot \text{GWP}_{\text{ext}j}$$

$$\sum_m \sum_j \sum_p f_m \cdot \chi_{p,j} \cdot Q_{\text{wm}j,m} \cdot \text{GWP}_{\text{mp}p,j}$$

$$\sum_m \sum_j \sum_q \sum_z f_m \cdot f_{j,q} \cdot Q_{\text{wm}j,m} \cdot d_{j,q,z} \cdot \text{GWP}_{\text{tra}z}$$

where $Q_{\text{wm}\ j,m}$ is exactly the quantity of the waste material j coming from the operation m. For the *cuttingLeftSide* operation, given the weight of the *leftSidePanel* that is 4.493 kg, this quantity is 0.449 kg. As already seen, the extraction and material processing data for the melamine faced chipboard are aggregated. We thus obtain for this panel that the impact of these two phases for waste material is:

$$\text{GWP}_{\text{man(cuttingLeftSide,wm,ext + mp)}} = 1 \cdot 0.449 \cdot (-1.1560) = -0.519\ \text{kg CO}_2$$

Finally the transportation of these waste materials is calculated on the basis of the distance $d_{j,q,z}$ between the kitchen producer and the suppliers q, in this case Gear (423 km) and Tempus (172 km). The frequency $f_{j,q}$ aims at weighting the entity of the supplies provided by the two suppliers. In our example, Gear provides 90 % of the chipboard needed for the left side panel while Tempus the other 10 %. $\text{GWP}_{\text{tra}\ z}$ is the intrinsic emission of CO_2 of the mean of transportation z that for the used lorry is $0.16559 \cdot 10^{-3}$ kg CO_2/(kg·km).

This results in the following impact:

$$\begin{aligned}\text{GWP}_{\text{man(cuttingLeftSide,wm,tra)}} &= 1 \cdot (0.9 \cdot 0.449 \cdot 423 + 0.1 \cdot 0.449 \cdot 172) \cdot 0.16559 \\ &\quad \cdot 10^{-3} \\ &= 0.030\ \text{kg CO}_2\end{aligned}$$

At last, we have all the data to be summed for obtaining the impact of the manufacturing operations made on the left side panel:

$$\mathrm{GWP}_{(\mathrm{leftSidePanel})} = 0.067 - 0.519 + 0.030 = -0.422\ \mathrm{kg\ CO_2}$$

4.3.2.3 Assembly Phase

In this phase we will analyze the impact on the emission of CO_2 due to the operations that assemble together different components of the kitchen. Since the cabinet assembly is manually performed, what is left to be assessed are the edging operations which provide the finishing of each panel according to the personalization choices of the customer.

Tertium employs two different technologies for panel edging that are the standard gluing and a more innovative laser edging, which provides seamless borders for high-end kitchens. For this reason, gluing is applied to the finishing of the internal box edges whereas laser edging is performed on the front edges.

Similar to what has been done for the manufacturing phase, let us recall the formula for the $\mathrm{GWP}_{\mathrm{as}}$ of the assembly phase, splitting it in its three components:

1.

$$(1 + \mathrm{SRA}) \cdot \left(\sum_{o} f_o \cdot CS_o \cdot \mathrm{GWP}_{as\,o} \right)$$

2.

$$\mathrm{SRA} \cdot \left(\begin{array}{ll} \sum\limits_{a}\sum\limits_{j} f_a \cdot V_{a,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{ext}j} & + \sum\limits_{a}\sum\limits_{j}\sum\limits_{p} f_a \cdot \chi_{p,a,j} \cdot V_{a,j} \cdot \rho_j \cdot \mathrm{GWP}_{mp\,p,j} \\ & + \sum\limits_{a}\sum\limits_{j}\sum\limits_{l} f_a \cdot f_{a,j,l} \cdot V_{a,j} \cdot \rho_j \cdot \mathrm{GWP}_{\mathrm{EOL}j,l} \\ & + \sum\limits_{a}\sum\limits_{j}\sum\limits_{q}\sum\limits_{z} f_a \cdot V_{a,j} \cdot \rho_j \cdot f_{a,j,q} \cdot d_{a,j,q,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\ & + \sum\limits_{a}\sum\limits_{j}\sum\limits_{r}\sum\limits_{z} f_a \cdot V_{a,j} \cdot \rho_j \cdot f_{a,j,r} \cdot d_{\mathrm{EOL}r,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \end{array} \right)$$

3.

$$(1 + \mathrm{SRA}) \cdot \left(\begin{array}{ll} \sum\limits_{o}\sum\limits_{w} f_o \cdot Q_{\mathrm{aux}w,o} \cdot \mathrm{GWP}_{\mathrm{ext}w} & + \sum\limits_{o}\sum\limits_{w}\sum\limits_{p} f_o \cdot \sum\limits_{p,w} \cdot Q_{\mathrm{aux}w,o} \cdot \mathrm{GWP}_{mp\,p,w} \\ & + \sum\limits_{o}\sum\limits_{w}\sum\limits_{1} f_o \cdot f_{w,l} \cdot Q_{\mathrm{aux}w,o} \cdot \mathrm{GWP}_{\mathrm{EOL}w,l} \\ & + \sum\limits_{o}\sum\limits_{w}\sum\limits_{q}\sum\limits_{z} f_o \cdot f_{w,q} \cdot Q_{\mathrm{aux}w,o} \cdot d_{w,q,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\ & + \sum\limits_{o}\sum\limits_{w}\sum\limits_{r}\sum\limits_{z} f_o \cdot f_{w,r} \cdot Q_{\mathrm{aux}w,o} \cdot d_{\mathrm{EOL}r,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \end{array} \right)$$

If we consider as reference example the laser edging operation (*drawerFrontEdgeUp*) carried out on the horizontal borders of the cabinet 6,035 drawers, both the scrap rate of the assembly operation (SRA) and the quantity of auxiliary materials $Q_{\mathrm{aux}\ w,o}$ drop to zero, thus eliminating the last two terms of the equation. We can then focus on the first one that is simplified to:

$$f_{\mathrm{o}} \cdot \mathrm{CS}_{\mathrm{o}} \cdot \mathrm{GWP}_{\mathrm{aso}}$$

The frequency of the operation can be easily determined by recalling that in cabinet 6,035 we have three drawers that means six horizontal borders. However, cabinet 6,035 is chosen by the customer only 40 % of the times and also its width can be customized selecting among six different dimensions and thus also the length of the edging can vary accordingly. The frequency f_{o} for a single customization option, like the 275 width, is then equal to:

$$\begin{aligned} & 6(\text{drawers horizontal edges}) \cdot 0.4(\text{cabinet 6035 frequency}) \\ & \quad \cdot 0.05(\text{width 275 frequency}) \\ & \quad = 0.12 \end{aligned}$$

For the estimation of $\mathrm{GWP}_{\mathrm{aso}}$ we could not obtain from database any applicable value. Therefore, we gathered data from the equipment producer who stated that the power consumption of the machine is 7.8 Wh per m of edging. By taking the assumption that no direct emission is caused by the operation, we obtained the $\mathrm{GWP}_{\mathrm{as\ o}}$ by multiplying this value by the electricity equivalent emission of CO_2 in Switzerland, where the machine is being used (0.029872 kg CO_2/kWh).

In Table 4.6, these data are summarized and the emitted CO_2 for each width of the drawers front calculated.

The resulting GWP for the whole *drawerFrontEdgeUp* operation is then $0.302 \cdot 10^{-3}$ kg CO_2 which compared with the previously obtained contribution can be considered negligible.

4.3.2.4 Transport Phase

The last that we will study in this example is the transport phase where the impact of resource transportation within the supply chain. Let us take as reference the GWP formula for this phase as defined in Sect. 3.3.5.1:

Table 4.6 Calculation of $\mathrm{GWP}_{\mathrm{as}}$ for the edging of the drawers front horizontal borders

Assembly operation	Cabinet width	f_{o}	CS_{o} (mm)	$\mathrm{GWP}_{\mathrm{as\ o}}$ (kg CO_2/m)	$\mathrm{GWP}_{\mathrm{as}}$ (kg CO_2)
DrawerFrontEdgeUp	275	0.12	271	$0.234 \cdot 10^{-3}$	$0.008 \cdot 10^{-3}$
	400	0.12	396	$0.234 \cdot 10^{-3}$	$0.011 \cdot 10^{-3}$
	450	0.12	446	$0.234 \cdot 10^{-3}$	$0.013 \cdot 10^{-3}$
	500	0.12	496	$0.234 \cdot 10^{-3}$	$0.014 \cdot 10^{-3}$
	550	0.96	546	$0.234 \cdot 10^{-3}$	$0.123 \cdot 10^{-3}$
	600	0.96	596	$0.234 \cdot 10^{-3}$	$0.134 \cdot 10^{-3}$

$$
\begin{aligned}
\mathrm{GWP}_{\mathrm{tra}} = & \sum_i \sum_j \sum_q \sum_z f_i \cdot V_{i,j} \cdot \rho_j \cdot f_{i,j,q} \cdot d_{i,j,q,z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\
& + \sum_i \sum_j \sum_z f_i \cdot V_{i,j} \cdot \rho_j \cdot d_{\mathrm{cust}z} \cdot \mathrm{GWP}_{\mathrm{tra}z} \\
& + \sum_i \sum_j \sum_r \sum_z f_i \cdot V_{i,j} \cdot \rho_j \cdot f_{i,j,r} \cdot d_{\mathrm{EOL}r,z} \cdot \mathrm{GWP}_{\mathrm{tra}z}
\end{aligned}
$$

The formula appears to be the sum of three contributions: the first is referred to the impact of transportations taking place in the upstream supply chain, the second in the downstream supply chain and the latter considers the transportations between the customer and the facility where the product is treated at its end of life.

In this example, we do not deal with the third contribution as it is not controlled by the company and heavily dependent on the market where the product is sold.

Focusing on the upstream supply chain, some practical considerations can be drawn. The first concerns the implications of using aggregated datasets in the other lifecycle phases. In fact, many times, transports are already included in the impact calculated in the extraction phase datasets. This is, for instance, the case of chipboard panel material extraction in which the transport impact between the location of the tree harvest and that of the supplier producing the panels is already considered in the extraction dataset. So at first we had to separate the supplies which required an additional transport contribution to be set up from those who didn't.

Let us follow a case where the whole path needs to be studied like the production and delivering of the drawers and fronts handles to the kitchen producers. Here the extraction dataset for steel has been retrieved from the Ecoinvent database which doesn't include the transports occurred between the location of material processing and the supplier (we have two in our example: JKH and Chiefard). Still the transport between the mines and the material processing locations is considered by the Ecoinvent dataset.

Therefore, referring to the supply chain structure presented in Fig. 4.5, another step is added in order to reflect this situation. In the absence of precise information about the second tier suppliers (this is something the sustainability manager has to be prepared to!), an estimation of the average distance covered by this kind of transports has been determined in 500 km, measured on the top 25 European steel producers.

The second consideration we must pay attention to is about the frequency of supply coming from the different providers. In our case, JKH is responsible for 80 % of the handle supplies while Chiefard for the remaining 20 %. This combines with the frequency of appearance of each specific handle in the bought products according to the defined product mix. Now, we should be familiar with the calculation formula for this one. Let us see it once more for handle 00395:

$$f_{00395} = 0.013(\%\ \text{sale } 00395) \cdot 1.8(\text{handle frequency}) = 0.023$$

In Table 4.7 the data needed for the transports impacts calculation is summarized.

Table 4.7 Calculation of GWP_{tra} for the handle components

Component	Supplier	f_q	f_i	Transported weight (kg)	Distance to 2nd tier (km)	Distance to Tertium (km)	$GWP_{tra\ z}$ [kg CO_2/(kg·km)]	GWP_{tra} (kg CO_2)
00395	JKH	0.8	0.023	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.229 \cdot 10^{-3}$
	Chiefard	0.2	0.023	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.040 \cdot 10^{-3}$
00394	JKH	0.8	0.074	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.736 \cdot 10^{-3}$
	Chiefard	0.2	0.074	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.128 \cdot 10^{-3}$
00393	JKH	0.8	0.013	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.129 \cdot 10^{-3}$
	Chiefard	0.2	0.013	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.023 \cdot 10^{-3}$
00391	JKH	0.8	0.067	0.080	500	251	$0.16559 \cdot 10^{-3}$	$0.533 \cdot 10^{-3}$
	Chiefard	0.2	0.067	0.080	500	23	$0.16559 \cdot 10^{-3}$	$0.093 \cdot 10^{-3}$
00392	JKH	0.8	0.148	0.110	500	251	$0.16559 \cdot 10^{-3}$	$1.620 \cdot 10^{-3}$
	Chiefard	0.2	0.148	0.110	500	23	$0.16559 \cdot 10^{-3}$	$0.282 \cdot 10^{-3}$
00390	JKH	0.8	0.126	0.100	500	251	$0.16559 \cdot 10^{-3}$	$1.254 \cdot 10^{-3}$
	Chiefard	0.2	0.126	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.218 \cdot 10^{-3}$
00307	JKH	0.8	0.031	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.308 \cdot 10^{-3}$
	Chiefard	0.2	0.031	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.054 \cdot 10^{-3}$
00308	JKH	0.8	0.011	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.109 \cdot 10^{-3}$
	Chiefard	0.2	0.011	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.019 \cdot 10^{-3}$
00309	JKH	0.8	0.045	0.100	500	251	$0.16559 \cdot 10^{-3}$	$0.448 \cdot 10^{-3}$
	Chiefard	0.2	0.045	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.078 \cdot 10^{-3}$
00339	JKH	0.8	0.086	0.045	500	251	$0.16559 \cdot 10^{-3}$	$0.385 \cdot 10^{-3}$
	Chiefard	0.2	0.086	0.045	500	23	$0.16559 \cdot 10^{-3}$	$0.067 \cdot 10^{-3}$
00337	JKH	0.8	0.214	0.100	500	251	$0.16559 \cdot 10^{-3}$	$2.129 \cdot 10^{-3}$
	Chiefard	0.2	0.214	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.371 \cdot 10^{-3}$
00389	JKH	0.8	0.427	0.100	500	251	$0.16559 \cdot 10^{-3}$	$4.248 \cdot 10^{-3}$
	Chiefard	0.2	0.427	0.100	500	23	$0.16559 \cdot 10^{-3}$	$0.740 \cdot 10^{-3}$
00345	JKH	0.8	0.538	0.120	500	251	$0.16559 \cdot 10^{-3}$	$6.423 \cdot 10^{-3}$
	Chiefard	0.2	0.538	0.120	500	23	$0.16559 \cdot 10^{-3}$	$1.118 \cdot 10^{-3}$

Table 4.8 Summary of the lifecycle impacts on equivalent CO_2 emission

Lifecycle phase	GWP (kg CO_2)
Extraction	−9.843
Material processing	1.754
Part manufacturing	14.389
Assembly	0.221
Transport	3.430

The total emission of equivalent CO_2 for the transportation of the handle components is then obtained by summing the values in the last column and is $21.781 \cdot 10^{-3}$ kg CO_2.

4.3.2.5 Sustainability Assessment Results

At the end of this exercise, the keen reader should be able to understand the formulas and to apply them in many common situations for the sustainability assessment of its products. He should also have absorbed the concept of performing sustainability considerations on a mass customized solution space that, for its inner nature, presents multiple choices leading to surely predefined, but still numerous possible product configurations.

It is also, at this point, useful to draw some conclusions on the specific assessment carried out in the previous sections. In order to do so, in Table 4.8, we will present the final results coming from the carried out assessment.

Therefore the total amount of equivalent CO_2 emitted for the whole lifecycle of a single unit of the customizable product or, otherwise said, the measure of the Global Warming Potential associated to the solution space is 9.951 kg CO_2.

The analysis of the results quickly brings to identify part manufacturing as the main contributor for determining the impact of the solution space with a share of 73 % of the emitting phases. On the other hand, extraction plays a positive role by abating significantly the emissions generated, thanks to the CO_2 absorption of the trees planted for feeding the chipboard panel production.

Another relevant remark is that the impact of transport phase, although second only to the part manufacturing is relatively small due to the short supply chain implemented by the company that is typical of this kind of mass customized productions in the furniture sector.

Chapter 5
Ideas and Trends from Research Activities

5.1 Introduction

Several different research initiatives have been funded by the European Commission in order to provide solutions to the challenges proposed in this work. These experiences are here presented by pointing out their key concepts and main finding and by mapping them on the MCIT template discussed in Chap. 2. The template is here used to quickly summarize the RTD effort main area of concerns and relation, while its main purpose is to support in defining an MC implementation strategy: while we yield to this improper usage, we acknowledge that this procedure makes the presented RTD initiatives' navigation easier and simply comparable. It is important to notice that these projects, as they never go into real production, seldom make a conscious synthesis (by defining a Stable Solution Space) of the target groups' needs confronted with the customization options offered by the developed technological innovations. All information are derived from project documents deemed with non-confidentiality.

5.2 CoReNet Project

5.2.1 Short Description

The CoReNet project—Customer ORiented and Eco-friendly NETworks for healthy fashionable goods—(http://www.corenet-project.eu/, still on-going in 10/2012) is meant to meet the needs and expectations of a wide segment of target groups in Europe, namely elderly, obese, disabled, and diabetic people, who usually look for clothes and footwear with particular functional requirements while at the same time being fashionable, high quality, eco-sustainable, and sold at an affordable price. The target market is wide as 19 % of EU population is between 50 and 64 years old, and 17 % over 65 years old, while 35 % of EU population is overweight, and 13 % obese.

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_5,

In order to pursue these objectives, the project develops tools and methods addressing aspect of custom product design, manufacturing, and supply chain, in the footwear and clothing sectors. In particular, the development activities are carried out following four research fronts:

1. Customer cooperative environments enabling garments and footwear co-design;
2. Methods and tools supporting production co-planning and supply chain network configuration;
3. Rapid manufacturing technologies addressing multi-purpose machines for the footwear sector and machines for digital textile printing;
4. Reference model supporting organizations to form and operate collaborative networks of suppliers.

5.2.2 Project Analysis

The process to develop an MC offer starts with the individuation of the needs of a specific target group (namely obese, elder, disable people) where a gap with current market proposals is emphasized. The study of the target group [block1 of the MCIT template] highlights two important customization needs: (1) improved shoe and garments fitting and (2) increased aesthetical look. Those are translated into formalized customization requirements [block 3]: (1) tailor made fitting, and (2) co-design system for the co-creation of aesthetically customized, fashionable products (textile pattern). In order to match these requirements, CoReNet develops all the supporting technologies and tools at production system level, supply chain level, and Means level to offer the following customization options [block 2]: (1) color and material customization for the shoe; (2) garment fitting customization; (3) garment fabrics, collars and cuffs customization. In term of Means, Customer requirements are gathered by a web-based collaboration tool supporting product co-design (both fitting and aesthetical features) as a main channel. Customization data gathered are also directly sent to the manufacturing system [block 6]. The Manufacturing system must then be capable to handle those data and to quickly produce the desired product by new enabling technologies [block 5]: (1) a multi-purpose machine for footwear engraving and (2) a digital printing machine system for garments color digital management, aiming at enabling a fast, flexible, and reliable on-demand production. The project also takes into consideration the need of the definition of partners and workflows within a flexible and temporary supply chain, by developing appropriate software tools [block 7] (Fig. 5.1).

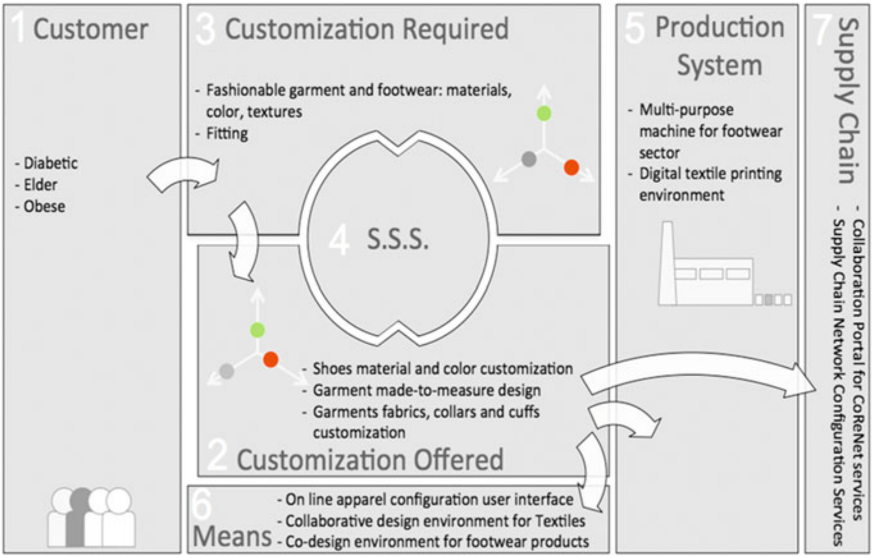


Fig. 5.1 MCIT instantiated for the CoReNet project

5.3 ShopInstantShoe Project

5.3.1 Short Description

ShopInsantShoe deals with the development of a cost-effective shoe based on shape memory materials (http://www.instantshoe.com/, concluded). Women fashionable footwear's aesthetic constraints demand a more accurate fitting to guarantee footwear functionality and comfort. But differences in human foot morphology between subjects make really difficult, providing an appropriate fitting to each single user, and make women footwear especially uncomfortable and unhealthy (the Hallux Valgus is the most frequent foot deformation affecting one of every five women at adult age). For these reasons, the main objective of this project is the development of a customizable and fashionable women footwear upper and an innovative service providing customers with personalization of the shoe fitting at the retail shop. The project thus develops a shape memory textile that will be used to manufacture customizable footwear upper and a shop tool capable of molding the footwear upper shape according to measured individual foot proportions, and recovering its original shape in case the client rejects to buy the shoes.

5.3.2 *Project Analysis*

When evaluating to implement an MC solution, there are three possible drivers leading to the final decision: the identification of a market segment with specific needs, the availability of a very flexible productive system that could be able to manufacture MC products or the availability of a new Mean able to simplify customer-manufacturer interaction.

ShopInstantShoe approaches MC implementation with a parallel approach: (1) identifying a customer need in a specific market segment and a gap in the current technologies for its fulfillment; (2) offering the solution to the aforementioned gap by the application of a technology new in this sector, namely a shape memory material used to realize a fabric capable to perfectly adapt to a given morphology.

The identified market need and the available technology meet in the solution space enabling the definition of a fitting customizable shoe. In order to enable the shift toward this kind of product customization, the project develops the supporting tools required to manufacture the aforementioned fabric and to enable the setting of fabric shape at point of sale, namely a POS textile molding system.

Supply chain aspects are neglected (Fig. 5.2).

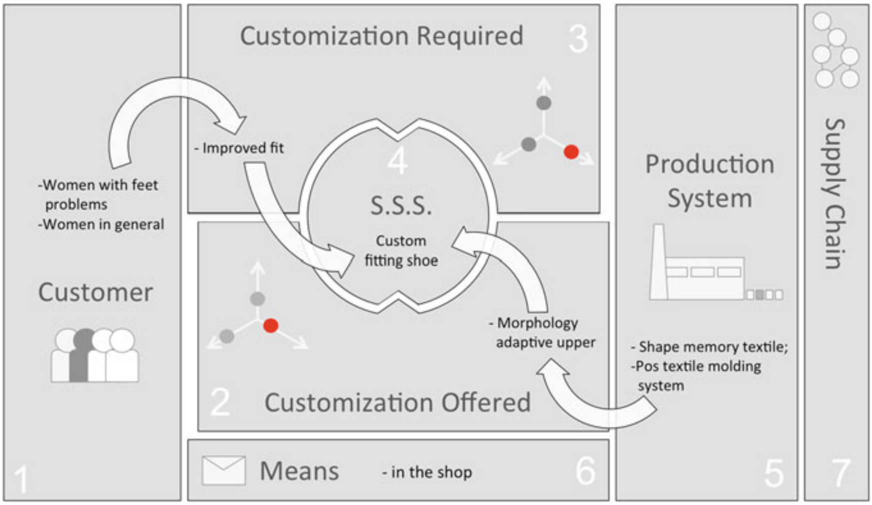


Fig. 5.2 MCIT instantiated for the ShopInstantShoe project

5.4 FIT4U Project

5.4.1 Short Description

FIT4U—Framework of Integrated Technologies for User Centered Products (http://www.fit4u.eu/, concluded)—aims at responding to the growing demand for consumer-oriented product personalization by conceiving a set of tools and manufacturing technologies necessary to realize customized footwear and gloves. In order to integrate customers in product conception and design, tools for the virtualization of customer profile, gathering also relevant feet metrics by means of a novel biomechanical sensor network, are developed. Basing on the data of the virtual profiles, a 3D design tool taking into account aesthetical and functional product requirements is developed. Product fitting requirements are also improved by developing innovative high-performing materials guaranteeing comfort and health/safety through features like breathability, antifungal etc., addressing professional/safety and sport segments. The production of customer centered products is therefore guaranteed by the development at shop floor level of a fast production machine for differentiated lasts and footbeds and a new modular sole.

5.4.2 Project Analysis

FIT4U identifies, as main driver, a prolific market sector that is expected to follow a rising trend in the next years, namely customized shoes and gloves for working or sport activities. The project does not answer to a particular customer need, but seems to address solutions deriving from current research on technologies and manufacturing processes. In this sense, fitting and functionality customization is empowered by the development of supporting tools for product customization at Means and Production System Level. In particular, customer fitting requirements are tackled through the development of (1) a consumer virtual profiler able to gather customer information, (2) an innovative sensor network used to characterize user-footwear biomechanical interaction, and (3) a software capable to use the information gathered in the aforementioned tools in order to define manufacturing parameters for the definition of consumer-driven products.

The customization data gathered by the aforementioned tools are associated, at production level, by novel materials and technologies concurrently developed, enabling a fast and flexible product realization. Low-cost machine to be used for customized production of lasts and or/for prototyping in a design department are thus studied while the investigation of novel materials and customizable outsoles offering different functional requisites (breathability, antifungal) push the introduction of innovative functional customizations.

Supply chain is not taken into account (Fig. 5.3).

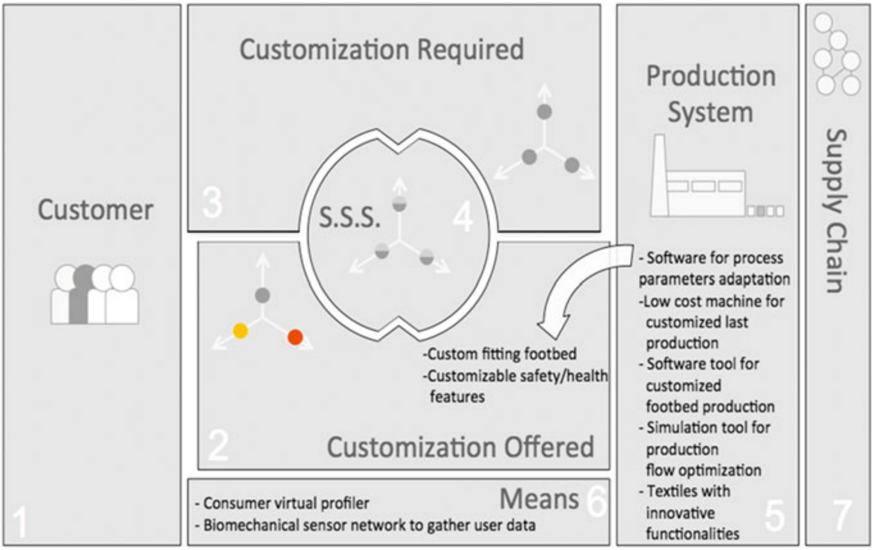


Fig. 5.3 MCIT instantiated for the FIT4U project

5.5 MY Wear Project

5.5.1 Short Description

MY Wear—Customized Green, Safe, Healthy, and Smart Work- and Sports-Wear—(http://www.mckn.eu/projects/mywear/, still on-going in 10/2012) addresses the production of health, safe, and eco-friendly customized work-wear and sports-wear for specific target groups, such as elderly, disabled, diabetics, and obese people, as seen in the CoReNet project. Aim of the project is the realization of garments and shoes capable to meet safety and comfort needs of the aforementioned target groups, also integrating sensors to monitor physiological sensible data. In order to meet this objective, the project is articulated under five main pillars:

1. Definition of reliable integrated data platform for gathering customers data and requirements during design and usage phase;
2. Eco-design of customized products by use of “light” recyclable materials and integrated LCA methodologies, exploiting and testing new bio materials and components meant to achieve functional requirements and to meet green and health-related constraints;
3. Development of technologies for constant monitoring of customer bio-metric parameters;
4. Development of new adaptive production systems and processes toward the production of customized goods;
5. Implementation of pilot plants to produce a first series of prototypes.

5.5.2 *Project Analysis*

In this project, a specific target group with well-defined product customization and functional requirements in the sport and working sector has been identified. The level of customization offered by project is the answer to the aforementioned needs and drives the technology development at production system level.

The project thus develops enabling solutions focused mainly on the increase of flexibility of the manufacturing system: (1) adaptive CAD-CAM solutions capable to integrate consumer data and expectations and translate them into efficient production solutions; (2) new robotized cells for flexible upper roughing and cementing; (3) innovative robot-based solutions for flexible sole injection; (4) cell for the automated production of customized insole/footbed in shoe models. The production is enabled by a platform capable to gather customer data before and during product use, in first instance gathering information required to build-up the correct customized options, in the latter, giving health and safety-related feedbacks from the data acquired during product use phase (Fig. 5.4).

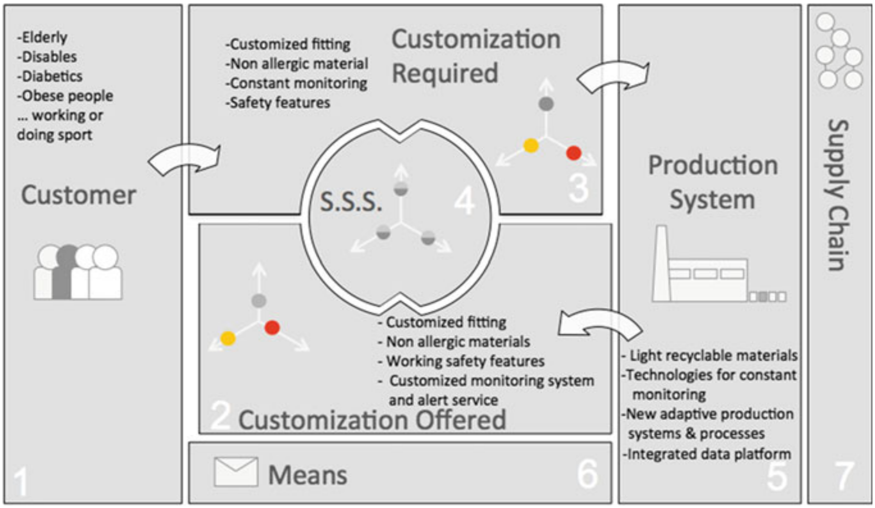


Fig. 5.4 MCIT instantiated for the MY Wear project

5.6 Net-Challenge Project

5.6.1 *Short Description*

Net-Challenge (http://www.netchallenge.org/, concluded) starts from the observation that, in order to respond to evolving market opportunities, European SMEs have to adopt new business models and establish dynamic and non-hierarchical networks assuring quick response, fast time to market, differentiated offerings, and competitive prices. Sustainability for SMEs seems indeed to rely on high variety, lot size one businesses, related with complex products manufacturing. However, there are currently no proven, effective methodologies, approaches, or tools to support SMEs in creating, managing, and dissolving this type of dynamic and non-hierarchical networks. Net-Challenge aims at covering this gap developing a bundle of methodologies, processes, and ICT decision support tools and, in particular:

- A methodology to help SMEs in the qualification, formation, and operation of dynamic networks (able to quickly respond to market opportunities characterized by low volume, high-variety and customer-centered products);
- Reference collaboration processes for non-hierarchical networks, to be used in promoting and facilitating real collaborative business processes;
- Distributed decision support tools to help companies to manage manufacturing and logistics processes;

5.6.2 Project Analysis

With respect to already reviewed projects, Net-Challenge addresses Mass Customization from a different perspective: it doesn't consider a specific target market or processes and technologies required to realize a specific product, but works at higher level, trying to develop tools and methods supporting companies in the creation of networks able to respond to current rapidly changing, high-variety markets, namely MC markets. The beneficiary of the project is thus mainly the product manufacturer and all the related network of collaborating firms.

The project aims at supporting an MC production system providing all the external supporting means necessary to enable it. The augmented complexity brought by the necessity of a flexible manufacturing system and the need of defining flexible but still fast responsive logistic channels are thus supported by a tool aiming at simplifying the design of an operative network for a firm entering MC environment.

In parallel, the ICT tools developed in the project support the management of Business Communities and Collaboration Projects, including decision support tools for collaborative product concept definition, operations planning, monitoring, and event management (Fig. 5.5).

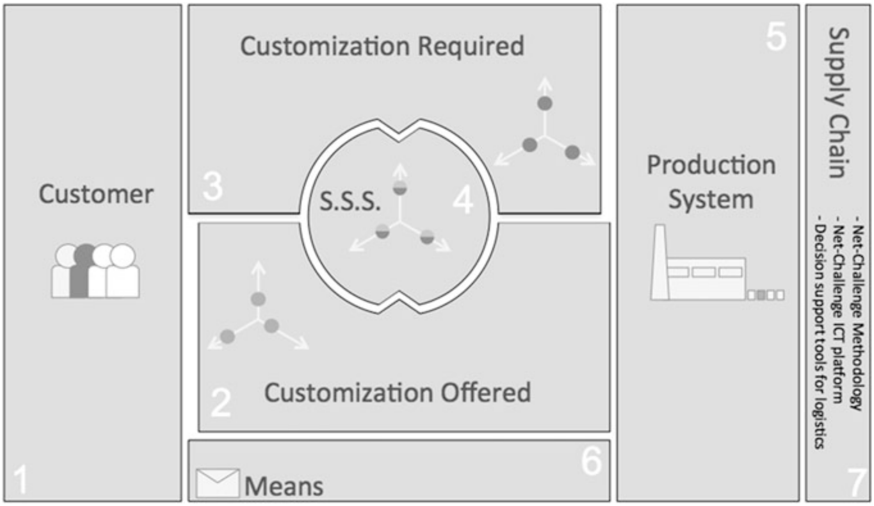


Fig. 5.5 MCIT instantiated for the NET-challenge project

5.7 Dorothy Project

5.7.1 Short Description

DOROTHY (http://www.mckn.eu/projects/completed-projects/dorothy/, concluded) aims at supporting EU shoe industry and its related business model by developing tools for the design of customer-driven shoes and ICT tools for the design, configuration, and reconfiguration of flexible multi-site multi-nation production factories, thus strengthening Europe’s manufacturers ability to compete in terms of high added value for the customer. The aforementioned objectives are pursued by three research clusters:

1. Design tools for customer-driven and customer fit shoe, as added-value product/service;
2. Design tools for advanced industrial engineering of multi-site and multi-nation production systems and factories, based on the customer-driven shoe;
3. New business models for the multi-nation multi-site shoes industry associated with the above-mentioned paradigm, meant to support it.

5.7.2 Project Analysis

In order to face the stronger and stronger competitive pressure brought by low-wage countries, the Dorothy project fosters a new vision toward shoes manufacturing: a new model, namely multi-site mass customized shoes production, is

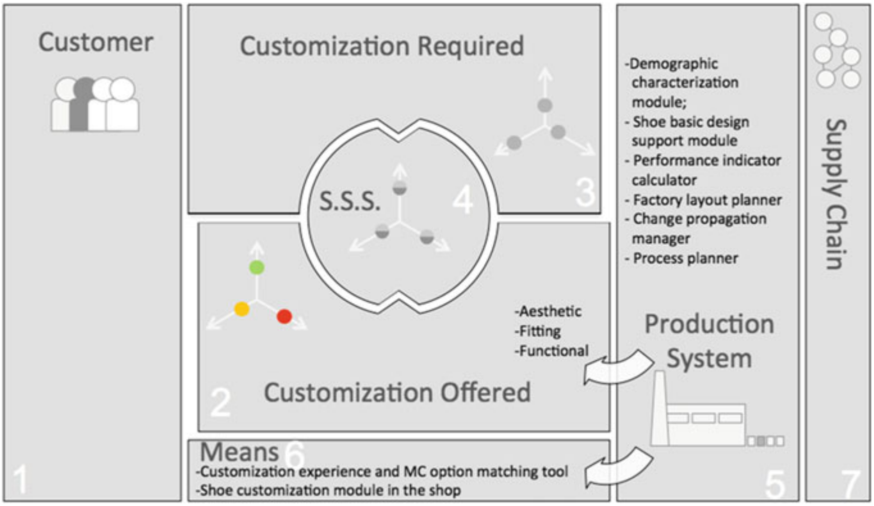


Fig. 5.6 MCIT instantiated for the Dorothy project

thus conceived. The research activities then focus on tools and methods at Product and Production system design, able to support this paradigm.

An extended scanning campaign, meant to measure feet morphologies, has been performed in order to provide the guidelines for the development of the most suitable production strategies to achieve superior fitting. In order to meet the challenges set up by the new Business Model and in particular, considering the aspects of multi-site production of mass customized items, a multi-client server application supporting collaborative factory layout planning and a tool enabling planning, analysis, and management of manufacturing processes are concurrently developed (Fig. 5.6).

5.8 S-MC-S

5.8.1 Short Description

Sustainable mass customization—Mass customization for sustainability (S-MC-S http://www.mckn.eu/projects/smcs, on-going in 10/2012) argues that, despite growing consensus toward Mass Customization and hundreds of real cases already trying to apply it, many companies still fail in MC implementation being not yet able to build up a real networked environment based on an appropriate Supply Chain and on specific methodologies and tools to handle it. Moreover, nowadays EU customer requirements are shifting from a pure customization request to a more and more sustainability conscious product approach, this increasing product conceiving and manufacturing complexity.

The S-MC-S project tries to close the current gap between sustainability-driven and mass customized products developing tools and methods for a sustainable mass customized (S-MC) production and supply chain.

In order to do so, the project takes into account different aspects related to the manufacturing of a sustainable MC product: I) the definition of design tools capable to manage the growing complexity of products, production and supply chain configurations imposed by MC implementation II) the definition of an assessment model needed to evaluate the impact of production systems and different supply chain configurations III) study of framework and strategies supporting the creation of economic, social, and ecological value through the systematic implementation of the S-MC-S paradigm IV) research on new specific MC technology in three different sectors (woodwork, leather, stone), to support manufacturing transition toward sustainable MC production thanks to new capability to produce with high variance in small series.

5.8.2 Project Analysis

S-MC-S set up a research activity addressing the needs of firms aiming at increasing their competitive advantage within the currently evolving market of Mass Customization. In this field, customers' demand is asking not only for personalized products, but is more and more considering sustainable aspects related to production and supply chain, this requiring a redesign of manufacturing and supply processes according with an S-MC vision. Customers MC requirements are thus leading the research path, not concentrating on single aspects of Customization but driving a more general definition of means and tools supporting the design of Sustainable Mass Customization solution spaces.

To this end, design tools addressing product and process are developed as enablers of the definition of the MC solution space. In parallel, a sustainability assessment tool fostering the design of a S-MC product together with its production system and supply chain is developed, aiming at identifying, within each step of product lifecycle, the most impacting aspects of product customization, thus supporting product designers in the review of those processes that mostly impact product sustainability. Design tools supporting the design of the supply chain complete the bundle of tools required to implement an S-MC Solution Space. Thus, S-MC-S mainly deals with Design Tools, and it is thus somehow a meta-project on Mass Customization and Sustainability, developing the tools needed by others who would like to implement sustainable MC.

In order to test those tools, S-MC-S develops three scenarios in three different sectors, as MC requires specific enabling technologies in order to be successfully implemented:

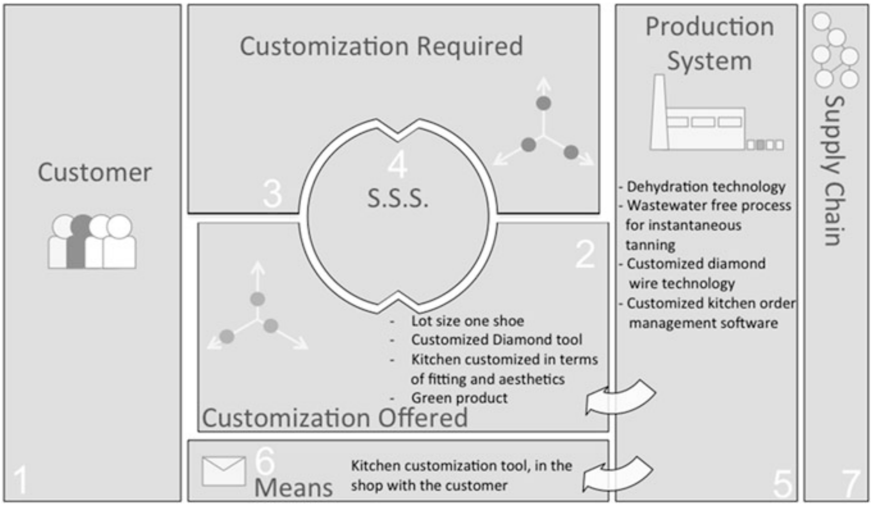


Fig. 5.7 MCIT instantiated for the S-MC-S project

- Leather goods sector: development of a continuous-flow tanning system of leather in lot size one, avoiding the current long, wasteful, and polluting processing of large batches. This is based on the development of a new chemical-free intermediate commodity product, the Dried Collagenic Biomaterial, which, due to its dehydration and spongy fibrous structure allows the instantaneous penetration of auxiliary tanning chemical products, with immediate effect.
- Stone cutting sector: development of advanced custom made diamond wire-rod tools meant also to introduce significant improvement of tool expected life. The process will address the implementation of new SMA (Shape Memory Alloys) rod to customize tool specifications.
- Furniture sector: flexible production technologies for this sector are available, and thus the scenario will focus on the sustainable supply chain definition and customized order management system (Fig. 5.7).

5.9 CEC Made Shoe

5.9.1 Short Description

CEC Made shoe—Custom, Environment, and Comfort made shoe (concluded)—aims at transferring the approach to product realization from an industry-driven, resource-based activity, to a market led knowledge-based activity. Overall project goal is thus to move the footwear sector to a human centered approach represented

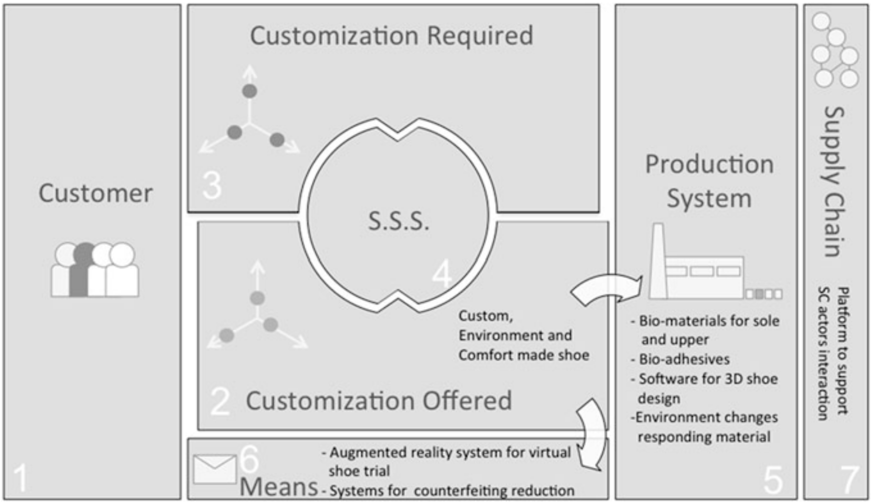


Fig. 5.8 MCIT instantiated for the CEC-made shoe project

by three dimensions of human being: *Comfort,* focus on the foot in all aspects of walking, running, standing, *Environment,* nature friendly materials and process sustainability, *Custom,* Consumer involvement focusing on style and fashion.

In order to address these objectives, the project follows three research clusters, each represented by a particular type of shoe:

- The Snap shoe: definition of materials and manufacturing processes addressing the realization of shoes not requiring stitching or bonding processes, manufacture directly on desired shape thus not requiring last shaping;
- The Bio shoe: research on environmental friendly materials and manufacturing processes supporting the production of biodegradable shoes;
- The active shoe: design of materials able to actively respond to environment changes and introduction of sensor within the shoe, in order to monitor sensible biomechanical and health parameters.

5.9.2 Project Analysis

CEC Made shoe aims at reinventing the way of thinking footwear, increasing product value by transforming it in a customer-centric, design-oriented, and environmental conscious product. The main driver of research is thus the product, whose total redesign requires the support of innovative tools and methods to be applied at each level of the value chain.

Starting from the central role that product has, a 3D shoe design software enabling customized product conceiving is developed, in order to support manufacturers in the definition of customizable shoe product lines. At POS level, the customization potential is thus transferred to the customer by means of a virtual mirror enabling the visualization of customer designed shoes as really being on feet, thus mimicking a real process of shoe trying.

The multilevel approach to the shoe fostered by the project comprehends also a redefinition of material and processes supporting ecologic customizable shoe manufacturing. To this end, the project focuses on the development of new ecologic materials at upper, sole, and adhesives level, enabling shoe customization together with a reduced impact of the shoe at environmental level.

Eventually, the increased complexity introduced by product Mass Customization is also considered at supply chain level by the development of a platform easing connections between different supply chain actors (Fig. 5.8).

Bibliography

Coronet Website. http://www.corenet-project.eu/. Accessed 15 Dec 2012
ShopInstantShoe website. http://www.instantshoe.com/. Accessed 15 Dec 2012
Fit4U website. http://www.fit4u.eu/. Accessed 15 Dec 2012
MyWear website. http://www.mckn.eu/projects/mywear/. Accessed 15 Dec 2012
NetChallenge website. http://www.netchallenge.org/. Accessed 15 Dec 2012
Dorothy website. http://www.mckn.eu/projects/completed-projects/dorothy/. Accessed 15 Dec 2012
S-MC-S website. http://www.mckn.eu/projects/smcs. Accessed 15 Dec 2012

Chapter 6
Hic Sunt Dracones: Here Be Dragons

6.1 Mass Customization

“Mass Customization refers to customer co-design process of products and services, which meets the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment.” This definition, our starting point, was further decomposed it into four statements and a visual reference framework was proposed in Chap. 2, in order to provide a full understanding of the MC concept.

In a nutshell, Mass Production is based on making the products according to what the market seems to require and then send them to the shops, stores, supermarket, hoping that a customer will be interested to buy them. In Mass Customization, the customer first chooses the product he wants to buy, adapts the design or features to his own taste and needs, then he orders the product (paying for it in advance, at least most of the time). The manufacturer then makes the product according to the customer specifications, and ships it. The transition from Mass Production to Mass Customization implies a radical change in the company business model. In Chap. 2 we indeed proposed the MCIT template (shown in Fig. 6.1) as an exploitable tool to successfully implement an MC transformation, equipped with a set of questions supporting the entrepreneur in understanding the key elements to be considered for each block of the MCIT.

As mentioned, we may step into the template in different blocks. There is no right starting block, or exact logical sequence: each mass customization implementation will have its own genesis, sector specificity, and evolution paths. And the MCIT, along with the proposed questions, is meant as a guide for a profitable journey toward MC.

C. R. Boër et al., *Mass Customization and Sustainability*,
DOI: 10.1007/978-1-4471-5116-6_6, © Springer-Verlag London 2013

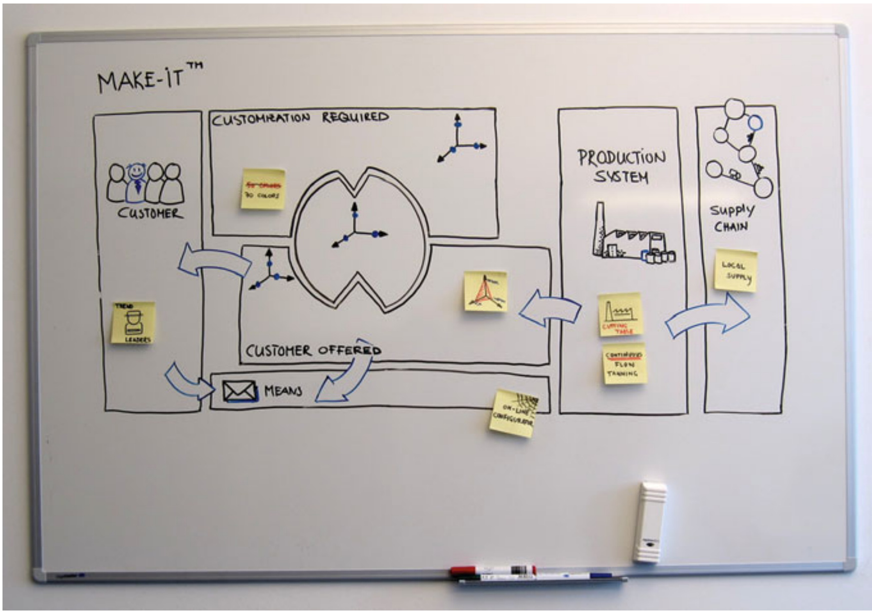


Fig. 6.1 MCIT template drawn on a whiteboard during an implementation discussion

6.2 Sustainability

The concept of sustainability is defined as “to meet the needs of the present generation without compromising the ability of future generations to meet their own needs.” Today, “being sustainable” is a bottom line requirement. “Measuring” the level of this sustainability is a horse of a very different color. Thus Chap. 3 provided a quantitative measurement (meaning numbers: clear, reliable, and exploitable) of environmental, economic, and social performances related to a stable solution space (SSS).

First, a set of selection criteria was suggested to safely navigate through the many proposals offered by literature and market. Then those criteria were applied to choose and refine a set of 35 indicators. The calculation of each indicator value (based on the concept of Impact Potentials) was performed adding up the contribution of each product lifecycle phase (Extraction, Material processing, Part manufacturing, Assembly, Product use, Repair, End of life, Transportation). A comprehensive handbook was provided to guide through the calculation of each indicator.

As an example, the well-known GWP (global warming potential) indicator measures the contribution to the global warming caused by the emission of greenhouse gases in the atmosphere. The calculation formula addresses both the direct emission of greenhouse gases and the indirect ones caused by the energy consumed by the activity carried out during the lifecycle phases of the product. The greenhouse gas emissions are translated into equivalent kilos of CO_2 emitted using the carbon dioxide as a reference gas. Thus $GWP = GWP_{Extraction} + GWP_{Material\ Processing} + GWP_{Manufacturing} + GWP_{Assembly} + GWP_{Use} + GWP_{Repair} + GWP_{End\ Of\ Life} + GWP_{Transportation}$ measured in kg eq. CO_2/kg.

This practical tool, the SAM model, was used to assess sustainability in a real-life case in Chap. 4.

6.3 Mass Customization and Sustainability

Here we are. Is there a link between Mass Customization and Sustainability indexes? "Here be dragons" is a phrase used to point out dangerous or unexplored territories, and indeed the lack of literature on this issue and of conclusive considerations led us to propose three different interpretations.

Three different points of view are thus proposed in the following paragraphs with the goal to provide a comprehensive vision of such an advanced research topic.

The first approach relies on an initial assumption stating that MC uses the same production process as MP, with almost the same efficiency. Impacts on especially social and environmental sustainability are then derived and discussed under this hypothesis.

A second approach tries to investigate in detail from an analytical point of view the MC product compared with an MP solution, abandoning the "equality" hypothesis between MC and MP production systems. Impacts are detailed for the different product lifecycle steps.

A third vision highlights the importance of external factors influencing the actual sustainability performances of an MC solution in comparison to an accurately selected benchmark, also listing a set of tips prospective MC entrepreneurs have to take into account for a valuable assessment.

6.3.1 MC Outperforms MP Using Similar Production Means

Starting from the definition of Tseng and Jiao, MC consists in "producing goods and services to meet individual customer's needs with near mass production efficiency". In order to determine if MC is also more sustainable, let us assume that "near" becomes "equal." Then all the production parameters can be assumed as unchanged and all the indexes on economic and ecological measurement will have the same value for MC and MP. Furthermore, several aspects are certainly in favor of MC, for example highlighting that an MC footwear is more comfortable, more fitting, and more responding to the desires of the customer than an MP footwear (of course considering markets requiring customized shoes. Actually, we know by previous research—EUROShoE project—that this is the case for at least 30 % of the MP market in Europe).

In the footwear sector, statistics report an unsold rate of 20 %. This is for MP produced shoes. All the MC shoes are instead sold. The savings in terms of materials is then again the 20 %, whatever material is used in the shoes. The saving of 20 % in energy is also assured in this case. This can be quantified, only for the final assembly step, in around 3 kWh per shoe. There is another 15–20 kWh per shoe needed to extract, produce, and manufacture the material.

So, at this stage and under the initially stated hypothesis, we can say that it is sure, in the footwear sector, that MC shoes are more sustainable than MP shoe, referring to the same SSS as defined in Chap. 2. More research is needed in order to quantify this assertion and to transpose the same reasoning to other manufacturing sectors.

6.3.2 Index by Index

The second approach addresses the issue from a different point of view. To tackle the link between Mass Customization and Sustainability indexes, we must first take a look back to ITEM4 of the MC definition in Sect. 2.1 (the "adequate price"), to set up a preliminary hypothesis: we are confronting, especially referencing to the footwear sector, a Mass Customized Shoe with a similar Mass Produced one, whose similarity makes them comparable and whose final price makes the two shoes to belong to the same segment. This is an important statement as it endorses a comparison between the two shoes in terms of sustainability indexes. We call $\mathrm{SSS}_{\mathrm{MC}}$ and $\mathrm{SSS}_{\mathrm{MP}}$ the SSS related with the Mass Customized and Mass Produced shoe. The sustainability indexes mentioned in Chap. 3, $\mathrm{SustIndex}_i$ from now on (with i ranging from 1 to 35), define the positioning of the two shoes produced within the two SSSs as far as sustainability is concerned. Index by index, we must look into specific characteristics of the mass customization implementation that makes this MC production system to perform better than the mass production one, in relation to that specific index. In other words, we confront $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MC}})$ with $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MP}})$, with i ranging from 1 to 35. Clearly $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MC}}) = \mathrm{function}(\mathrm{shoe}_{\mathrm{MC}}, \mathrm{SSS}_{\mathrm{MC}})$, as the performances of the $\mathrm{SustIndex}_i$, referred to a specific mass customized shoe, is definitely depending from the specific configuration chosen and from the SSS that produces that specific shoe. If we can reasonably state that $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MC}})$ outperforms the correspondent $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MP}})$, based on the inherent characteristics of $\mathrm{SSS}_{\mathrm{MC}}$ over $\mathrm{SSS}_{\mathrm{MP}}$, then we score a point in presenting Customization as one of the main promoter of Sustainability.

As an example, let us address the Global Warming Potential (GWP—CO_2 emissions) related to transportations of finished goods, where these goods are shoes with strong customization in the fitting dimension (e.g., LeftFoot Company). This type of mass customized shoes, taking into consideration the companies that nowadays are producing them, have a very short supply chain (if compared with Mass Produced shoes), clearly demonstrating a built-in advantage over the traditional long supply and distribution chains of correspondent mass produced shoes. This is clearly a qualitative reasoning, limited to a shoe segment that needs the actual calculation of GWP index for a wide range of companies and situations to be confirmed or revised. But it leads us to think that MC can have an edge over MP in this sustainability index.

As proposed in Sect. 3.3.4, the expected final value of the sustainability indicators is calculated by assessing the contributions related to the product lifecycle phases:

Extraction: equivalent impact caused by the extraction of raw materials constituting the product, its packaging, and the surface treatments (e.g., paint, nickel used in galvanic processes…).

Material processing: equivalent impact caused by the material processing of the raw materials constituting the product and its packaging.

Part manufacturing: equivalent impact caused by manufacturing operations.

Assembly: equivalent impact caused by assembly operations.

Product use: equivalent impact caused by the product use.

Repair: equivalent impact occurred during the extraction, the material processing, the manufacturing processes, the transportations (from the suppliers and to the EOL facilities and customers), and the EOL treatments of the spare parts.

End of life: equivalent impact caused by end of life treatments carried out on the product and its packaging.

Transportation: equivalent impact caused by transportations of raw materials and components from suppliers, transportation of the finished product (product plus packaging) to retailers or customers, and transportations of the finished product to end of life facilities.

As far *Extraction* and *Material processing* are concerned, we want to introduce here a consideration, born from experience and intrinsic characterization of an MC production system, that is also applicable to all the other lifecycle phases. In the footwear sector, as in many other manufacturing sectors as well, an unsold rate of 20 % is to be expected (as previously mentioned). Thus, out of 100 produced shoes to stock, 80 will be sold. In the Mass Customization case, the shoe is produced just when it is sold. Facing a demand of 80 shoes, 80 will be produced. This clearly reflects in a magnifying effect over each $\mathrm{SustIndex}_i(\mathrm{shoe}_{\mathrm{MC}})$, whose performance results to be increased by an average rate of 20 %. This consideration is true for the shoe sector (it represents an average over the whole footwear production), and is clearly common to other. This is an initial score in favor of Mass Customization, an intrinsic characteristic of its business model that pushes toward a more sustainable approach.

End of good news as we now move to *Part manufacturing* and *Assembly*: modularity has always been considered an important enabler and a strategy itself for successful mass customization (from Pine to Piller, already mentioned in Chap. 2). Thus most producers of mass customized goods apply modular product architectures. A modular product architecture, while promoting flexibility in final product configurations, cannot achieve the same performances of a rigid integral architecture: properties like size and weight will tend to be in favor of an integral architecture thus it could be expected that more material resources are necessary to produce an MC product. Looking back at the indicators proposed in Chap. 3, mass customized products may have a worse sustainability impact during part Manufacturing and Assembly due to a higher material usage. Also, product variety is a characterizing feature of MC that points to considerably variable Part Manufacturing and Assembly processes: this may lead to an increased difficulty to optimize the production processes, in respect to MP, in terms of energy and material consumption. This may imply a greater environmental impact than MP. However, in the footwear sector, specific considerations may lead to think differently. Let us take for example again the case of LeftFoot. This company does not release detailed information on its production process but the owners have been interacting with the authors of the present book in few occasion. It is clear that their customization level is that best match fit [we make reference to the levels depicted in block II of the MCIT in Chap. 2, (1) standard set of grading; (2) best match fit; (3) tailor made]. Shoes are configured according to measurement of the feet of the customer made in LeftFoot shops with a 3D scanner and with the customer testing of some reference models. These operations lead to a matching with existing models and sizes in the factory. Therefore, the production process will be very similar to mass produced shoes because all the lasts, the tools for cutting the upper and the soles and other components are the same. The choices given to the customers are limited in term of colors of the upper and the type of soles (rubber, leather, or mix). The main difficulty will be related to the production organization so that the setup for each pair of customized shoes is as short as possible or similar customizes shoes can be grouped to use similar tools and/or material. Therefore, in the case of the LeftFoot customization (a best match fit), we may think that there is no need to change the production process and that the final MC product has a similar architecture to the MP one, thus that no significant variance over part manufacturing and assembly can be highlighted.

In terms of *product use*, we may assume that, as MC provides a product with better fitting, the replacement rate would be inferior and consequently so would be the waste produced. Additionally, if an MC product is configured so that it performs diverse functions, this product may be able to substitute multiple standard mass produced products for a longer time. This would imply that fewer products would need to be produced for assuring the same utility level for the customer, with the expected positive impact over sustainability indexes.

As far as *end of life* is concerned, we may again think to product modularity as a key element in MC, which would, in turn, have positive impact on the EOL treatments needed, as modular architecture is by far more compatible with service, remanufacturing, recycling, and disposal if compared with an integral architecture.

Transportation is where really MC could have an edge: in mass production, a finished product may go through several levels of distribution before reaching the final customer. Mass customized products are produced for one specific customer and shipped to him directly. The product will not travel across all the distribution layers and is expected to have a shorter route from producer to consumer, which could again point to less energy consumption and fewer emissions.

Casting these considerations over the sustainability indexes, we can conclude that there is a link between Mass Customization and Sustainability, that MC has a great potential to influence Sustainability assessment, but it's impossible to state, at an universal level across all the manufacturing sectors, whether MC promotes sustainability or not.[1] Indeed there are elements of mass customization which impact sustainability, although in both ways: toward more sustainable or less sustainable products.

Beside the undisputed commercial and social values, it seems thus difficult to reach the conclusion that MC (or any other production paradigm) has an overall benefit on Sustainability as a whole. The challenge to analyze individual indexes and their actual evaluation in real cases is definitely sector specific: there is no shortcut, no general principle. We have to consider index by index, MC implementation by MC implementation. Chapter 3 provides the definition of measurable sustainability indexes, related to a given SSS, that offers the actual tool to confront $\mathrm{SustIndex}_i(\mathrm{Product}_{\mathrm{MC}})$ with $\mathrm{SustIndex}_i(\mathrm{Product}_{\mathrm{MP}})$ for any sector-specific case, and points out a method to address the relation between Mass Customization and Sustainability in the MC implementation we are facing each specific time. Abridging, the SAM assessment model can guide the user in an MC implementation that is highly performing in terms of ecological, social, and economics behavior.

6.3.3 *Is MC the Most Sustainable Answer to Personalization Requirements?*

In the previous paragraph, sustainability indicators have been used in order to compare "a Mass Customized Shoe with a similar Mass Produced one, whose similarity makes them comparable and whose final price makes the two shoes to belong to the same market segment." Two products are thus taken into account, addressing the needs of customers with a similar purchasing power but manufactured with different production approaches.

This comparison methodology somehow relies on Piller's assumption: "as a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment," implicitly admitting that the new (MC) products can be offered to the same *market* of (already existing) MP products having a similar price. With this approach, we are taking a customized and a non-customized shoe, that are "similar" in some intrinsic characteristics (shape, context of use, distribution means) and comparable in terms of price and we use the sustainability indicators in order to evaluate their *performances*.

In this paragraph, we try to propose a third point of view triggered by this doubt: is a "similar" MP product the right reference to judge whether the MC

---

[1] This is the same result pointed out by Petersen et al. (2011)

solution positively impacts on sustainability? In other words we discard the hypothesis at the basis of Sect. 6.3.2 dissertation.

Let’s start from the McCarthy’s definition of MC: “the capability to manufacture a relatively high volume of product options for a relatively large market (or collection of niche markets) that demands customization, without tradeoffs in cost, delivery, and quality.” Here “market […] that demands customization” is proposed as something like a preliminary hypothesis, namely arguing “when your (current/envisaged) market demands customization, MC is an efficient answer.” Also Tseng and Jiao’s “producing goods and services to meet individual customer’s needs with near mass production efficiency” proposes this view: MC is a strategy meant to efficiently answer to (given) markets customization demand. According to these considerations, a “similar” MP product does not appear to be a good reference for judging MC solutions sustainability performances. Better: we can still use MP as a benchmark, but we have to consider MP products sold to “market that demands customization”. Making it general, we can argue that good confrontations should compare:

1. MC products and MP products offered to markets demanding for customization.
2. MC products and otherwise customized products offered to markets demanding for customization.

When producing “non-customized” products, MP productions usually outperform MC in terms of production efficiency (production throughput times, magnitude of production indirect costs, economies of scale); the two options can be comparable in terms of costs for stocks and transports (actually, a “traditional” Make To Stock MP is obviously less performing than a pure Make To Order MC, but MP productions can be also managed to minimize or avoid stocks. On the other side, we previously stated that direct transport to the final customer should limit useless transports through the different elements of a long value chain. A clever reader could object that transports along MP supply chains are usually fully optimized, with many products transferred together and simultaneously in an efficient way). The sole certain advantage of MC derives from the abatement of unsold products: customized solutions, designed together with the customer and made to order, have a really low likelihood to remain unsold. Simplifying, we can thus state that MC is better than MP if the reduced production efficiency is more than compensated by the minimized number of unsold products. Actually, the probability to have MP products unsold is higher in a “market that demands customization,” thus the effort spent to minimize the reduced production efficiency in MC productions has a greater chance to be successful.

Using MP production chains to manufacture customized products is, instead (and by definition), less efficient than producing custom goods with MC production chains.

Craft production can be taken into account as an alternative customization strategy (point nr.2 above). Comparing MC and Craft addressing a customization-demanding market, we can argue that MC is by far more efficient, while the only advantage of Craft production is the level of customization. And what about other customization strategies? MC is, by definition, a way to efficiently manage customization, thus any customization strategy enabling the production of personalized goods in an efficient manner, can be included under the MC umbrella.

Summing up, MC is (by definition) more efficient than other customization strategies (e.g., craft production), while it is not possible to generalize the same statement when comparing to MP productions: a case-by-case or, at least, a sector-specific and market segment-specific evaluation needs to be performed time by time.

And efficiency is just one of the (35) indicators for measuring sustainability. Apart from indications provided in the previous paragraph, also considering the specific prerogative of markets demanding customized solutions, we are still not able to state that MC is always more sustainable than MP.

This book has an operative and proactive attitude. For these reasons, we *proactively* propose a new definition of MC, described as "a strategy pursuing the production of goods and services to meet individual customer's needs with higher than mass production sustainability" and we also try to propose some practical tools prospective entrepreneurs can *operatively* use to pursue sustainability within their MC initiatives. Empirical practices with industrial applications have triggered a set of suggestions and recommendations meant to effectively guide the sustainable MC implementers:

- Select *the benchmark*. As discussed in Chap. 3, the absolute value of each sustainability indicator is not that significant whether not carefully compared/standardized. It is thus fundamental to have a comparative benchmark to refer to. Some principles used to identify a proper benchmark follow:
  - consider a product you know in detail and you can easily collect information and data about (e.g., your current MP solution);
  - be ambitious. Select the solution with the best sustainability performances in order to have a challenging benchmark;
  - select a product somehow similar to the MC solution you are going to develop/commercialize. Similarity may concern one or more of the following elements: the target customer (obviously prefer customization-demanding market segments with a purchasing power compatible with your MC offer), the offer intrinsic characteristics (usage context, functional performances), and price (not more than 20 % lower than your MC offer's one). The more similar elements you find, the better it is. In some cases, it has been effective to collect some data from a small sample of the target market in order to create a likely set of indifference curves expressing the marginal rate of substitution between the benchmark and the sketched MC offer.
- Consider and represent the entire *lifecycle*. Define all the lifecycle steps for both the MC and the selected benchmarking products using a generic lifecycle template (as the path outlined in Sect. 6.3.2).

- Evaluate the sustainability *performances*. Consider the same market segment for both the compared products and estimate the indicators' value in all the lifecycle steps. When comparing an MC and an MP solution, be careful in estimating the number of unsold products and their effect especially on economic and environmental sustainability. Use as many indicators as possible: the more the known points, the clearer the profile.
- Compare and ponder. Read the results using *your sustainability vision*. Create your envisaged sustainability profile, either from scratch or qualitatively as a shift from the benchmark.

  Alternative MC solutions can be mapped using the MCIT presented in Chap. 2. For each alternative, the lifecycle steps and the consequent estimation of indicators value are eased by the quick descriptions proposed for each element of the MCIT template. Ranking among alternatives is rarely obvious because solutions better performing under all the sustainability aspects are really uncommon (especially if the selected alternatives are all reasonable and eligible). Here the sustainability vision supports the decision makers: expressed attention put on social aspects or emphasis put on environmental performances in middle of life steps… can result in completely different choices.

6.4 A Step Beyond Sustainable Production

In Chap. 1, Table 1.1 we referred to "Sustainable Production" as the latest manufacturing paradigm for the 2020 horizon, described as the one that will be able "to respond to the society needs of clean products" within a market demand for the "environment." Is this sufficient? And what about the "society needs of customization?"

With this book we tried to pave the way for a further step toward the future of manufacturing, exploring innovative approaches and proposing operative methodologies inspiring entrepreneurs aiming at *pursuing the production of goods and services to meet individual customer's needs with the highest sustainability*.

Further investigations are obviously needed and state-of-the-art researches (as reported in Chap. 5) are currently running in order to shed some light on this still hazy topic. In this conclusive paragraph, we decided to plant a final visionary seed based on a simplified (and easy-to-remember) model meant to provocatively describe the interaction between the different parameters involved in the MC paradigm:

$$\mathrm{E} = \mathrm{MC}^2$$

where:

E Economic benefit/profit/gains, etc.
M Mass production efficiency, economy of scale, etc.

C Customization/customer centric/market/etc.
$()^2$ Importance/to the maximum extent/etc.

For the new strategy aimed at “pursuing the production of goods and services to meet individual customer’s needs with the highest sustainability,” we propose a modified version:

$$E_i = MC^2$$

where:

E_i Is the incremental benefit index, with $i \in \{\text{ecological, social, economic}\}$
M Mass of produced products
C Customization level (see below for a simplified description of the levels)

$C = 1$ first level of customization
$C = 2$ second level of customization
$C = 3$ third level of customization

The level of customization are described in Chap. 2, Item 2 but we are referring here to a simplified view referred to the footwear sector as it was described in an already cited book on MC published by Springer (Boër and Dulio 2007):

1. Style Customization—based on standard lasts (and sizes), consumers can choose style options (colors, fabrics, leather, accessories) within constraints set by the manufacturer. This can be offered as a separate market option or be included in other customization levels.
2. Best-Matched Fit—the feet of each customer are examined (using devices called foot scanners) and matched to an existing library of lasts, insoles, and soles with a much higher granularity than in today’s mass production systems. Additionally, some style customization may be possible.
3. Custom Fit—the feet of each customer are examined and his or her specific habits are analyzed and used to make an individual last, insole, and sole. Additionally, some style customization may be possible.

It is interesting to note that the above formulation leads to some indications about the interactions among the various parameters that make possible an MC.

For example, if we take $C = 1$ we are in fact with MP production even if a company offers some style customization (first level).

If $C = 2$ or 3 the customization complexity increases and it seems that the benefit index will increase. This is true only if the M is, however, high or, in other words, if we are in conditions near to MP as in the definition of MC given by Tseng and others.

Furthermore, it is possible to use the simplified view to show the impact of applying an MC paradigm with no unsold item and an MP paradigm with 20 % unsold items. We leave the reader to extrapolate this result by himself.

Our research continues in order to determine a formulation similar to the above that include the sustainability indexes defined in the present book and to obtain an empirical validation of the model.

Bibliography

Boër CR, Dulio S (2007) Mass customization and footwear: myth, salvation or reality?. Springer, Berlin

Petersen T, Nielsen K, Taps S, Jørgensen K (2011) Is mass customization sustainable? In: Proceeding of the 2011 world conference on mass customization, personalization, and co-creation, San Francisco