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
	Contribution to economic development	local supply
	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	$GWP_{mp} = \sum_i \sum_j \sum_p f_i \times \chi_{p,i,j} \times V_{i,j} \times \rho_j \times GWP_{mp\,p,j}$
	$GWP_{mp\ p,j}$ [kg eq. CO_2/kg] = GWP for the material processing p used for material 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 $Q_{wm\ j,m}$ [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 $GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o a = ath assembly of the final customizable product f_a = frequency of the ath assembly in the expected product mix $V_{a,j}$ [cm^3] = volume of the part of the ath assembly, made by material j $GWP_{ext\ j}$ [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 ath assembly; otherwise 0 $GWP_{mp\ p,j}$ [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 ath scrap assembly $GWP_{EOL\ j,l}$ [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 ath assembly provided by supplier q $d_{a,j,q,z}$ [km] = distance between supplier q (providing material j for the ath assembly) 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	$GWP_{as} = (1+SRA) \times \left(\sum_o f_o \times CS_o \times GWP_{aso}\right)$ $+\ SRA \times \Big(\sum_a \sum_j f_a \times V_{a,j} \times \rho_j \times GWP_{extj}$ $+\sum_a \sum_j \sum_p f_a \times \chi_{p,a,j} \times V_{a,j} \times \rho_j \times GWP_{mpp,j}$ $+\sum_a \sum_j \sum_l f_a \times f_{a,j,l} \times V_{a,j} \times \rho_j \times GWP_{EOLj,l}$ $+\sum_a \sum_j \sum_q \sum_z f_a \times V_{a,j} \times \rho_j \times f_{a,j,q} \times d_{a,j,q,z} \times GWP_{traz}$ $+\sum_a \sum_j \sum_r \sum_z f_a \times V_{a,j} \times \rho_j \times f_{a,j,r} \times d_{EOLr,z} \times GWP_{traz}\Big)$ $+\ (1+SRA) \times \Big(\sum_o \sum_w f_o \times Q_{auxw,o} \times GWP_{extw}$ $+\sum_o \sum_w \sum_p f_o \times \chi_{p,w} \times Q_{auxw,o} \times GWP_{mpp,w}$ $+\sum_o \sum_w \sum_l f_o \times f_{w,l} \times Q_{auxw,o} \times GWP_{EOLw,l}$ $+\sum_o \sum_w \sum_q \sum_z f_o \times f_{w,q} \times Q_{auxw,o} \times d_{w,q,z} \times GWP_{traz}$ $+\sum_o \sum_w \sum_r \sum_z f_o \times f_{w,r} \times Q_{auxw,o} \times d_{EOLr,z} GWP_{traz}\Big)$

(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	
	$Q_{aux\ w,o}$ [kg/operation] = quantity of the auxiliary material w used during the operation o	
	$GWP_{ext\ w}$ [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	
	$f_{w,q}$ = 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	
	$d_{EOL\ r,z}$ [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] = $P \times$ US P [kW] = power dissipated in the use phase by the product US [h] = usage scenario—hours of use in the product usage $\text{GWP}_{\text{en } y,c}$ [kg eq. CO_2/kWh] = GWP for energy y production in country c GWP_{up} [kg eq. CO_2/h] = GWP 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 $\text{GWP}_{\text{ext } j}$ [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 $\text{GWP}_{\text{mp } p,j}$ [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 $\text{GWP}_{\text{EOL } j,l}$ [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 $\text{GWP}_{\text{tra } z}$ [kg eq. CO_2/(kg km)] = GWP 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	$\text{GWP}_{\text{use}} = \sum_c \sum_y f_c \times f_y \times E_{\text{use}} \times \text{GWP}_{\text{en } y,c}$ $+ \text{GWP}_{\text{up}} \times \text{US}$ $+ \sum_k n_{\text{cons}\,k} \times \Big(\sum_j f_k \times V_{\text{cons}\,k,j} \times \rho_j \times \text{GWP}_{\text{ext}\,j}$ $+ \sum_j \sum_p f_k \times \chi_{p,k,j} \times V_{\text{cons}\,k,j} \times \rho_j \times \text{GWP}_{\text{mp}\,p,j}$ $+ \sum_j \sum_l f_k \times f_{k,j,l} \times V_{\text{cons}\,k,j} \times \rho_j \times \text{GWP}_{\text{EOL}\,j,l}$ $+ \sum_j \sum_q \sum_z f_k \times V_{\text{cons}\,k,j} \times \rho_j \times f_{k,j,q} \times d_{k,j,q,z} \times \text{GWP}_{\text{tra}\,z}$ $+ \sum_j \sum_z f_k \times V_{\text{cons}\,k,j} \times \rho_j \times d_{cust\,z} \times GWP_{tra\,z}$ $+ \sum_j \sum_r \sum_z f_k \times V_{\text{cons}\,k,j} \times \rho_j \times f_{k,j,r} \times d_{EOL\,r,z} \times GWP_{tra\,z} \Big)$ $+ \sum_g f_g \times \text{CS}_g \times \text{GWP}_{\text{man}g}$

(continued)

Table 3.12 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
	$d_{EOL\ r,z}$ [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 $GWP_{man\ g}$ [kg eq. CO_2/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 $GWP_{ext\ j}$ [kg eq. 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 $GWP_{mp\ p,j}$ [kg eq. 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 $GWP_{EOL\ j,l}$ [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 $d_{cust\ z}$ [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 $d_{EOL\ r,z}$ [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 $GWP_{man\ m}$ [kg eq. CO_2/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 $GWP_{as\ o}$ [kg eq. CO_2/CS_o] = GWP for the assembly operation o	$GWP_{rep} = \sum_i n_{s\ i} \times \Big(\sum_j f_i \times V_{i,j} \times \rho_j \times GWP_{ext\ j} + \sum_j \sum_p f_i \times \chi_{p,i,j} \times V_{i,j} \times \rho_j \times GWP_{mp p,j} + \sum_j \sum_l f_i \times f_{i,j,l} \times V_{i,j} \times \rho_j\ GWP_{EOL j,l} + \sum_j \sum_q \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,q} \times d_{i,j,q,z} \times GWP_{traz} + \sum_j \sum_z f_i \times V_{i,j} \times \rho_j \times d_{cust\ z} \times GWP_{tra\ z} + \sum_j \sum_r \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,r} \times d_{EOL\ r,z} \times GWP_{tra\ z} \Big) + \sum_m f_{s\ m} \times CS_m \times GWP_{man\ m} + \sum_o f_{s\ o} \times CS_o \times GWP_{as\ o}$

(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 $GWP_{EOL\ j,l}$ [kg eq. CO_2/kg] = GWP for the EOL of material j, done with treatment l	$GWP_{EOL} = \sum_i \sum_j \sum_l f_i \times f_{i,j,l} \times V_{i,j} \times \rho_j \times GWP_{EOL\ j,l}$
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 $GWP_{tra\ z}$ [kg eq. CO_2/(kg km)] = GWP for transportation done by the mean z $d_{cust\ z}$ [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 $d_{EOL\ r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	$GWP_{tra} = \sum_i \sum_j \sum_q \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,q} \times d_{i,j,q,z} \times GWP_{tra\ z} + \sum_i \sum_j \sum_z f_i \times V_{i,j} \times \rho_j \times d_{cust\ z} \times GWP_{tra\ z} + \sum_i \sum_j \sum_r \sum_z f_i \times V_{i,j} \times \rho_j \times f_{i,j,r} \times d_{EOL\ r,z} \times GWP_{tra\ z}$

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
$EDP_{en\ y,c}$ [MJ/kWh] = EDP for energy y production in country c
EDP_{up} [MJ/h] = EDP of the use phase
k = kth consumable component
$n_{cons\ k}$ = 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
$V_{cons\ k,j}$ [cm^3] = volume of the part of the kth consumable component made by the material j
$EDP_{ext\ j}$ [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
$EDP_{mp\ p,j}$ [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
$EDP_{EOL\ j,l}$ [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
$EDP_{tra\ z}$ [MJ/(kg km)] = EDP for transportation done by the mean z
$d_{cust\ z}$ [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
$d_{EOL\ r,z}$ [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
$EDP_{man\ g}$ [MJ/CS$_g$] = EDP for manufacturing operation g

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

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 $EC_{y,c}$ [€/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 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 $WC_{i,j,c}$ = waste coefficient when processing material j for the ith component in country c $KC_{i,j}$ [kWh/kg] = energy consumption per extracted kg of material j for the ith component $WH_{ext\ op}$ [h/year] = hours worked in one year by the operator op extracting materials j in the extraction department of the company	$UPVC_{ext} = \sum_i \sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times C_{i,j,q} + \sum_i \sum_j \sum_c \sum_y (1 - \sum_q f_{i,j,q}) \times f_i \times f_{i,j,c} \times f_y \times (V_{i,j} \times \rho_j)/(1 - WC_{i,j,c}) \times KC_{i,j} \times EC_{y,c} + (\sum_{op} WH_{extop} \times salary_{op}/thw_{op})/N$

(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 = ith component of the final customizable product	$\mathrm{VAT} = 100 \times \left(\sum_j \sum_m \mathrm{PT}_{j,m} + \sum_j \sum_p \mathrm{PT}_{j,p} + \sum_i \sum_m \mathrm{PT}_{i,m} + \sum_a \sum_o \mathrm{PT}_{a,o} \right) / \left[\sum_j \mathrm{MT}_j + \sum_i \mathrm{MT}_i + \sum_a \mathrm{MT}_a + \sum_j \sum_m (\mathrm{PT}_{j,m} + \mathrm{ST}_{j,m} + \mathrm{QT}_{j,m}) + \sum_j \sum_p (\mathrm{PT}_{j,p} + \mathrm{ST}_{j,p} + \mathrm{QT}_{j,p}) + \sum_i \sum_m (\mathrm{PT}_{i,m} + \mathrm{ST}_{i,m} + \mathrm{QT}_{i,m}) + \sum_a \sum_o (\mathrm{PT}_{a,o} + \mathrm{ST}_{a,o} + \mathrm{QT}_{a,o}) \right]$
	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 = ath 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	$CUR = TR/TR_i \times 100$
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	UEGP = Pr − [UPVC + (Pr × N/S_c) × (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	RDI_{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	$\text{RDII}_{ext} = \text{RDI}_{ext} \times (S_{ss}/S_c)/N + \sum_i \sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times \text{RDI}_q \times (C_{i,j,q}/\text{ST}_q)$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Material Processing	RDI_{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	$RDII_{mp} = RDI_{mp} \times (S_{ss}/S_c)/N + \sum_i \sum_j \sum_p \sum_q f_i \times V_{i,j} \times \rho_j \times f_{i,j,p,q} \times RDI_q \times (C_{i,j,p,q}/ST_q)$
Part manufacturing	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 $f_{i,q}$ = 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 $Q_{aux\ w,m}$ [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	$RDII_{man} = RDI_{man} \times (S_{ss}/S_c)/N$ $+ \sum_i \sum_q f_i \times f_{i,q} \times RDI_q \times (C_{i,q}/ST_q)$ $+ \sum_m \sum_w \sum_q f_m \times f_{w,q} \times Q_{aux\ w,m} \times RDI_q \times (C_{w,q}/ST_q)$ $+ \sum_m \sum_w \sum_q f_m \times f_{w,p,q} \times Q_{aux\ w,m} \times RDI_q \times (C_{w,p,q}/ST_q)$ $+ \sum_m \sum_w \sum_r f_m \times f_{w,r} \times Q_{aux\ w,m} \times RDI_r \times (C_{EOL\ w,r}/ST_r)$ $+ \sum_m \sum_w \sum_q \sum_t \sum_z f_m \times f_{w,q} \times f_{w,t,z} \times Q_{aux\ w,m} \times d_{w,q,z} \times RDI_t \times (C_{tra\ w,t,z}/ST_t)$ $+ \sum_m \sum_w \sum_r \sum_t \sum_z f_m \times f_{w,r} \times f_{w,t,z} \times Q_{aux\ w,m} \times d_{EOL\ r,z} \times RDI_t \times (C_{tra\ w,t,z}/ST_t)$ $+ \sum_m \sum_j \sum_q f_m \times f_{j,q} \times Q_{wm\ j,m} \times RDI_q \times (C_{j,q}/ST_q)$ $+ \sum_m \sum_j \sum_q f_m \times f_{j,p,q} \times Q_{wm\ j,m} \times RDI_q \times (C_{j,p,q}/ST_q)$ $+ \sum_m \sum_j \sum_r f_m \times f_{j,r} \times Q_{wm\ j,m} \times RDI_r \times (C_{EOL\ j,r}/ST_r)$ $+ \sum_m \sum_j \sum_q \sum_t \sum_z f_m \times f_{j,q} \times f_{j,t,z} \times Q_{wm\ j,m} \times d_{j,q,z} \times RDI_t \times (C_{tra\ j,t,z}/ST_t)$ $+ \sum_m \sum_j \sum_q \sum_t \sum_z f_m \times f_{j,r} \times f_{j,t,z} \times Q_{wm\ j,m} \times d_{EOL\ r,z} \times RDI_t \times (C_{tra\ j,t,z}/ST_t)$

(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	
	$C_{EOL\ w,r}$ [€/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	
	$C_{tra\ w,t,z}$ [€/(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	
	$d_{EOL\ r,z}$ [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	
	$Q_{wm\ j,m}$ [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	
	$C_{EOL\ j,r}$ [€/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	
	$C_{tra\ j,t,z}$ [€/(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	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 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 $Q_{\text{aux } w,o}$ [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 $C_{\text{tra } w,t,z}$ [€/(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 $d_{\text{EOL } r,z}$ [km] = distance to the EOL facility r covered by the mean of transportation z	$RDII_{as} = RDI_{as} \times (S_{ss}/S_c)/N$ $+ \sum_a \sum_q f_a \times f_{a,q} \times RDI_q \times (C_{a,q}/ST_q)$ $+ \sum_o \sum_w \sum_q f_o \times f_{w,q} \times Q_{\text{aux } w,o} \times RDI_q \times (C_{w,q}/ST_q)$ $+ \sum_o \sum_w \sum_q f_o \times f_{w,p,q} \times Q_{\text{aux } w,o} \times RDI_q \times (C_{w,p,q}/ST_q)$ $+ \sum_o \sum_w \sum_r f_o \times f_{w,r} \times Q_{\text{aux } w,o} \times RDI_r \times (C_{\text{EOL } w,r}/ST_r)$ $+ \sum_o \sum_w \sum_q \sum_t \sum_z f_o \times f_{w,q} \times f_{w,t,z} \times Q_{\text{aux } w,o} \times d_{w,q,z} \times RDI_t \times (C_{\text{tra } w,t,z}/ST_t)$ $+ \sum_o \sum_w \sum_r \sum_t \sum_z f_o \times f_{w,r} \times f_{w,t,z} \times Q_{\text{aux } w,o} \times d_{\text{EOL } r,z} \times RDI_t \times (C_{\text{tra } w,t,z}/ST_t)$

(continued)

Table 3.37 (continued)

LC phase	Data from design tools, data entry, and databases	Formula
Product use	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 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	$\mathrm{RDII}_{use} = \mathrm{RDI}_{use} \times (S_{ss}/S_c)/N$ $+ \sum_k n_{\mathrm{cons}\,k} \times (\sum_j \sum_q f_k \times f_{k,j,q} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{k,j,q}/\mathrm{ST}_q)$ $+ \sum_j \sum_p \sum_q f_k \times f_{k,j,p,q} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{k,j,p,q}/\mathrm{ST}_q)$ $+ \sum_q f_{k,q} \times \mathrm{RDI}_q \times (C_{k,q}/\mathrm{ST}_q)$ $+ \sum_j \sum_r f_k \times f_{k,j,r} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times \mathrm{RDI}_r \times (C_{\mathrm{EOL}\,k,j,r}/\mathrm{ST}_r)$ $+ \sum_j \sum_q \sum_t \sum_z f_k \times f_{k,j,q} \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{k,j,q,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t)$ $+ \sum_j \sum_t \sum_z f_k \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{\mathrm{cust}\,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t)$ $+ \sum_j \sum_r \sum_t \sum_z f_k \times f_{k,j,r} \times f_{k,j,t,z} \times V_{\mathrm{cons}\,k,j} \times \rho_j \times d_{\mathrm{EOL}\,r,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\,k,j,t,z}/\mathrm{ST}_t))$

(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	$\mathrm{RDII}_{\mathrm{rep}} = \mathrm{RDI}_{\mathrm{rep}} \times (S_{ss}/S_c)/N$ $+\sum_i n_{s\,i} \times (\sum_j \sum_q f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{i,j,q}/\mathrm{ST}_q)$ $+\sum_j \sum_p \sum_q f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_q \times (C_{i,j,p,q}/\mathrm{ST}_q)$ $+\sum_q f_i \times f_{i,q} \times \mathrm{RDI}_q \times (C_{i,q}/\mathrm{ST}_q)$ $+\sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_r \times (C_{\mathrm{EOL}\ i,j,r}/\mathrm{ST}_r)$ $+\sum_j \sum_q \sum_t \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_t \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\ z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t)$ $+\sum_j \sum_r \sum_t \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times (C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t))$

(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	$\mathrm{RDII}_{\mathrm{EOL}} = \mathrm{RDI}_{\mathrm{EOL}} \times (S_{ss}/S_c)/N + \sum_i \sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times \mathrm{RDI}_r \times \left(C_{\mathrm{EOL}\ i,j,r}/\mathrm{ST}_r\right)$
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	$\mathrm{RDII}_{\mathrm{tra}} = \mathrm{RDI}_{\mathrm{tra}\ z} \times (S_{ss}/S_c)/N + \sum_i \sum_j \sum_q \sum_t \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right) + \sum_i \sum_j \sum_t \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{cust}\ z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right) + \sum_i \sum_j \sum_r \sum_t \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\mathrm{EOL}\ r,z} \times \mathrm{RDI}_t \times \left(C_{\mathrm{tra}\ i,j,t,z}/\mathrm{ST}_t\right)$

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 $RC_{b^{ext}}$ = 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) $SR_{(b^{ext},s^{source},s^{targ})}$ = 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) $SR_{(b^{ext},s^{source},s^{targ})}$ = boolean: 1 if the resource b_{ext} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{ext},s^{targ}}$ = boolean: 1 if the resource b_{ext} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$SR_{ext} = 1 - \Pi_{(b^{ext},s^{targ})}[1 - RC_{b^{ext}} \times \Pi_{(b^{ext},s^{source},s^{targ})}(SR_{(b^{ext},s^{source},s^{targ})})^{\chi_{b^{ext},s^{source},s^{targ}}}]^{\chi_{b^{ext},s^{targ}}}$
Material Processing	b_{mp} = resource transported within the supply chain in the material processing phase $RC_{b^{mp}}$ = 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) $SR_{(b^{mp},s^{source},s^{targ})}$ = 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) $\chi_{b^{mp},s^{source},s^{targ}}$ = boolean: 1 if the resource b_{mp} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{mp},s^{targ}}$ = boolean: 1 if the resource b_{mp} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$SR_{mp} = 1 - \Pi_{(b^{mp},s^{targ})}[1 - RC_{b^{mp}} \times \Pi_{(b^{mp},s^{source},s^{targ})}(SR_{(b^{mp},s^{source},s^{targ})})^{\chi_{b^{mp},s^{source},s^{targ}}}]^{\chi_{b^{mp},s^{targ}}}$

(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 $RC_{b^{pm}}$ = 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) $SR_{(b^{pm},s^{source},s^{targ})}$ = 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) $\chi_{b^{pm},s^{source},s^{targ}}$ = boolean: 1 if the resource b_{pm} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{pm},s^{targ}}$ = boolean: 1 if the resource b_{pm} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$SR_{pm} = 1 - \Pi_{(b^{pm},s^{targ})}[1 - RC_{b^{pm}} \times \Pi_{(b^{pm},s^{source},s^{targ})} (SR_{(b^{pm},s^{source},s^{targ})})^{\chi_{b^{pm},s^{source},s^{targ}}}]^{\chi_{b^{pm},s^{targ}}}$
Assembly	b_{as} = resource transported within the supply chain in the assembly phase $RC_{b^{as}}$ = 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) $SR_{(b^{as},s^{source},s^{targ})}$ = 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) $\chi_{b^{as},s^{source},s^{targ}}$ = boolean: 1 if the resource b_{as} is provided by supply chain member s_{source} to the supply chain member s_{targ}; otherwise 0 $\chi_{b^{as},s^{targ}}$ = boolean: 1 if the resource b_{as} is provided to supply chain member s_{targ} within the supply chain; otherwise 0	$SR_{as} = 1 - \Pi_{(b^{as},s^{targ})}[1 - RC_{b^{as}} \times \Pi_{(b^{as},s^{source},s^{targ})} (SR_{(b^{as},s^{source},s^{targ})})^{\chi_{b^{as},s^{source},s^{targ}}}]^{\chi_{b^{as},s^{targ}}}$

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:
RDI_{ext} [€] = average yearly R&D investments made by the company in extraction activities	NI_{ext} [#] = average yearly number of injuries occurred in the company in extraction activities
$RDII_{ext}$	II_{ext}
RDI_{mp} [€] = average yearly R&D investments made by the company in material processing activities	NI_{mp} [#] = average yearly number of injuries occurred in the company in material processing activities
$RDII_{mp}$	II_{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	NI_{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
$RDII_{man}$	II_{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	NI_{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
$RDII_{as}$	II_{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:
RDI_{ext} [€] = average yearly R&D investments made by the company in extraction activities	SE_{ext} [€] = average yearly safety expenditures made by the company in extraction activities
$RDII_{ext}$	SEI_{ext}
RDI_{mp} [€] = average yearly R&D investments made by the company in material processing activities	SE_{mp} [€] = average yearly safety expenditures made by the company in material processing activities
$RDII_{mp}$	SEI_{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	SE_{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
$RDII_{man}$	SEI_{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	SE_{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
$RDII_{as}$	SEI_{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	SE_{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 $\mathrm{UVC_{mp}}$ [€] = 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	$\mathrm{IL_{mp}} = \sum_s w_{\mathrm{mp}\,s} \times \mathrm{IL}_s/\mathrm{IL_{avg}}$ where : $w_{\mathrm{mp}\,s} = c_{\mathrm{mp}\,s}/(\mathrm{PE_{SS}}/N + \mathrm{UVC_{SS}})$ $c_{\mathrm{mp}\,s} = c_{\mathrm{mp}\,q}$ if $s = qc_{\mathrm{mp}\,s} = \mathrm{UVC_{mp}}$ if s = company $c_{\mathrm{mp}\,q} = \sum_i \sum_j \sum_p f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times C_{i,j,p,q}$ $\mathrm{UVC_{mp}} = \sum_i \sum_j \sum_p \sum_c \sum_y (1 - \sum_q f_{i,j,p,q}) \times f_i \times f_{i,j,p,c} \times f_y \times (V_{i,j} \times \rho_j)/(1 - \mathrm{WC}_{i,j,p,c})$ $\times\ \mathrm{KC}_{i,j,p} \times \mathrm{EC}_{y,c} + (\sum_{\mathrm{op}} \mathrm{WH_{mp\,op}} \times \mathrm{salary_{op}}/\mathrm{thw_{op}})/N$

(continued)

Table 3.45 (continued)

LC Phase	Data from design tools, data entry, and databases	Formula
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 $WC_{m,c}$ = 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 $WH_{\text{man op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$IL_{\text{man}} = \sum_s w_{\text{man } s} \times IL_s/IL_{\text{avg}}$ where : $w_{\text{man } s} = c_{\text{man } s}/(PE_{SS}/N + UVC_{SS})$ $c_{\text{man } s} = c_{\text{man } q}$ if $s = q$ $c_{\text{man } s} = UVC_{\text{man}}$ if $s =$ company $c_{\text{man } q} = \sum_i f_i \times f_{i,q} \times C_{i,q}$ $UVC_{\text{man}} = \sum_m \sum_c \sum_y f_{m,c} \times f_y \times [1/(1 - WC_{m,c})] \times CS_m \times KC_m \times EC_{y,c}$ $+ (\sum_{\text{op}} WH_{\text{man op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$
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 $WC_{o,c}$ = 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 $WH_{\text{as op}}$ [h/year] = hours worked in one year by the operator op carrying out operations m in the part manufacturing department of the company	$IL_{\text{as}} = \sum_s w_{\text{as } s} \times IL_s/IL_{\text{avg}}$ where : $w_{\text{as } s} = c_{\text{as } s}/(PE_{SS}/N + UVC_{SS})$ $c_{\text{as } s} = c_{\text{as } q}$ if $s = q$ $c_{\text{as } s} = UVC_{\text{as}}$ if $s =$ company $c_{\text{as } q} = \sum_a f_a \times f_{a,q} \times C_{a,q}$ $UVC_{\text{as}} = \sum_o \sum_c \sum_y f_{o,c} \times f_y \times [1/(1 - WC_{o,c})]$ $\times CS_o \times KC_o \times EC_{y,c} + (\sum_{\text{op}} WH_{\text{as op}} \times \text{salary}_{\text{op}}/\text{thw}_{\text{op}})/N$

(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 *k*th consumable $c_{k\ q}$ [€] = unitary cost of the *k*th consumable paid to *q* $\mathrm{UVC_{use}}$ [€] = unitary variable cost faced by the company for consumables production k = *k*th 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 *k*th consumable in the expected product mix $f_{k,j,q}$ = frequency of the material *j* for *k*th consumable component provided by the supplier *q* $V_{\mathrm{cons}\ k,j}$ [cm^3] = volume of the part of the *k*th 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 *k*th 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* $\mathrm{WH}_{\mathrm{mank\ op}}$ [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	$w_{EOL\ s}$ = weight of the supply chain member performing EOL of the product $c_{EOL\ s}$ [€] = unitary cost of the EOL treatments $c_{EOL\ q}$ [€] = unitary cost of the EOL treatments paid to q UVC_{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 $C_{EOL\ i,j,r}$ [€/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 $WC_{i,j,c}$ = waste coefficient when processing material j for the ith component in country c $KC_{i,j}$ [kWh/kg] = energy consumption per extracted kg of material j for the ith component $KC_{i,j,l}$ [kWh/kg] = energy consumption of the EOL treatment l carried out on material j for the ith component $WH_{EOL\ op}$ [h/year] = hours worked in one year by the operator op treating j in the EOL department of the company	$IL_{EOL} = \sum_s w_{EOL\ s} \times IL_s / IL_{avg}$ where : $w_{EOL\ s} = c_{EOL\ s} / (PE_{SS}/N + UVC_{SS})$ $c_{EOL\ s} = c_{EOL\ q}$ if $s = q$ $c_{EOL\ s} = UVC_{EOL}$ if s = company $c_{EOL\ q} = \sum_i \sum_j \sum_r f_i \times f_{i,j,r} \times V_{i,j} \times \rho_j \times C_{EOL\ i,j,r}$ $UVC_{EOL} = \sum_i \sum_j \sum_l \sum_c \sum_y (1 - \sum_q f_{i,j,q}) \times f_i \times f_{i,j,c} \times f_y$ $\times (V_{i,j} \times \rho_j) / (1 - WC_{i,j,c}) \times KC_{i,j,l} \times EC_{y,c} + (\sum_{op} WH_{EOL\ op} \times salary_{op} / thw_{op}) / N$

(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 = 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 [€]/IL_{avg} [€] = average income of the supply chain member's employees divided by average income of employees in the country where s is operating	$\chi_{LS\ q}$ = boolean that is equal to 1 if s uses child labor, 0 otherwise
IL_{ext}	LS_{ext}
$w_{ext\ s}$ = weight of the supply chain member performing material extraction	$w_{ext\ q}$ =weight of supplier q performing material extraction $\left(w_{ext\ q} = c_{ext\ q}/(PE_{SS}/N)\right)$
$c_{ext\ s}$ [€] = unitary cost of the extraction processes	$c_{ext\ q}$[€] =unitary cost of the extraction processes paid to q $\left(c_{ext\ q} = \sum_i \sum_j f_i \times f_{i,j,q} \times V_{i,j} \times \rho_j \times C_{i,j,q}\right)$
IL_{mp}	LS_{mp}
$w_{mp\ s}$ = weight of the supply chain member performing material processing	$w_{mp\ q}$ =weight of supplier q performing material processing $\left(w_{mp\ q} = c_{mp\ q}/(PE_{SS}/N)\right)$
$c_{mp\ s}$ [€] = unitary cost of the material processing processes	$c_{mp\ q}$[€] =unitary cost of the material processing processes paid to q $\left(c_{mp\ q} = \sum_i \sum_j \sum_p f_i \times f_{i,j,p,q} \times V_{i,j} \times \rho_j \times C_{i,j,p,q}\right)$
IL_{man}	LS_{man}
$w_{man\ s}$ = weight of the supply chain member providing components	$w_{man\ q}$ =weight of supplier q providing components $\left(w_{man\ q} = c_{man\ q}/(PE_{SS}/N)\right)$
$c_{man\ s}$ [€] = unitary cost of the ith component processes	$c_{man\ q}$[€] =unitary cost of the ith component processes paid to q $\left(c_{man\ q} = \sum_i f_i \times f_{i,q} \times C_{i,q}\right)$
IL_{as}	LS_{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 $\left(c_{\text{tra}\ t} = \sum_i \sum_j \sum_q \sum_z f_i \times f_{i,j,q} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{i,j,q,z} \times C_{\text{tra}\ i,j,t,z} + \sum_i \sum_j \sum_z f_i \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{cust}\ z} \times C_{\text{tra}\ i,j,t,z} + \sum_i \sum_j \sum_r \sum_z f_i \times f_{i,j,r} \times f_{i,j,t,z} \times V_{i,j} \times \rho_j \times d_{\text{EOL}\ r,z} \times C_{\text{tra}\ i,j,t,z}\right)$

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