# Chapter 2
# Selection of Impact Categories and Classification of LCI Results to Impact Categories

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**Abstract** This chapter concerns 'selection of impact categories' and 'assignment of LCI results to selected impact categories (classification)'. These elements are the first two mandatory elements of Life Cycle Impact Assessment (LCIA). They have largely been developed during the 1990s. In practice these mandatory steps are often performed using default lists of impact categories and default lists of inventory items classified to these default impact categories as part of LCA handbooks, guides and software tools. Despite these default lists, it is still important to pay sufficient attention to both these steps in any LCA case study. Every practitioner of LCA will always need to justify the completeness of default lists of impact categories and default classification lists for their study. In addition, the handling of missing information needs to be reported explicitly and transparently, and needs to be taken into consideration when developing conclusions and recommendations for the study at stake. After the 1990s, the attention to selection of impact categories and classification in LCA methodology studies and papers has been limited. Still, there are issues that deserve further attention from LCA method developers such as the harmonisation of naming impact categories while distinguishing or not between names for midpoint impact categories and names for endpoint category indicators, keeping default lists of impact categories manageable, and the classification of inventory results that relate to more than one impact category.

**Keywords** Assignment to impact categories • Classification • Impact categories • LCA • LCIA • Life cycle assessment • Life cycle impact assessment • Selection of impact categories

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# 1 Introduction

According to ISO 14040 (1997, 2006a), the first two mandatory elements of LCIA concern:

- selection of impact categories, category indicators and characterisation models;
- assignment of LCI results to the selected impact categories (classification);

The result of these two elements is that LCI results like resource uses and emissions are assigned to different impact categories such as for example acidification; see Fig. 2.1.

From the early 1980s until today, LCIA rapidly evolved from a simple first impact assessment method, where airborne and waterborne emissions were divided by semi-politically set limits for those emissions and aggregated into so-called critical volumes of air and critical volumes of water, to full-fledged fate-exposure-impact based assessment methods of today. The developments in the field of selection of impact categories and classification on the other hand were much less spectacular. In Sect. 2, we will first briefly discuss the history of these two mandatory elements. Subsequently, we will discuss the purpose of selection and classification (Sect. 3), the choice of impact categories (Sect. 4), how LCI results are assigned to impact categories (Sect. 5), and finally we will discuss some potential research needs and expected future developments (Sect. 6).

Similarities and differences between LCA handbooks, guides and other method proposals will be discussed within particularly Sects. 3, 4 and 5.

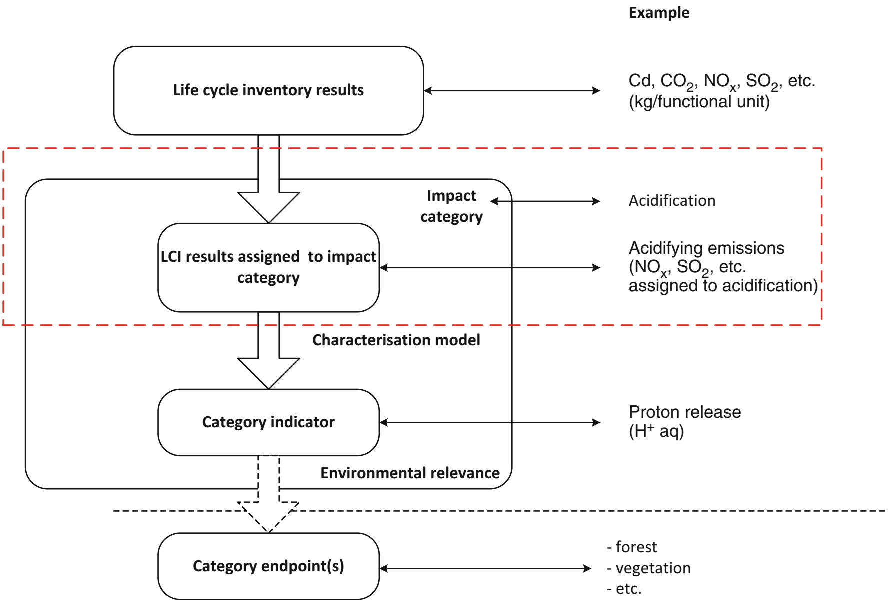


**Fig. 2.1** The conceptual framework for defining category indicators (Slightly adapted from: ISO 14042 2000)

## 2 History of Selection of Impact Categories and Classification

ISO does not provide explicit definitions for selection of impact categories and classification. One may say that for this, ISO built on the preparatory work done by Udo de Haes (1996) who wrote in his report that selection of impact categories addresses the topic of defining impact categories: "the types of impact of the given interventions (elementary flows) are identified and a number of relevant impact categories are defined which cover impacts as much as possible". According to Udo de Haes (1996) classification addresses "the assignment of the environmental interventions (LCI results) to the defined categories" and this is basically also the definition that ISO 14042 adopted implicitly (ISO 14042 2000).

Although the topics covered were the same, selection of impact categories and classification used to be referred to as just 'classification' in the 1990s. The first time the term 'classification' was introduced with this meaning was as part of the work on the first Dutch LCA Guide (Heijungs et al. 1992). They defined classification as "the third component of a life cycle assessment in which the contribution made by the environmental interventions to the potential environmental effects is determined through model-based calculations". Note that classification at that time thus included selection of impact categories and classification, but also selection of category indicators and characterisation models and the characterisation itself, although the terminology for all of these elements was also different at that time.

One of the first workshops on LCA was held in Leuven (de Smet 1990) in 1990 and shortly after LCA as a topic was embraced by the Society of Environmental Toxicology and Chemistry (SETAC). SETAC started playing a leading and coordinating role in bringing LCA practitioners, users and scientists together to collaborate on the continuous improvement and harmonisation of LCA framework, terminology and methodology and a first workshop on LCA was held in Leiden, The Netherlands in 1992 (Anonymous 1992a). The workshop agreed to a three-step approach to the Classification phase: "(1) a classification based on main processes of the relevant effect chains, (2) the definition of units to measure these classes of effects and (3) an aggregation of the effects in terms of these units" (Udo de Haes 1992; Guinée 1992). Also as part of this workshop both Guinée (1992) and Baumann et al. (1992) proposed a list of environmental problems or environmental effects (later on referred to as 'impact categories'), which at the workshop were merged into a first common list of 'headings for classification' (impact categories; Udo de Haes 1992). This first common list was largely (with minor adaptations) adopted in the LCA Guide by Heijungs et al. (1992) and a short list was adopted in the LCA book of the Nordic Council (Anonymous 1992b) later on.

Shortly after the SETAC-Europe Leiden workshop, SETAC-US organised a similar exercise at the SETAC Sandestin workshop Florida in 1992 (Fava et al. 1993). The Sandestin workshop participants adopted the three-step approach to classification as agreed upon in the Leiden workshop, but proposed different names for these steps (classification, characterisation and valuation) and a new name for the Classification phase: Life Cycle Impact Assessment. This workshop also introduced the term ‘stressor’, i.e. sets of conditions that may lead to human health, ecological and resource depletion impacts. In addition the workshop introduced the term ‘impact categories’ but it referred to what was later called ‘areas of protection’: ecological health, human health, resource depletion and social welfare. Main question then was how this division was related to the common list of ‘headings for classification’ discussed during the Leiden workshop (Udo de Haes 1992).

In 1993, the SETAC Code of Practice (CoP, Consoli et al. 1993) combined the results from the Sandestin and Leiden workshops. One of the main aims of the CoP was to define a common methodological framework in order to streamline further methodological discussions and progress. The CoP adopted the Sandestin term ‘Life Cycle Impact Assessment’ (LCIA) for this phase of LCA and the Sandestin terms for its three steps: classification, characterisation and valuation. The other problem that had to be solved in the Code of Practice was the apparent contrast between the protection areas of the Sandestin workshop 1992 (Fava et al. 1993) and the common list of ‘headings for classification’ discussed during the Leiden workshop (Udo de Haes 1992). The CoP concluded that this was indeed an apparent contrast and not a principal one. Integration of protection areas and ‘headings for classification’ seemed possible by defining a matrix with one axis representing the protection areas and the other axis representing the impact categories (see Table 2.1). Note that in the CoP in this way the definition of impact categories as adopted by the participants of the Sandestin workshop was changed into ‘general areas of protection’, and that the Leiden ‘headings of classification’ was changed into ‘impact categories’. A default list of relevant impact categories for LCA studies was not drafted in the CoP. Last but not least, the CoP also provided a

**Table 2.1** Relationship between general areas of protection and specific impact categories

| Specific impact categories (examples) | General areas of protection | | |
|---|---|---|---|
| | Resource | Human health | Ecological health |
| *Resource depletion* | | | |
| Depletion of abiotic resources | + | | |
| Depletion of biotic resources | + | | |
| *Pollution* | | | |
| Global warming | | (+) | + |
| Ozone depletion | | (+) | (+) |
| Human toxicity | | + | |
| Ecotoxicity | | (+) | + |
| Photochemical oxidant formation | | + | + |
| Acidification | | (+) | + |
| Eutrophication | | | + |
| *Degradation of ecosystems and landscape* | | | |
| Land use | | | + |

From Consoli et al. (1993)

slightly modified definition for the classification step: "the classification is the step in which the data from the inventory analysis [...] are grouped together into a number of impact categories".

Developments, of course, continued after the CoP, but changes to the CoP remained marginal until 1996. As mentioned above, Udo de Haes (1996) distinguished for the first time between selection of impact categories and classification and this was then adopted by ISO 14040–14044 (2006a, b) series of LCA Standards. The ISO Standards provided the requirements for these two steps, and these were copied into most LCA handbooks and guides afterwards without any significant modifications.

ISO describes procedures rather than specific default lists, methodologies or models for LCIA, implying that any impact category, methodology or model is acceptable as long as it satisfies the general ISO criteria. This left sufficient space for further elaboration of particularly two main topics related to 'selection of impact categories' and 'classification':

- The choice of impact categories including
  - the way of defining relevant impact categories for an LCA study: should we do that case by case or should we aim for a default list of impact categories that is basically valid for all LCA studies?
  - the difference between midpoint and endpoint approaches.
- The assignment of LCI results to impact categories including topics as
  - what to do with inventory results that cannot be assigned (yet) to impact categories, and
  - how to handle inventory results that relate to more than one impact category.

These topics will be further discussed in Sects. 4 and 5, respectively. First we will briefly discuss the purpose of selection of impact categories.

## 3 The Purpose of Selection of Impact Categories and Classification

In the impact assessment phase the results of the inventory analysis are transposed into contributions to relevant impact categories. To this end, relevant impact categories must be identified. This can be done case by case or can be facilitated by defining a default list of impact categories, with a possible distinction between 'baseline' impact categories, 'study-specific' impact categories and 'other' impact categories. The purpose of the ISO-element 'Selection of impact categories' is to compel LCA practitioners to explicitly select those categories relevant to the goal of their particular study. LCA practitioners generally do this, mostly as part of the Goal and Scope definition.

In the classification, the inventory results are assigned on a purely qualitative basis to the various pre-selected impact categories. Again, this can be done on a case by case basis or can be facilitated by defining a default list of elementary flows, for which characterisation factors have previously been derived. The classification step then involves no actual work as these elementary flows have already been assigned to the various impact categories. In the case of other elementary flows the practitioner will have to adopt an appropriate procedure of his own. The purpose of the ISO-element 'Classification' is to compel LCA practitioners to explicitly assign inventory results to impact categories. For some impact categories with a limited number of contributing flows, such as global warming/climate change, stratospheric ozone depletion, acidification and eutrophication, assigning inventory results to impact categories has in practice been solved. For other impact categories with a huge number of contributing flows, such as the toxicity-related impact categories, the task remains with the practitioner to assign the relevant flows to these categories, which in practice is often not explicitly or appropriately done.

Selection of impact categories and classification are mandatory elements of LCIA, which force the practitioner to make explicit choices on impact categories considered and not considered and on inventory results assigned and not assigned.

## 4 Selection of Impact Categories

According to ISO 14044 (2006b), the necessary 'selection of impact categories' components for each impact category includes:

- identification of the category endpoint(s),
- identification of appropriate LCI results that can be assigned to the impact category, taking into account the chosen category indicator and identified category endpoint(s)

ISO 14044 (2006b) states that this procedure "facilitates the collection, assignment, and modelling of appropriate LCI results" and "helps to highlight the scientific and technical validity, assumptions, value-choices and degree of accuracy in the model". It further states that "the category indicator can be chosen anywhere along the environmental mechanism between the LCI results and the category endpoint(s)".

With respect to the selection of impact categories, ISO defined the following requirements:[1]

- the selection of impact categories [. . .] shall be consistent with the goal and scope of the LCA study;
- the sources for impact categories [. . .] shall be referenced;

[1] Text referring to selection of category indicators and models has been left out of the requirements (indicated as [. . .]) as this Chapter does not deal with these topics.

- the selection of impact categories [...] shall be justified;
- accurate and descriptive names shall be provided for the impact categories [...];
- the selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied taking the goal and scope into consideration.

In addition a number of recommendations is given for the selection of impact categories, indicators and models:

- the impact categories [...] should be internationally accepted i.e. based on an international agreement or approved by an international body;
- the impact categories should represent the aggregated emissions or resource use of the product system on the category endpoint(s) through the indicators;
- value-choices and assumptions made during the selection of impact categories [...] should be minimised;
- the impact categories [...] should avoid double counting unless required by the Goal and scope definition, for example when the study includes both human health and carcinogenicity.

Based on these ISO requirements and recommendations developers of LCA handbooks, guides and LCIA methods have come up with proposals for impact categories and have elaborated default lists of impact categories. There are hardly any institutes or practitioner(s) that develop impact categories on a case by case basis. Below, we will first discuss different ways of defining impact categories (e.g., midpoint and endpoint approaches) and then discuss different defaults lists proposed for midpoint and for endpoint approaches.

## *4.1 Different Ways of Defining Impact Categories*

Based on ISO, a "category indicator can be chosen anywhere along the environmental mechanism between the LCI results and the category endpoint(s)". It is striking that ISO doesn't mention that the impact category can also be selected anywhere along the environmental mechanism between the LCI results and the category endpoint(s), as long as it is consistently chosen in relation to the corresponding category indicator(s). This has caused some confusion as from the ISO Standards one could read that names and definitions of impact categories remain the same, while category indicators can be different and also defined at different point along the environmental mechanism. A number of method-developers and practitioners have done otherwise and differentiated between midpoint impact categories (global warming, acidification, eutrophication, ozone layer depletion, etc.) and endpoint category indicators (for example, damage to human health, damage to ecosystem quality and loss of resources; endpoint impact categories are often formulated in terms of 'damage to' protection areas with all possible related confusion (Klöpffer and Grahl 2009, 2014)); the UNEP-SETAC group on LCIA even provided separate definitions for 'midpoint impact category' and 'damage impact category' (Jolliet et al. 2003a). Others have held on to the ISO-line of

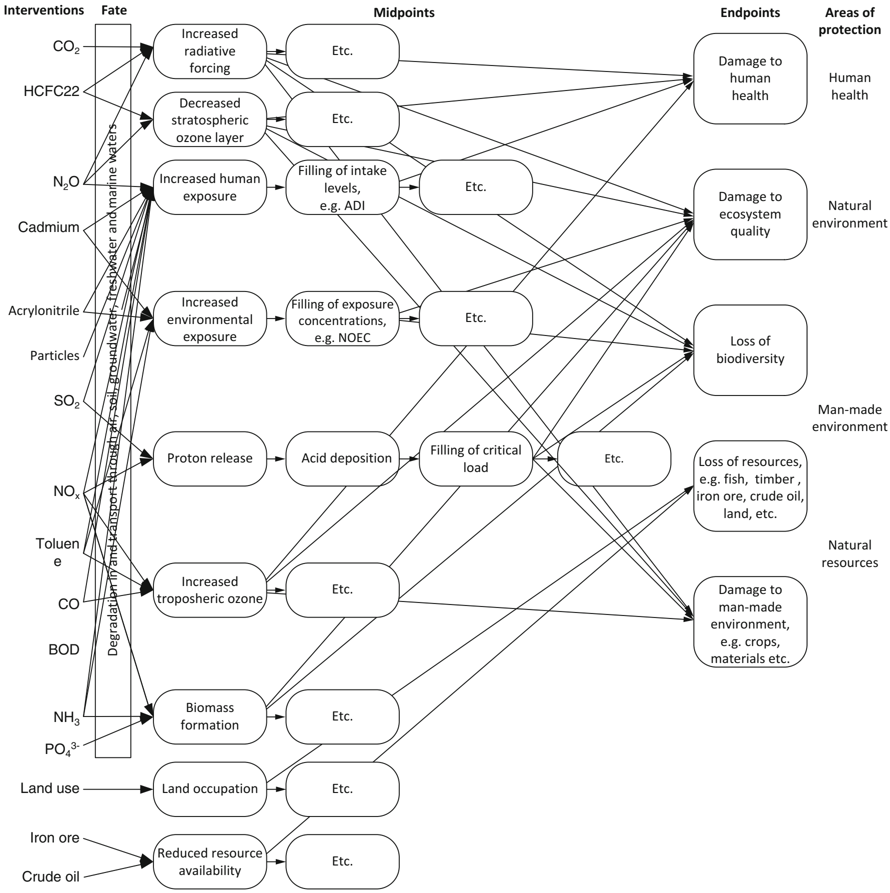


**Fig. 2.2** Overview of the causal relationships between elementary flows (environmental interventions), midpoints and (category) endpoints (Freely adapted from figure presented by Udo de Haes et al. 1999)

thinking and adopted equal impact category names for both midpoint and endpoint indicator approaches (e.g., Itsubo and Inaba 2012).

One of the major characteristics of impact assessment methods is thus the point in the environmental mechanism at which the category indicators defined. As illustrated by Fig. 2.2, they may be defined close to the elementary flow or intervention (the midpoint, or problem-oriented approach, e.g. Heijungs et al. 1992; Udo de Haes 1996; Wenzel et al. 1997; Hauschild and Wenzel 1998; Udo de Haes et al. 1999; Jolliet et al. 2003b; Guinée et al. 2002; Hauschild and Potting 2005; Toffoletto et al. 2007; Frischknecht et al. 2009; Bare 2011; EC-JRC 2011; Goedkoop et al. 2012). The guiding principle in defining midpoint impact categories to that the midpoint should (ideally) be selected at the earliest point in the impact pathway beyond which the environmental processes are the same for all substances classified to that impact category (EC-JRC 2011; Goedkoop et al. 2012; Hauschild et al. 2013). Alternatively, they may be defined at the level of category endpoints (the endpoint, or damage approach, e.g. Steen 1999a, b; Goedkoop and Spriensma 2000; Itsubo and Inaba 2012). A cluster of category endpoints of recognisable value to society is referred to as an 'area of protection', for example human health, natural resources, the natural environment and the man-made environment. Different definitions of areas of protection exist (cf. Udo de Haes et al. 1999, Steen 1999a, b).

The result of the distinction between midpoint and damage or endpoint approaches is that there are default lists of midpoint impact categories and default lists of damage or endpoint impact categories. These different lists will be discussed below.

## *4.2 Default List of Impact Categories*

In order to facilitate the LCA practitioner's work with easy-to-apply LCIA methods, several authors have developed default lists of impact categories, often supported by default classification lists (see Sect. 5.1). The definition of impact categories can – as also illustrated by Fig. 2.2 – be done in several ways either or not representing a specific midpoint or endpoint modelled. Several authors have developed different default lists of impact categories, of which a selection is presented in Table 2.2.

Table 2.2 shows that the diversity and overlap in impact categories among different methods is huge (Klöpffer and Grahl 2009, 2014). Sometimes it is merely a matter of semantics and the differences are likely to be minor, although that cannot be definitely concluded from the name of the impact category alone. For that, we need a more detailed description of, for example, the inventory items included and excluded. Sometimes differences are much more fundamental. For example, the way that EPS2000 (Steen 1999a, b) defines midpoint impact categories is fundamentally different from the way that Guinée et al. (2002), Hauschild and Potting (2005) and Bare (2011) have done. EPS2000 basically is an endpoint-approach and derives midpoint impact categories from endpoints. Guinée et al. (2002), Hauschild and Potting (2005) and Bare (2011) define midpoint impact categories basically from problem-oriented cross-media approach adopting environmental themes as defined in environmental policy (Anonymous 1992a). Despite the ISO-recommendation to minimise value-choices and assumptions during the selection of impact categories, the selection and definition of relevant problem fields is highly value-laden (Steen 1999a, b) as is also shown by Udo de Haes (1992): "A related question was which problem fields should be taken into account: which problems are to be regarded as environmental problems? [...] Thus, product safety was considered to be outside the scope of LCA. The opinions differed about occupational health [...]." Such normative discussion will continue and therefore 'default lists' may always change again, if it is only for the fact that new insight and problems may rise. Sometimes the differences are subtle but not futile, like in the case for resources where some approaches adopt just one category for abiotic

**Table 2.2** Default lists of midpoint impact categories

| Midpoint categories | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Abiotic resource depletion | | | | | | | | X | | | |
| 2. Depletion of abiotic resources | | | | X | | | | | | | X |
| 3. Depletion of biotic resources | | | | X | | | | | | | |
| 4. Depletion of element reserves (element) | | | | | | X | | | | | |
| 5. Depletion of fossil reserves (coal) | | | | | | X | | | | | |
| 6. Depletion of fossil reserves (gas) | | | | | | X | | | | | |
| 7. Depletion of fossil reserves (oil) | | | | | | X | | | | | |
| 8. Depletion of mineral reserves (ore) | | | | | | X | | | | | |
| 9. Mineral extraction | X | | | | | | | | | | |
| 10. Mineral resources consumption | | | | | | | X | | | | |
| 11. Gravel | | | | | | | | | X | | |
| 12. Energy resources | | | | | | | | | X | | |
| 13. Non-renewable energy | X | | | | | | | | | | |
| 14. Fossil fuel consumption | | | | | | | X | | | | |
| 15. Fossil fuel depletion | | | | | | | | | | X | |
| 16. Resource depletion, water | | | | | | | | | | | X |
| 17. Resources | | | | | | | | | X | | |
| 18. Fish and meat production capacity | | | | | | X | | | | | |
| 19. Crop production capacity | | | | | | X | | | | | |
| 20. Wood production capacity | | | | | | X | | | | | |
| 21. Forest resources consumption | | | | | | | X | | | | |
| 22. Freshwater | | | | | | | | | X | | |
| 23. Land competition | | | | X | | | | | | | |
| 24. Land occupation | X | | | | | | | | | | |
| 25. Agricultural land occupation | | X | | | | | | | | | |
| 26. Natural land transformation | | X | | | | | | | | | |
| 27. Rural land occupation | | X | | | | | | | | | |
| 28. Land use | | | | | | | X | X | X | | X |
| 29. Impacts of land use | | | | X | | | | | | | |
| 30. Share of species extinction [NEX] | | | | | | X | | | | | |
| 31. Loss of biodiversity | | | | X | | | | | | | |
| 32. Loss of life support functions | | | | X | | | | | | | |
| 33. Global warming/climate change | X | X | | X | X | | X | X | X | X | X |
| 34. (Stratospheric) ozone (layer) depletion (destruction) | X | X | | X | X | | X | X | X | X | X |
| 35. Photochemical oxidation (formation)/photochemical ozone formation/photochemical smog (formation) | X | X | | X | X | | X | X | | X | X |
| 36. Volatile organic compounds (NMVOCs) | | | | | | | | | X | | |
| 37. Acidification | | | | X | X | | X | X | X | X | X |

(continued)

**Table 2.2** (continued)

| Midpoint categories | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 38. Base cation capacity [$H^+$] | | | | | | X | | | | | |
| 39. Terrestrial acidification/ nutrification | X | X | | | | | | | | | |
| 40. Eutrophication | | | | X | | | X | | | X | |
| 41. Eutrophication, aquatic | | | | | | | | | | | X |
| 42. Aquatic eutrophication/freshwater eutrophication | X | X | | | X | | | X | | | |
| 43. Terrestrial eutrophication | | | | | X | | | X | | | X |
| 44. Marine eutrophication | | X | | | | | | | | | |
| 45. Nitrogen (nitrate) | | | | | | | | | X | | |
| 46. Freshwater aquatic ecotoxicity | | | | X | | | | | | | X |
| 47. Groundwater emissions | | | | | | | | | X | | |
| 48. Hazardous wastes in underground landfills | | | | | | | | | X | | |
| 49. Heavy metals | | | | | | | | | X | | |
| 50. Human health cancer | | | | | | | | | | X | |
| 51. Human health criteria pollutants | | | | | | | | | | X | |
| 52. Human health non-cancer | | | | | | | | | | X | |
| 53. Human toxicity | X | X | | X | X | | X | X | | | |
| 54. Human toxicity cancer | | | | | | | | | | | X |
| 55. Human toxicity non-cancer | | | | | | | | | | | X |
| 56. Particulate matter formation | | X | | | | | | | | | |
| 57. Particulate matter/respiratory inorganics | | | | | | | | | | | X |
| 58. PM10 and diesel soot | | | | | | | | | X | | |
| 59. Respiratory effects | X | | | | | | | X | | | |
| 60. Life expectancy | | | | | | X | | | | | |
| 61. Endocrine disruptors | | | | | | | | | X | | |
| 62. Soil emissions | | | | | | | | | X | | |
| 63. Surface water emissions | | | | | | | | | X | | |
| 64. Urban area air pollution | | | | | | | X | | | | |
| 65. Indoor air contamination | | | | | | | X | | | | |
| 66. Impacts of ionising radiation | | | | X | | | | | | | |
| 67. Ionising radiation, ecosystems | | | | | | | | | | | X |
| 68. Ionising radiation, human health | | | | | | | | | | | X |
| 69. Ionizing radiation | X | X | | | | | | | | | |
| 70. Aquatic ecotoxicity/freshwater ecotoxicity | X | X | | | | | | | | | |
| 71. Ecotoxicity (aquatic and terrestrial) | | | | X | X | | X | X | | X | |
| 72. Freshwater sediment ecotoxicity | | | | X | | | | | | | |
| 73. Terrestrial ecotoxicity | X | X | | X | | | | | | | |
| 74. Marine ecotoxicity | | X | | X | | | | | | | |

(continued)

**Table 2.2** (continued)

| Midpoint categories | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 75. Marine sediment ecotoxicity | | | | X | | | | | | | |
| 76. Malodourous air | | | | X | | | | | | | |
| 77. Malodourous water | | | | X | | | | | | | |
| 78. Carbon in bio-reactive landfills | | | | | | | | | X | | |
| 79. Casualties | | | | X | | | | | | | |
| 80. Desiccation | | | | X | | | | | | | |
| 81. Noise | | | | X | X | | X | | X | | |
| 82. Plant protection products | | | | | | | | | X | | |
| 83. Production capacity for water (drinking water) | | | | | | X | | | | | |
| 84. Radioactive | | | | | | | | | X | | |
| 85. Radioactive wastes in final repositories | | | | | | | | | X | | |
| 86. Waste(s) | | | | | | | X | | X | | |
| 87. Morbidity | | | | | | X | | | | | |
| 88. Severe morbidity and suffering | | | | | | X | | | | | |
| 89. Nuisance | | | | | | X | | | | | |
| 90. Severe nuisance | | | | | | X | | | | | |
| 91. Waste heat | | | | X | | | | | | | |

*1* IMPACT2002+ (Jolliet et al. 2003b), *2* ReCiPe (Goedkoop et al. 2012), *3* EI99 (Goedkoop and Spriensma 2000), *4* CML 2002 (Guinée et al. 2002), *5* EDIP 2003 (Hauschild and Potting 2005), *6* EPS 2000 (Steen 1999a, b), *7* LIME2 (Itsubo and Inaba 2012), *8* LUCAS (Toffoletto et al. 2007), *9* Swiss Ecoscarcity 2006 (Frischknecht et al. 2009), *10* TRACI 2.0 (Bare 2011), *11* ILCD (EC-JRC 2011)

resources and other define categories for subclasses of abiotic resources including fossil fuels or different fossil fuels and minerals.

As a sort of reaction to and supplement of default lists of impact categories, several proposals for new impact categories have been published. These new proposals often address specific sectors of LCA studies. For example, in aquaculture and fisheries LCA studies, proposals for the following impact categories have been drafted over the past 10 years: biotic resource use (Papatryphon et al. 2004; Pelletier et al. 2007); water dependency (Aubin et al. 2009; d'Orbcastel et al. 2009); the area altered by farm waste, changes in nutrient concentration in the water column, the percentage of carrying capacity reached, the percentage of total anthropogenic nutrient release, release of wastes into freshwater, the number of escaped salmon, the number of reported disease outbreaks, parasite abundance on farms, and the percentage reduction in wild salmon survival (Ford et al. 2012). These proposals are often made by sector-experts who have very good and specific knowledge of their field and aim for better and more site-specific impact assessments requiring additional site-specific data. As a consequence, the methods proposed are generally not applicable or feasible for the average LCA case study.

**Table 2.3** Default lists of damage or endpoint impact categories

| Damage or endpoint categories | 1 | 3 | 6 | 7 |
|---|---|---|---|---|
| 1. (Damage to) human health | X | X | X | |
| 2. (Damage to) ecosystem quality | X | X | | |
| 3. Climate change (life support systems) | X | | | |
| 4. Resources | X | X | X | |
| 5. Ecosystem production | | | X | |
| 6. Biodiversity | | | X | |
| 7. Urban area air pollution | | | | X |
| 8. Global warming | | | | X |
| 9. Ozone layer destruction | | | | X |
| 10. Toxic chemicals (human toxicity) | | | | X |
| 11. Biological toxicity (ecotoxicity) | | | | X |
| 12. Acidification | | | | X |
| 13. Eutrophication | | | | X |
| 14. Photochemical oxidant | | | | X |
| 15. Land use | | | | X |
| 16. Mineral resources consumption | | | | X |
| 17. Fossil fuel consumption | | | | X |
| 18. Forest resources consumption | | | | X |
| 19. Indoor air contamination | | | | X |
| 20. Noise | | | | X |
| 21. Waste | | | | X |

*1* IMPACT2002+ (Jolliet et al. 2003b), *3* EI99 (Goedkoop and Spriensma 2000), *6* EPS 2000 (Steen 1999a, b), *7* LIME2 (Itsubo and Inaba 2012)

Different default lists of impact categories have also been developed for damage or endpoint approaches and these are shown in Table 2.3.

Table 2.3 shows that the diversity in damage or endpoint impact categories among different methods is significant but not as huge as for midpoint impact categories. The differences are actually dominated by the approach taken in LIME. LIME chose to use the same names for midpoint and endpoint impact categories elaborating different indicators for each of them, which results in two similar lists of LIME impact categories in Tables 2.2 and 2.3.

Bare and Gloria (2008) observed that there is a need to discuss the range of impacts which could and should be included. In their paper, they present a meta-model to facilitate an expanded discussion of the taxonomy of impact, impact category, midpoint, endpoint, damage, etc. Their taxonomy meta-model includes the existing impacts found in LCIA literature, and then expands to be more comprehensive and includes a larger set of impacts than are normally included within LCIA. The taxonomy meta-model represents a first attempt to facilitate a standard vocabulary and structure in the field of LCA impact category discussions, and is to help ensure that the selection of impact categories is truly comprehensive.

## 5 Assignment of LCI Results to Impact Categories (Classification)

In the classification, the inventory results (elementary flows including resource uses, land uses, and all kind of chemical emissions) are assigned on a purely qualitative basis to the various selected impact categories. When working with a default list of elementary flows, for which characterisation factors have previously been derived, the actual work to be done by an LCA-practitioner as part of the classification step is significantly reduced. All inventory results have then – as far as scientific knowledge and data allows so – been pre-classified to pre-selected impact categories. Several LCA handbooks, guides and software tools listed above provide such default lists. For generally acknowledged and well-defined impact categories with a limited number of contributing flows, such as global warming/climate change, stratospheric ozone depletion, acidification and eutrophication, the default classification lists are highly similar between different LCIA methods. This may be different for other impact categories. Particularly for human and ecotoxicity related impact categories the coverage of chemicals not only differs significantly between methods, but is by definition far from complete as there are more than 100,000 different substances known on the so-called EINECS (**E**uropean **IN**ventory of **E**xisting **C**ommercial chemical **S**ubstances) list. Hauschild and Wenzel (1998) developed a screening tool supporting the classification of substances contributing to human or ecotoxicity. Based on some key characteristics of a substance, it is considered potentially toxic or not and is classified as such.

Despite default classification lists, there is always some work left for the LCA practitioner in the classification step. For example, for inventory results for which no pre-classification for any of the pre-selected impact categories is available, the practitioner will have to adopt an appropriate procedure of his own. Either the practitioner then develops additional characterisation factors for elementary flows for which characterisation factors are lacking and for which certain impacts are known, or inputs and outputs with lacking characterisation factors are reported separately from the characterisation results.

With respect to classification, ISO defined the following recommendations:

- Assignment of LCI results to impact categories should consider the following, unless otherwise required by the goal and scope:
  - assignment of LCI results that are exclusive to one impact category;
  - identification of LCI results that relate to more than one impact category, including
    - distinction between parallel mechanisms (e.g. $SO_2$ is apportioned between the impact categories of human health and acidification), and
    - assignment to serial mechanisms (e.g. $NO_x$ can be classified to contribute to both ground-level ozone formation and acidification).

The second point is about how to handle LCI results that relate to more than one impact category and this topic will be discussed below separately first (Sect. 5.1). Subsequently, we will discuss the handling of elementary flows for which impact categories/characterisation factors are lacking (Sect. 5.2), for which ISO also provides guidance. Finally we will discuss how to handle missing information.

The ILCD handbook (EC-JRC 2010) adds to this by stating that "the practitioner is [. . .] responsible to ensure that the inventory elementary flows are correctly linked with the LCIA factors [. . .] and [. . .] to derive or develop missing impact factors if potentially relevant for the study". The ILCD handbook also explicitly mentions the fact that LCA practitioners are responsible for checking the completeness of default classification lists for their study, particularly for 'newly created or imported elementary flows' (i.e., elementary flows that were not on the default classification list and newly created by a practitioner or imported from another database, etc.). The ILCD handbook concludes that "it is one of the most widely found errors to not classify and characterise newly introduced flows despite of their environmental relevance".

## *5.1 Identification of LCI Results That Relate to More Than One Impact Category*

Guinée (1995), Lindfors et al. (1995), Udo de Haes (1996) and Wenzel et al. (1997) discuss the topic of inventory results that relate to more than one impact category. They conclude that this topic mainly relates to multiple impacts of chemical releases and together they distinguish the following four categories of emissions (Guinée et al. 2002):

- Emissions with parallel impacts, i.e. emissions of substances that may theoretically contribute to more than one impact category but in practice only to one, e.g. an emission of $SO_2$ which may have either toxic or acidifying impacts.
- Emissions with serial impacts, i.e. emissions of substances that may in practice have successive impacts, e.g. emissions of heavy metals which may first have eco-toxicological impacts and subsequently, via food chains, impacts on human health.
- Emissions with indirect impacts, i.e. emissions of substances having a primary impact that in turn leads to one or more secondary impacts, e.g. aluminium toxicity induced by acidification, or methane contributing to photo-oxidant formation, with the produced ozone contributing in turn to climate change, which in turn may contribute to stratospheric ozone depletion.
- Emissions with combined impacts, i.e. emissions of substances having a mutual influence on each other's impacts, e.g. synergistic or antagonistic impacts of toxic substance mixes, or $NO_x$ and VOC, both of which are required for photo-oxidant formation.

In order to avoid double counting, for emissions having parallel impacts, it is generally recommended in the literature that the respective contributions of such emissions to relevant impact categories be specified. However, no guidelines are available on how this task is to be performed. In general, such specification should be performed only in those cases where it really matters (where the contribution of the substance to one impact category substantially lessens its potential contribution to another, e.g. acidification or eutrophication by $NH_3$. Rough calculations show that $SO_2$, for example, is less relevant in this respect; see Heijungs et al. 1992). If it is unclear how such emissions are to be allocated, they are often assigned in their entirety to all relevant impact categories.

For emissions having serial and indirect impacts the literature generally recommends allocating such emissions in their entirety to all relevant (i.e. serial and indirect) impact categories unless characterisation factors for this purpose are lacking, as in the case of missing (indirect) GWP factors.

For emissions having combined impacts the literature generally recommends introducing assumptions regarding background concentrations of the other relevant substances. In practice this is currently only feasible for $NO_x$ as a precursor in photo-oxidant formation, but not for synergistic or antagonistic impacts of toxic substance mixes, as knowledge on these issues is virtually entirely lacking.

Recently Ventura (2011) proposed two new approaches for classification and handling of inventory results that relate to more than one impact category: equiprobable classification and zone classification. Equiprobable classification is not entirely new since Guinée et al. (2002) already proposed it as one way of handling parallel impacts. Ventura (2011), however, also applies this principle to indirect impacts. The approach aims at avoiding double counting of impacts by simply equally dividing inventory results over all impact categories that they could potentially contribute to. Zone classification is a new approach and is based on two steps: (1) defining an impacted zone around the source, inside which the emitted chemicals are expected to majorly diffuse or spread, and (2) scoring the chemical to the occurrence of the chemical target inside the impacted zone (Ventura 2011). The zone classification approach has been applied to one process, which is not an LCA, and needs site-specific spatial data that are not available from general LCA databases. This approach is clearly not applicable for generic LCAs, and its feasibility in terms of data needs and if it works with functional unit based full LCAs will need to be tested further.

There has been notably little attention for this topic for the last decade or more (Reap et al. 2008) except for the proposals by Ventura (2011). This is due to the complexity of the problems involved including spatial and temporal dimensions of inventory results that are hard to cover in sufficient detail within LC(I)A. Depending on what is considered the prime purpose of LCA, this may be or may not be experienced as a problem. For example, if LCA is considered merely an encompassing systems analysis of environmental mass loadings (and not concentrations) based on the 'precautionary principle', the lack of progress – if possible at all – may not be considered that problematic.

## 5.2 Handling Missing Information

Finally, we discuss the issue of missing data or missing knowledge. In clause 4.4.2.5 ISO states that "After characterisation and before the optional elements described in 4.4.3, the inputs and outputs of the product system are represented, for example, by

- a discrete compilation of the LCIA category indicator results for the different impact categories referred to as an LCIA profile,
- a set of inventory results that are elementary flows but have not been assigned to impact categories e.g. due to lack of environmental relevance, and
- a set of data that does not represent elementary flows."

This implies that ISO requires inventory results that cannot be assigned to impact categories and data that do not represent elementary flows to be reported separately.

The main problem with missing information in the LCIA phase is that data are aggregated, reducing the number of data entries, but that data that are left out of this aggregation because of missing data or knowledge 'disappear' or 'get lost'.

The main problems in terms of missing information for the 'Selection of impact categories' and 'Classification of LCI results' steps concern:

- inventory results that cannot be assigned to an impact category;
- flows that are not specified in terms of environmental interventions, like energy, metals or solid waste.

The basic strategy is 'reporting'. Inventory results that cannot be assigned to an impact category but are assumed to be environmentally relevant, should be reported – in line with ISO clause 4.4.2.5 – separately (e.g. as 'missing important'; EC-JRC 2011), in addition to the LCIA category indicator results. Inventory results anticipated to be environmentally irrelevant may be excluded from the LCIA category indicator results, but this should be transparently justified in the LCA study report at stake, e.g. as 'missing unimportant' (EC-JRC 2010; Guinée et al. 2002).

Preferably, every effort should be made to avoid flows that are not specified in terms of environmental interventions. If that is not feasible, it again comes down to proper reporting. For example, all flows that cannot be specified in terms of elementary flows, should then be listed in a separate category including a qualitative (e.g. 'hazardous waste' and 'non-hazardous waste') and, wherever possible, quantitative (e.g. input of $10^{-12}$ truck) description (Guinée et al. 2002; EC-JRC 2011).

## 6 Conclusions and Research Recommendations

Selection of impact categories and classification are the first two mandatory steps of LCIA according to ISO. In practice these mandatory steps are implemented in default lists of impact categories and default lists of inventory items classified to the default impact categories, either as part of LCA handbooks, guides or software tools. These two steps have not always received proper attention in LCA case studies and also in LCA methodology studies or papers over the last decades.

For LCA case studies it is important to pay sufficient attention to both these steps. The selection of impact categories is often already made as part of the Goal and Scope definition. The selection of impact categories should basically be as comprehensive as needed for the specific goal of the study. As LCA is essentially a method looking at all possible impacts, LCA studies should preferably cover all relevant environmental issues related to the analysed (product or service) system, unless a limitation was set in the goal definition as e.g. in the case of Carbon footprint studies, where exclusively Climate change relevant interventions are considered (EC-JRC 2010). One may argue that such limitations violate the ISO requirement that “the selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied taking the goal and scope into consideration”. However, since this ISO requirement exists of two parts that basically contradict each other, the argument may easily be refuted again. Most importantly, the initial exclusion of relevant impacts needs to be clearly documented and considered in the interpretation of the results, potentially limiting conclusions and recommendations of the study (EC-JRC 2010). Proper attention to classification in LCA case studies is also essential. LCA practitioners are responsible for checking the completeness of default classification lists for their study, and particularly the handling of missing information needs to be reported explicitly and transparently, and needs to be taken into consideration when defining conclusions and recommendations for the study at stake.

After the 1990s, the attention to selection of impact categories and classification in LCA methodology studies and papers has focused on several proposals for new impact categories and one proposal for classification of inventory results that relate to more than one impact category. Still, there are some issues that deserve attention from LCA method developers.

The first issue concerns the harmonisation in terms of naming impact categories. As shown in Table 2.2, there are various different names for seemingly similar impact categories, which is rather confusing. It could be very helpful to harmonise naming of impact categories that address the same endpoint(s) and inventory results (see, for example, the taxonomy proposals by Bare and Gloria (2008)). A minor issue of attention in this harmonisation process might be the way impact categories are named in general. Some are named quite ‘negative’ like ozone layer destruction, loss of biodiversity or respiratory diseases, while others are named more ‘positive’ like damage to human health, particulate matter formation or life expectancy.

The second issue is that considering the continuous flow of proposals for new impact categories, default lists of impact categories can potentially explode. As these new proposals often address specific sectors of LCA studies, it might be useful to distinguish between different types of default lists. For example, a default list of baseline midpoint impact categories could include categories as depletion of fossil resources, depletion of mineral resources, climate change, etc., while on top of this baseline default list a default list of aquaculture and fisheries midpoint impact categories could include biotic resource use, water dependency, the area altered by farm waste, etc., for specific aquaculture and fisheries LCA case studies.

The third issue concerns the classification of inventory results that relate to more than one impact category. As discussed above, it is arguable whether this is really a problem or not for LCA. However, if there were one, all-encompassing fate and exposure model available covering all impact categories, rather than the diversity of models used for the various impact categories today, parallel impacts would no longer constitute a problem. Current fate and exposure models specify the compartment (or target organism) in which the substance has its principal impact and which impact categories are thus potentially relevant (e.g. emissions to the air may end up in soil or water, with consequent terrestrial or aquatic ecotoxic impacts, respectively). Then, the 'Classification' step will be restricted solely to the assignment of elementary flows to defined impact categories (Guinée et al. 2002).

Finally, it could be sensible to create more clarity, for example in the next update of the ISO 14040 series of standards, on the issue of whether or not to differentiate between names for midpoint impact categories and damage or endpoint category indicators, including different names for different midpoint impact categories (there are many different midpoints possible between inventory results and endpoints) and possibly also between different damage or endpoint impact categories.

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