ENVIRONMENTAL LIFE CYCLE ASSESSMENT

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average contribution of a product or service to a number of environmental impacts (Pennington et al. 2006). Local maximum permissible concentrations or acute toxicity events are thus not usually addressed by an LCA.

2.3.2.4 Comparison between Material Flow Analysis and LCA

MFA and LCA both use mass balance modeling. An MFA merely tracks material flows in a region, whereas an LCA uses these flows in modeling the economic system and unit processes, calculating the emissions and extractions of raw materials related to these material flows.

2.3.2.5 Comparison between Carbon Footprint and LCA

The CF is simply the global warming component of the LCA, and can thus be applied to a product, activity, or company. While an LCA can estimate how various scenarios can shift impacts among different impact categories, a CF focuses solely on the greenhouse effect category.

> In summary, an LCA quantifies material flows throughout the life cycle of a product or service, from which the impacts can be estimated for a comprehensive set of environmental impact categories. LCA is the only method to relate multiple environmental impacts to the function of a product or service.

The life cycle concept is not limited to environmental impacts; the results of an environmental LCA can be combined with those of an economic analysis (Section 6.8.1), a technical analysis (life cycle engineering, Lundquist et al. 2000), or a social analysis (social LCA, Section 6.8.5), thereby integrating the different aspects of sustainability.

2.4 SIMPLE APPLICATION: COMPARING DIFFERENT TYPES OF CUPS

This section presents a comparison among different types of cups to illustrate how an LCA is carried out. The basic hypotheses for this example were adapted from Bättig (2002), where single-use cups are compared with multiuse cups. Chapter 8 presents a more elaborate case study demonstrating the application of LCA, comparing different options for sewage sludge treatment.

2.4.1 Goal and Scope Definition of Cup Case Study

The main objective of this LCA is to compare the environmental impacts of different types of cups used in stadiums during sporting or cultural events.

The functional unit used as a basis for comparison must be common to all scenarios and represent the considered function (Section 3.3). Since the purpose of the cup is to contain a certain volume of drink, the corresponding functional unit is one use of a 300 mL cup. Therefore, the various substance emissions and resource extractions listed in the inventory will be calculated for one use of one cup.

TABLE 2.2
Processes Included within the System Boundaries

Single-Use Cup	Multiuse Cup
Cup manufacturing	Cup manufacturing
Transportation (from production site to stadium)	Transportation (from production site to stadium)
Cleaning of the stadium	
	Transportation (to and from washing facility)
	Washing of the cup
Elimination (incineration)	Elimination (incineration)

The system processes considered are presented in Table 2.2. For a single-use cup, this includes the manufacturing of the cup, its transportation to the stadium where the event takes place, the cleaning of the stadium using air blowers, and the elimination of the cup. For a multiuse cup, the stadium cleaning is assumed to be unnecessary, since cups are collected and reused rather than left on the stadium floor, but washing the cup and its transportation to and from the washing facility must be included. The production and use of detergent for washing the cup are not considered here. The manufacturing and elimination of the infrastructure for cup production are excluded because their impact per cup produced over the entire lifetime of the production infrastructure is considered negligible.

Some of the key parameters in this study are the transportation variables and the number of times a cup is reused, both of which can vary considerably depending on event logistics and user behavior. The important transportation variables are the distance traveled, the mode of transportation, and the size of the load, all of which are necessary data for the calculation of the impacts of any transportation. The number of cup uses is also an important parameter, since any process that occurs only once in a cup's life (such as raw material extraction, manufacturing, and elimination) has its impacts distributed over each use. For a multiuse cup made of polycarbonate (PC) or polypropylene that can be reused 150 times, the impacts of the one-time processes (shaded in Table 2.2) should be divided by 150 to yield the impact contribution of one use of a cup (assuming no losses). The actual number of reuses, however, is much lower due to losses during the event or in transit (cups may be damaged, discarded, etc.). This can be accounted for by introducing a loss percentage.

To examine the influence of these parameters on the total impacts, the material, number of uses, and transportation parameters are varied as follows:

- A paper cup, used once
- A polyethylene (PET) cup, used once
- A PC cup, used 150 times, without accounting for transportation between the stadium and the washing facility
- A PC cup, used 150 times, with 5% losses at every event, and 50 km transportation distance to be washed (round trip to the cleaning facility by car loaded with 1000 cups)

Note that the last scenario derives from a sensitivity study carried out by the authors of this book and was not presented in the original study.

2.4.2 Inventory Analysis of Cup Case Study

The inventory quantifies the pollutant emissions to water, air, and soil, as well as the extractions of raw material from the environment, over all processes in the life cycle of each scenario. It does so by first quantifying the main intermediary flows required per cup use (e.g., key transportation distances and amounts of paper or PET used per functional unit), and then finding the pollutant emissions and resource extraction factors associated with each of these flows (see Section 4.1 for more details on the inventory). Table 2.3 shows an excerpt of this inventory for each scenario.

The PC multiuse cup, without losses or transport to washing facility systematically has the lowest emissions and extractions per functional unit. For the remaining three scenarios, it is not possible to define a ranking from the inventory results alone; the single-use paper cup has the highest emissions of cadmium in air and hexavalent chromium in water, while the single-use PET cup requires the extraction of a large amount of crude oil. When losses and transportation to the washing facility are taken into account, the PC cup emits more CO and N_2O in air than the other scenarios.

Therefore, it is difficult, based solely on the inventory results, to draw conclusions about the relative impacts of the different scenarios, or about the processes and emissions that contribute most to these impacts. This is precisely the purpose of the impact assessment phase, as demonstrated in the following section.

2.4.3 Impact Assessment of Cup Case Study

The impact assessment phase estimates the impacts of the inventory's emissions and extractions on various areas of protection (human health, ecosystem quality, natural resources, etc.). Different impact assessment methods can be used for this evaluation, each of which uses different models to calculate environmental impacts by category. In this example, the Eco-indicator 99 method is used, which is described in more detail in Section 5.5, along with other impact assessment methods.

Based on Eco-indicator 99 calculations, the single-use PET cup has the highest damage score for all three damage categories considered: human health, ecosystem quality, and resource degradation (Figure 2.4). The multiuse PC cup (assuming no losses or transportation to the washing facility) results in the least impact. The other two scenarios fall in the middle, with the paper cup having slightly less impact than the PC cup with losses and transportation for the three damage categories considered.

Since the relative ranking of scenarios is identical in all three damage categories, we simplify the remaining discussion by using the total aggregated impact. (Section 5.2.3 explains how different categories can be combined into a single score.) As defined in the Eco-indicator 99 method (Section 5.5.3), the total impact is calculated as a weighted sum of each area of protection. Here, we express this total impact score by contribution from each process (Figure 2.5).

TABLE 2.3
Excerpt from the Inventory of Pollutant Emissions and Resource Extractions for Each Scenario (per Functional Unit, i.e., One Use of One 300 mL Cup)

Substance	Unit	Paper	PET	PC	PC with Transportation and Losses
Emissions to Air					
Benzo[*a*]pyrene	g	3.4×10^{-9}	3.2×10^{-9}	4.9×10^{-10}	3.0×10^{-9}
Cd	g	4.4×10^{-7}	2.4×10^{-7}	1.1×10^{-8}	3.9×10^{-8}
CH_4	g	0.0277	0.0358	0.0016	0.0279
CO	g	0.013	0.148	0.006	0.277
CO_2	g	9.2	18.2	0.9	18.5
Hg	g	2.3×10^{-7}	2.6×10^{-7}	1.2×10^{-8}	1.2×10^{-7}
N_2O	g	2.0×10^{-4}	1.1×10^{-4}	1.0×10^{-5}	9.1×10^{-4}
NH_3	g	2.0×10^{-4}	9.0×10^{-6}	1.0×10^{-6}	6.0×10^{-6}
NMVOC	g	0.029	0.294	0.011	0.172
NO_x	g	0.044	0.161	7.0×10^{-3}	0.089
Particles	g	0.014	0.028	1.0×10^{-3}	0.011
Pb	g	2.7×10^{-6}	2.4×10^{-6}	3.0×10^{-7}	1.3×10^{-5}
SO_x	g	0.044	0.185	7.0×10^{-3}	0.074
Emissions to Water					
Al	g	0.00125	0.00155	0.00011	0.00078
As	g	2.5×10^{-6}	3.1×10^{-6}	2.1×10^{-7}	1.7×10^{-6}
BOD	g	0.0554	0.0096	0.0003	0.0025
Cr (VI)	g	1.3×10^{-6}	3.7×10^{-10}	4.1×10^{-11}	2.0×10^{-10}
Cu	g	6.6×10^{-6}	7.8×10^{-6}	5.2×10^{-7}	4.3×10^{-6}
NH_4^+	g	6.3×10^{-5}	2.6×10^{-4}	1.0×10^{-5}	4.7×10^{-4}
Ni	g	6.5×10^{-6}	8.0×10^{-6}	5.2×10^{-7}	4.5×10^{-6}
Pb	g	9.7×10^{-6}	1.1×10^{-5}	1.0×10^{-6}	5.2×10^{-6}
Emissions to Soil					
As	g	5.0×10^{-8}	3.1×10^{-8}	9.0×10^{-10}	5.8×10^{-9}
Cd	g	2.5×10^{-9}	1.7×10^{-9}	1.0×10^{-10}	7.0×10^{-10}
Cr	g	6.2×10^{-7}	3.9×10^{-7}	1.1×10^{-8}	7.2×10^{-8}
Cu	g	1.4×10^{-8}	8.6×10^{-9}	2.0×10^{-10}	1.2×10^{-9}
Hg	g	3.9×10^{-10}	2.4×10^{-10}	6.0×10^{-12}	3.7×10^{-11}
Ni	g	2.1×10^{-8}	1.3×10^{-8}	3.0×10^{-10}	1.9×10^{-9}
Pb	g	6.4×10^{-8}	3.9×10^{-8}	9.0×10^{-10}	5.7×10^{-9}
Zn	g	2.0×10^{-6}	1.3×10^{-6}	3.0×10^{-8}	2.0×10^{-7}
Resource Extraction					
Coal	g	0.78	1.17	0.07	0.55
Natural gas	dm^3	2.14	3.28	0.14	1.31
Copper ore	g	3.0×10^{-4}	2.2×10^{-4}	1.8×10^{-5}	1.0×10^{-4}
Lead ore	G	3.5×10^{-4}	3.6×10^{-4}	5.5×10^{-5}	4.1×10^{-4}
Crude oil	G	2.74	9.87	0.36	6.37

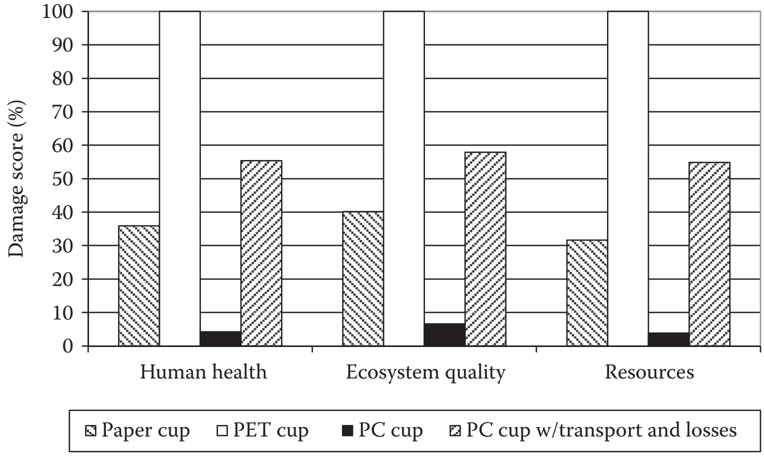

FIGURE 2.4 Proportional damage scores for the different cups, relative to the PET (polyethylene) cup. "PC cup" refers to the multiuse polycarbonate cup. Damage calculated using Eco-indicator 99.

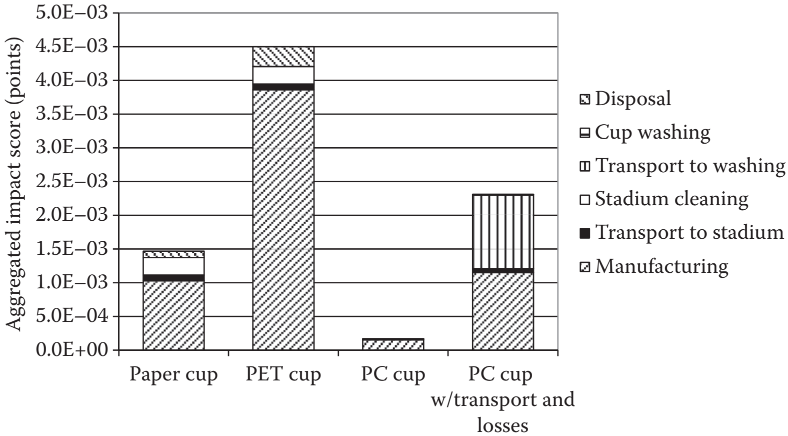

FIGURE 2.5 Total aggregated environmental impacts of the different cup scenarios and distribution by life cycle stage. The Eco-indicator 99 method was used to compare total impacts of a paper cup, a single-use polyethylene (PET) cup, and multiuse polycarbonate (PC) cups.

For all cups, the manufacturing stage (including raw material extraction) accounts for most of the total impact. The impacts of transportation to the stadium and cleaning of the stadium are limited. Assuming a 5% loss in the multiuse PC cup greatly increases each cup's manufacturing impact to a level equivalent to that of the single-use paper cup. Moreover, a 50 km round-trip between the stadium and the washing facility would almost double the impact of the PC cup with losses. The stadium cleaning stage is small in single-use cup scenarios (and assumed not to occur in the multiuse scenarios). The elimination at the end of the cup's life has a small contribution in all four scenarios.

2.4.4 Interpretation of Cup Case Study

The single-use PET cup is clearly the least advantageous scenario, and a multiuse PC cup with no losses or transportation for washing is clearly the best scenario. But, there is no clear-cut conclusion about which is the better scenario between the paper cup and the more realistic multiuse PC cup that assumes losses and washing transportation. A comparison of the two PC cup scenarios clearly shows the negative environmental impacts of losses and transportation for washing; we find that accounting for these reverses the relative ranking of the PC cup and the paper cup. This is partly because a 5% loss per event reduces the actual number of reuses from 150 to 20, increasing the manufacturing impact per functional unit by more than a factor of seven. Moreover, transportation to the washing facilities leads to considerable impacts. This study assumes a 50 km journey by a fully loaded truck with 1000 cups, but the actual impacts will depend on the type of vehicle and the load; a cup carried by a smaller or only partially loaded car has a bigger impact than a cup carried in a large truck containing 20,000 cups. The large impact contributions of losses and transportation demonstrate the sensitivity of the results to the hypotheses made, and the need to best reflect the actual situation.

Finally, it should be noted that the results of the impacts of washing do not account for the washing agent and should, therefore, be treated with caution. The impact of soap can indeed be significant, particularly on ecosystem quality (eutrophication and ecotoxicity).

2.4.5 Conclusions of Cup Case Study

For a single-use cup, this example finds that a paper cup has less environmental impact than a PET cup. It also shows the value of using multiuse cups if there are negligible losses and transportation needs. In practice, the losses should be assessed and included, since a loss of 5% causes the impacts of multiuse cups to become equivalent to or even more harmful than those of single-use paper cups.

Zooming out to consider such large entertainment events as a whole, it is clearly beneficial to reduce the environmental impacts of cups, but it is even better to act where the impacts are highest. For a sporting event, for example, the impact of the cups is relatively small compared with that of the transportation of people to the location of the event; in fact, the impact of one paper cup is approximately equivalent to the impact of transporting one person by car over only 100 m (Figure 2.6). This means that a 10 km trip is 100 times more harmful to the environment than a paper cup. Based on these results, efforts to reduce the impacts of such an event should focus first on the transportation of people to the stadium; for example, by active promotion of the use of public transport. Materials and waste management should be addressed as a second priority.

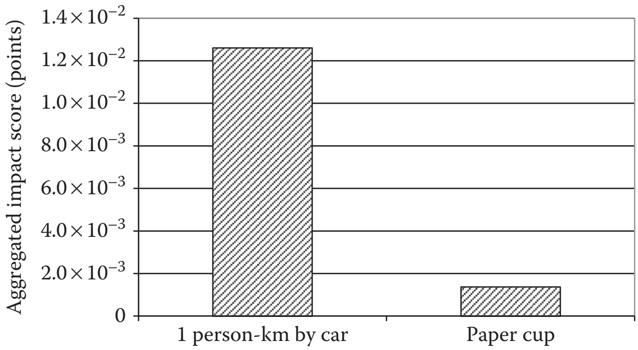

FIGURE 2.6 Comparison between the environmental impact of a single-use paper cup and the transportation of one person by car over 1 km (1 person-km).

EXERCISES

Exercise 2.1: Choose the Best Environmental Evaluation Method and Key Metrics

Decide which assessment method listed in Table 2.1 is most appropriate for the following situations. List key reasons for using this method, and find an appropriate metric/basis for comparison.

1. An electricity company is investing $50 million to integrate photovoltaics into the design of commercial and residential buildings. It wants to estimate the environmental benefits of this design, assuming 1000 buildings will be constructed around the country.
2. An airline company would like to optimize its company's greenhouse gas emissions.
3. You need decide whether to use paper or plastic bags to carry your groceries home.
4. An electricity company is deciding in which of two cities to build its new power plant.
5. You want to decide whether to take the car, bus, train, or airplane from Chicago to New York City based on environmental impacts.
6. A chemical leak occurs in a manufacturing plant, and it needs to decide whether or not to evacuate people from the area.
7. Afterward, the manufacturing plant in (6) must determine the best decontamination method for the site where this leak occurs.
8. Regional authorities are considering creating a recycling auction for old materials and want to decide which materials to include.
9. Congress wants to examine the impacts of using biofuels in the federal fleet of vehicles.

Exercise 2.2: Comparing Cups for a Stadium Event

Based on the information and example provided in Section 2.4, answer the following questions.

1. List two preliminary conclusions you can make based solely on the numbers in the inventory on Table 2.2. List two benefits of subsequently applying impact assessment to this inventory.
2. What are the key parameters affecting the environmental impact of the multiuse PC cup?
3. What is the approximate total aggregated impact score (in points) of a multiuse PC cup, still assuming 5% loss, but assuming that the washing facility is right next to the stadium (use Figure 2.5 for help)?
4. Which result surprised you most about the cup case study and why?
5. In performing an environmental assessment of a sports game, list two other factors to consider (and provide reasoning) (other than cup usage and transportation of spectators to the game).
6. Provide a functional unit that would enable you to compare the relative impacts of a spectator drinking from a cup at the game and the transportation of a spectator to the game.