BSESC—Life-Cycle Analysis

# Proficiency Level 2. Understand

## Learning Objective 2

List the steps needed for a full life-cycle analysis based on the International Organization for Standardization (ISO) Standard.

### Lecture Notes

Understanding life-cycle analysis (LCA) is often easier with a specific example. For this unit, we consider the simple question of replacing an incandescent light bulb with a compact fluorescent (CFL) or light-emitting diode (LED). Each step in the LCA is documented below, and a summary of the process is shown in Figure 1.



Figure . Summary of the LCA process, adapted from the ISO Standard (International Organization for Standardization 2006)

**Step 1. Determine the goal and scope for the LCA.**

The goal and scope step is used to define the parameters of the assessment, such as the product system to be studied, the system boundaries, the functional unit, and assumptions used.

The goal is a statement of the purpose of the LCA that ideally addresses several facets of the study. For our example on lighting, we want to make it clear what our intended application will be, our reasons for the study, the audience for the LCA, and how we will share our results. The goal statement for this example is stated below, but includes Table 1 as an outline of the other facets of the goal.

*Goal Statement: “The DOE is conducting a broad study to assess and compare the environmental impacts of general illumination LED lamps and luminaires with conventional lamps and luminaires.”* (Scholand and Dillon 2012).

Table 1. Summary of the goal statement for the LCA (Scholand and Dillon 2012)

| **LCA Element** | **Summary for this Work** |
| --- | --- |
| Intended Application | To compare the energy and environmental impact of LED lamps used in general illumination applications with traditional lighting products |
| Reasons for the Study | To quantify the energy and environmental impacts of LEDs  To address uncertainty in the existing body of literature and LCA reports concerning LED manufacturing methods and assumptions |
| Audience | Lighting designers, policy makers, researchers, and technical experts considering LED technology in general illumination applications |
| Public Results | Results of this study will be freely available and published on the DOE Solid State Lighting website: [www.energy.gov/eere/ssl/solid-state-lighting](http://www.energy.gov/eere/ssl/solid-state-lighting) |

The scope statement typically summarizes the limits of the LCA. The scope of this example study is a comparison between the energy and environmental impacts of LED technology used in general illumination applications and traditional light sources, namely incandescent lamps and CFLs. If we wanted to compare the products on the basis of cost, we would need to state that in the scope as well.

The selection of the functional unit is a critical part of the LCA. It should be related to the function of the product and be measurable. For example, in the case of electricity production, the functional unit might be the production of 1 kWh of electrical energy, and then we could evaluate the cost or environmental differences in production of electricity from wind or solar. Since we will use the functional unit as the basis for all calculations, we need to be careful to **structure this unit to capture the key features of the LCA goal**.

For our lighting example, we selected the functional unit as 20 million lumen-hours of lighting service, which was approximately representative of total light output of a Philips EnduraLED 12.5W lamp over its lifetime (Scholand and Dillon 2012). This functional unit captured two important elements of our study goal—the light (measured in lumens) and time (measured in hours). Since the functional unit is something that may be measured for each of the products we wish to compare in the LCA, it is a good choice. Figure 2 provides a visual summary of the functional unit for the lighting LCA.



Figure 2. Visual summary of the functional unit for the example LCA; the number of lamps needed to supply 20 million lumen-hours (Navigant Consulting 2012)

The **system boundaries** establish the inputs and outputs included in the LCA. This is important, since it limits the inputs and outputs for the next step in the LCA. For our example, we wanted to understand the environmental impacts of lighting options, so we included raw material inputs, manufacturing, transportation of the product, use and operation of the light, and the end of life. The system diagram provides additional detail in Figure 3.



Figure 3. System diagram for the example lighting LCA (Scholand and Dillon 2012)

**Step 2. Perform the inventory analysis for the LCA.**

In the inventory analysis section of the LCA, we gather data on all the processes shown in the system diagram on the basis of the functional unit. Essentially, we take each unit process in the system and determine how it contributes to the functional unit, while also including the outputs from the process. A simple example is the transportation phase of the lighting.

First, we estimated how far we believed the lighting product would need to travel after manufacture. The transportation assumptions were consistent for each product and were based on travel by sea from manufacturing in China to an end-use destination in the United States.

Travel by sea (transoceanic freight ship) for 10,000 km was converted to ton-km based on the weight of the final lighting product including packaging. Travel by land (truck greater than 16 ft fleet average) for 1,000 km was converted to ton-km based on the weight of the final LED product including packaging. Both the land and sea transportation values were based on published data from existing LCA databases, but since they were different processes, we need to keep them as separate elements in the matrix we will use to represent our system.

The matrix we built for this piece of the process is shown in Table 2, and we call it the technology [A] matrix. In the matrix version, the inputs to one process are shown as a negative value (-), while the outputs are positive (+). The lighting produced column tells us that to produce 20 million lumen-hours of lighting service in a home, we need the input of one unit of transportation. The next column tells us that one unit of transportation is really land and sea transportation and gives the ratio. This is not the only way to perform an LCA calculation, but it is a matrix based system that is well documented by Heijungs and Suh (2002). Using this approach, the technology matrix must be square.

Table 2. Example of the inventory analysis technology matrix [A], for the transportation of each lighting product

|  | **Units** | **Lighting Produced** | **Lighting Product Transportation** | **Sea Transportation** | **Road Transportation** |
| --- | --- | --- | --- | --- | --- |
| Light Produced | lumen-hrs | 20300000 | 0 | 0 | 0 |
| Lighting Transportation | pieces | -1 | 1 | 0 | 0 |
| Sea Transportation | ton-km | 0 | -2.3699665 | -1 | 0 |
| Road Transportation | ton-km | 0 | -0.23699665 | 0 | -1 |

The next level of information in the inventory phase is collecting the intervention matrix [B], shown in Table 3. This matrix will capture all the information about the consequences we are trying to understand. For environmental questions, we might want to understand the global warming potential and the cost. For a cost only LCA, we could just include the cost for each part of the transportation process. We include the two other columns about lighting and total transportation to make it tidy when we perform calculations, since matrix multiplication has specific rules.

Table 3. Example of the intervention matrix [B], for the transportation of each lighting product

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Lighting Produced** | **Lighting Product Transportation** | **Sea Transportation** | **Road Transportation** |
| Global Warming Potential | kgC02-eq |  |  | 0.0115 | 0.169 |
| Ozone-Depleting Potential | kgCFC11-eq |  |  | 1.86E-09 | 3.11E-08 |
| Hazardous Waste Landfilled | kg-waste |  |  | 9.1E-08 | 1.51E-06 |
| Non-Hazardous Waste Landfilled | kg-waste |  |  | 0.000196 | 0.119 |
| Cost | USD $ |  |  | 0.002 | 0.001 |

**Step 3. Calculate the impact assessment for the LCA.**

After the inventory is complete, we need to set up one additional matrix for our calculations, the demand vector based on the reference flow [f]. This matrix is defined based on our original functional unit for the problem. Traditionally, all the elements of the vector are zero except the functional unit reference. In our example, this would be shown as [f]. The number of rows of the vector will be determined by the final size of the [A] matrix.

The first step in the calculation is determining the scaling matrix [s], the matrix used to adjust all the processes in the LCA based on the functional unit. The scaling matrix also may be referenced as the characterization step in some LCA literature. For this step, we first calculate the inverse of the [A] matrix, and then multiply it by [f]. If you are not familiar with the details of [matrix inversion](https://en.wikipedia.org/wiki/Invertible_matrix#:~:text=Matrix%20inversion%20is%20the%20process,for%20matrices%20over%20any%20ring.) and [multiplication](https://en.wikipedia.org/wiki/Matrix_multiplication), you may want to review the calculation. Many software packages can perform this calculation for you. The process is essentially the solution of a set of simultaneous equations.

The scaling matrix [s], gives us the correct multiplication factor for determination of the final environmental impacts or costs. The final impact matrix is called [g], and is determined by matrix multiplication of the intervention matrix [B], and the scaling matrix [s]. [g] represents the results we were originally interested in.

**Step 4. Interpret and review results.**

The final step in an LCA is iterative. You want to check your work as you progress through each unit process and step of an LCA. For example, you might start by setting up your computational framework based on an existing LCA that has been published, make sure your calculations are correct, and then start adding processes to the system.

One important tool to interpret your work is the error estimate associated with each data source. Look at each column in [A] and [B] and identify how confident you are about the assumptions and errors. For our example, how sure are we that our lighting product will travel 1,000 miles by truck? Clearly this is an estimate, so we want to consider that as a possible source of uncertainty.

Sensitivity analysis can be a useful way to check on sources of error. Variation of the inputs—changing our assumption of 1,000 miles to 500 miles—and determining how that change effects the final results is helpful for this process. Think about interpretation and uncertainty at each step in the process, and set up your calculations so it is easy to perform a sensitivity analysis.

One important challenge of LCA is the way underlying assumptions may shift the calculations. This is why it is critical to use the ISO standards for LCA work whenever you perform this type of calculation. It is important to perform comparative LCA (comparing two options or products) to reduce errors rather than singular LCA work.

### References

Heijungs R and S Suh. 2002. *The Computational Structure of Life Cycle Assessment*. <https://doi.org/10.1007/978-94-015-9900-9>.

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