Chapter 1 : Life Cycle and Systems Thinking

In this chapter, we introduce the concept of "thinking" about life cycles. Whether or not you become a practitioner of LCA, this skill of broadly considering the implications of a product or system is useful. We first provide definitions of life cycles and a short history of LCA as it has grown and developed over the past decades, then give some examples where application of life cycle thinking (rather than completion of full-blown LCAs) will demonstrate where analyses can lead (or have already led) to poor decisions. The goal is to learn how to think about problems from a system wide perspective.

Learning Objectives for the Chapter

At the end of this chapter, you should be able to:

1. State (a) the concept of a life cycle and (b) its various stages as related to assessment of products.

2. Illustrate the complexity of life cycles for even simple products.

3. Explain why environmental problems, like physical products, (a) are complex and (b) require broad thinking and boundaries that include all stages of the life cycle.

4. Describe what kinds of outcomes we might expect if we fail to use life cycle thinking.

Overview of Life Cycles

We first learn about **life cycles** at a young age – the butterfly's genesis from egg to larva to caterpillar to chrysalis to butterfly; the path of water from precipitation into bodies of water, then evaporation or transpiration back into the air. Frogs, tomatoes in the garden, seasons throughout the year – all life cycles we know or experience in our own life cycle. Each individual stage along the cycle is given a distinct term to distinguish it from the others, yet each stage flows seamlessly into the next often with no clear breaks. The common theme is a continuous stepwise path, one stage morphing into the next, where after some time period we are back to the initial starting point. A dictionary definition of life cycle might be "a series of stages or changes in the life of an organism". Here we consider this definition for products, physical processes, or systems.

While we often are taught or consider life cycles as existing in the natural world, we can just as easily apply the concept to manmade products or constructs: aluminum's journey from beverage can to recycle bin back to beverage can; a cellphone we use for our 2-year contract period then hold onto (because it must have some value!) before donating to a good cause where (we presume) it is used again before…being recycled? … being thrown away? The same common theme – a continuous stepwise path, one stage morphing into the next, where after some time we are (or may be) back to the initial starting point. It is these kinds of life cycles for manmade products and systems that are the focus of this book.

As the domain of sustainable management has taken root, increasingly stakeholders describe the need for decision making that considers the "life cycle". But what does that mean? Where does that desire and intent come from?

The entire life cycle for a manmade product goes from obtaining everything needed to make the product, through manufacturing it, using it, and then deciding what to do with it once it is no longer being used. Returning to the natural life cycles described above this means going from the birth of the product to its death. As such, this kind of view is often called a "**cradle to grave**" view of a product, where the cradle represents the birthplace of the product and the grave represents what happens to it when we are done with it – often to be thrown into a landfill. Some life cycles may focus on the process of making the product (up to the point of leaving the factory) and have a "**cradle to gate**" view, where the word gate refers to the factory gate. If we have a fairly progressive view, we might think about alternatives to a "grave". That might mean recycling of some sort, or taking back the product and using it again. Building on this alternative terminology, proponents have also referred to the complete recycling of products as going from "**cradle to cradle**".

Consider some initial product life cycle views:

- A piece of fruit is grown on a farm which uses water and perhaps various fertilizers and equipment to bring it to market. There it is sold to either a food service business or an individual consumer. While much of it is hopefully eaten, some of it will not be edible and the remainder will be disposed of as food waste – either as compost or in the trash.

- A tuxedo is sewn together at a factory and then distributed and sold. It is purchased either for personal use (perhaps only being used once or twice a year), or for the purposes of renting it out for profit to people who need it only once, and maybe cannot justify the cost of buying one. The rental tuxedo will be rented several times a month, and after each rental it is cleaned and prepared for the next rental. Eventually the tuxedo will either be too worn to use, or the owner will grow out of it. At that point it is likely donated or thrown away.

- A car is put together from components at a factory. It is then delivered to a dealer, purchased by a consumer, and driven for a number of years. At some point the owner decides to get rid of the car – perhaps selling it to another driver who uses it for several years. Eventually its owner finds no sufficient value for it, and it will likely be shredded into small pieces and useful metals reclaimed.

- A computer is assembled from components manufactured across the world (all of which are shipped to an assembly line). It is bought and plugged in by the owner, consuming electricity for several years before becoming obsolete. At the end of its useful life it might be sold for a fraction of its purchase price, or may be donated to a party that still finds value in it, or it may be stored under a desk for several years. Like the car example above, though, eventually the owner will find no sufficient value for it and want to get rid of it.

We can already start to think about some implications of these basic life cycles. Using fuels and electricity generates pollution. Applying fertilizers results in runoff and stream contamination. Washing a tuxedo releases chemicals into wastewater systems that need to be removed. Making semiconductor chips consumes large amounts of water and uses hazardous chemicals. Finally, putting items in landfills minimizes our opportunity to continue extracting usefulness from those value-added items, takes up land that we cannot then use for other purposes, and, if the items contain hazardous components, leaks may eventually contaminate the environment.

This is a modern view of a product. We have not always been so broad and comprehensive in thinking about such things. In the next few sections we briefly talk about the related history of this kind of thinking, and also give some sobering examples of decisions and products that were made (or promoted) that had not fully considered the life cycle.

A Brief History of Engineering and The Environment

Before we further motivate life cycle thinking, let's briefly talk about the history of industrial production, environmental engineering, science, and management as it applies to managing the impacts of products. While engineers and others have been creating production or manufacturing processes for products for centuries, nearly all of the production systems we have created in that time are "linear", i.e., we need to keep feeding the system with input at one end to create output at the other. We design such linear processes independently of whether we will have long-lasting supplies of the needed inputs, and certainly have not made contingencies for how to change the process should we begin to run out of those resources. We also have thought quite linearly in terms of how well the natural environment could deal with any potential wastes from the production systems we have designed.

It is worth realizing that environmental engineering (i.e., the integration of science to improve our natural environment) is a fairly young discipline. While there is evidence of ancient civilizations making interesting and innovative solutions to dealing with wastes, the establishment of a real environmental engineering profession was not really formalized until around 1900. Initially, what we now call environmental engineering grew out of the need to better manage urban wastes, and thus most of the activity was originally referred to as "sanitary engineering". Such activities involved diversion of waste streams to distant sinks to avoid local health problems, such as sewer systems (Tarr 1996). Eventually, **end of pipe treatment** emerged. By end of pipe, we mean that the engineering problem was focused on what to do with the waste of a system (e.g., a factory or a social waste collection system) after it has already been produced. Releases of wastes and undesirable outputs to the environment are also called **emissions**. Another historical way of dealing with environmental problems has been through **remediation**. Remediation occurs after the pollution has already occurred, and may involve cleaning up a toxic waste dump, dredging a river to remove long-buried contaminants that were dumped there via an effluent pipe, or converting contaminated former industrial sites (brownfields) into new developments. The remediation activities may occur soon after or even decades after the initial pollution occurred.

An alternative paradigm was promoted in the 1980s, referred to as **pollution prevention (P2, or cleaner production)**. It is probably obvious that the whole point of this alternative paradigm was to make stakeholders realize that it is costly and late in the process to wait until the end of the pipe to manage wastes. If we were to think about the inevitable waste earlier in the process chain, we could create a system that produces less (or ideally, no) waste.

A newer paradigm is to promote **sustainability**. Achieving sustainability refers to the broader balancing of social, economic, and environmental aspects within the planet's ability to provide. The United Nations' Brundtland Commission (1987) suggested "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Almost all people in developed nations share the goals of improving environmental quality and making sure that future generations have sufficient resources. Unfortunately, consumers, business leaders, and government officials do not have the information required to make informed decisions. We need to develop tools that tell these decision makers the life cycle implications of their choices in selecting materials, products, or energy sources. These decisions are complicated: they depend on the environmental and sustainability aspects of all products and services that contribute to making, operating, and disposing of those materials, products, or energy sources. They also depend on being able to think non-linearly about our production systems and envision the possibilities of resource scarcity or a lack of resilience in the natural environment. Accomplishing these goals requires life cycle thinking, or thinking about environmental problems from a systems perspective.

Nowadays all of these activities are part of what we refer to as environmental engineering. Despite trends towards pollution prevention and sustainability, basic challenges remain to design better end of pipe systems even in the developed world where pollution prevention is well known but is deemed as too expensive for particular processes (or where all cost-effective

P2 solutions have already been implemented). But the general goal of the field is to reduce pollution in our natural environment, and a primary objective is to encourage broader thinking and problem solving that goes back before the end of the pipe and prevents pollution generation. Practically, we will not achieve a pollution-free world in our lifetimes. But we can help get there by thinking about environmental problems in a life cycle context, and ideally identify solutions that focus on stages earlier in the life cycle than the point where the waste pipe interfaces with our natural environment.

Life Cycle Thinking

Now that we have introduced the idea of a life cycle, and motivated why thinking about products as systems or life cycles is important, we can dive deeper into the ways this kind of thinking is defined and how it has evolved. Much of this development has come in the engineering and science communities, and thus the views and representations of life cycles are fairly technical. That said, given the typically focused and detailed views of scientists and engineers, you will see that the way these systems are studied is quite broad.

A conceptual view of the **stages of such life cycles** is in Figure 1-1. Beginning with the linear path along the top, we first extract raw materials from the ground, such as ores or petroleum. Second, these are processed, transformed or combined to make basic material or substance building blocks, such as metals, plastics or fuels. These materials are combined to manufacture a product such as an automobile. These final products are then shipped (while not shown) by some mode of transport to warehouses and/or stores to be purchased and used by other manufacturers or consumers. During a product's use phase it may be used to make life easier, provide services, or make other products, and this stage may require use of additional energy or other resources (e.g., water). When the product is no longer needed, it enters its "end of life" which means managing its disposition, possibly treating it as waste.

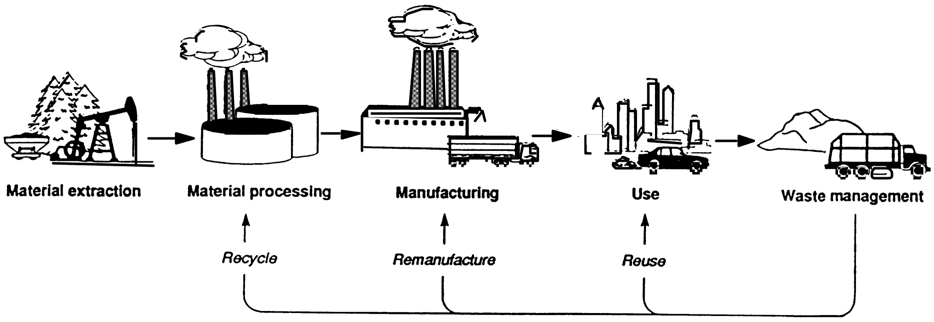

Figure 1-1: Overview of a Physical Product Life Cycle (OTA, 1992)

As Figure 1-1 also shows, at the end of life phase there are alternatives to treating a product as waste. The common path (linear path across the top) is for items to be thrown away, a process that involves collection in trucks and putting the item as waste in a landfill. However, the bottom row of lines and arrows connect the end of life phase back to previous stages of the typical life cycle through alternative **disposition pathways**. Over the course of a life cycle, products, energy and materials may change form but will not disappear. **Reuse** takes the product as is (or with very minor effort) and returns it to the use phase, such as a tuxedo. **Remanufacturing** returns the product to the manufacturing stage, which may mean partially disassembling the product but then re-assembling it into a new final product to be delivered, such as a power tool or a photocopier. Finally, **recycling** involves taking a product back to its raw materials, which can then be processed into any of a number of other products, such as aluminum beverage cans or cardboard boxes. This bottom row also reminds us that despite the colloquial use of the word "recycling" in society, recycling has a very distinct definition, as noted above. Other disposition options have their own terms. An Internet search would turn up hundreds more pictures of life cycles, but for our introductory purposes these will suffice. Once we discuss the actual ISO LCA Framework in Chapter 4 we will see the standard figures and some additional useful ones.

If you are from an engineering background, you might be asking where the other traditional product stages fit in to the product life cycle described above. In engineering, the typical product life cycle starts with initiation of an idea, as well as research and design iterations that lead to multiple prototypes, and eventually, mass production. One could classify all such activities as research and development (or R&D) that would come to the left of all activities (or perhaps in parallel with some activities such as material extraction) in Figure 1-1. We could imagine a reverse flow arrow for "Re-design" going along the bottom of Figure 1-1 to represent product failures or iterations. While not represented in the figure above, all of these R&D-like activities are relevant stages in the life cycle. As we will see, though, when analyzing life cycles for environmental impact, these stages are typically ignored.

Simple and Complex Life Cycles

Before we go further in our discussion of life cycles, it is useful to pause and think about all of the components of something with a very simple life cycle, like a paper clip. Get a blank sheet of paper, and write "paper clip" in a corner of the sheet. If we think very simply about its life cycle (e.g., using Figure 1-1 as a guide), we can work backwards from the paper clip we are used to. To get its shape, it is coiled with machinery. We can write "coiling" and draw an arrow from the words "coiling" to "paper clip". Before coiling it is just a straight wiry piece of steel. Steel is made from iron and carbon. We can write "steel" and draw an arrow to "coiling". Iron ore and the carbon source both need to be extracted from the ground. All of these components and pieces are shipped between factories by truck, rail, or other modes of transportation. Any or all of these stages of the life cycle could be added to the diagram.

Putting all these materials and processes into a diagram is not so simple. Even that description above for a paper clip was very terse. If we think a little more, we realize that all of those stages have life cycles of their own. For example, the machinery that coils the steel wire into a paper clip must be manufactured (its use phase is making the paper clip!). The metal and other parts needed to make the machine also must be processed and extracted. The same goes for all of the transportation vehicles and the infrastructure they travel on and the factories to make iron and steel, etc. Figure 1-2 shows what the diagram might look like at this point.

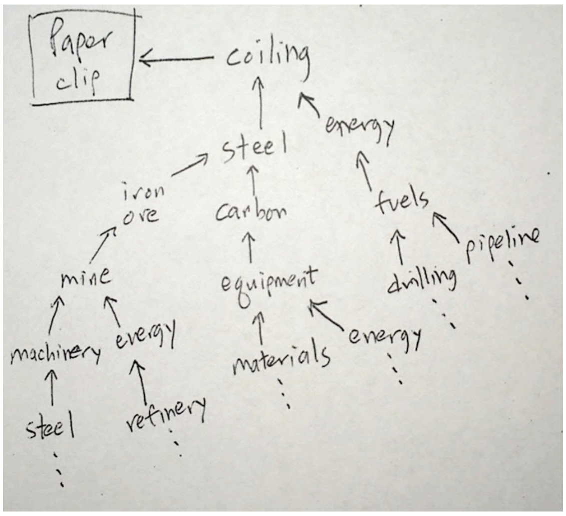

Figure 1-2: Exploded View Diagram of Production of Paper Clip

This chain goes back, almost infinitely, and the sheet of paper is quickly filled with words and arrows. Even a product as simple as a paper clip has a complex life cycle. Thus a product that we consider to be "complex" (for example a car) has a ridiculously complex life cycle! Now that we can appreciate the complexity of all life cycles, you can begin to understand why our thought processes and models need to be sufficiently complex to incorporate them.

Without going in to all of the required detail, but to impress upon you the complexity of LCA for more complex products, consider that a complete LCA of an automobile would require careful energy and materials balances for all the stages of the life cycle:

1. the facilities extracting the ores, coal, and other energy sources;

2. the vehicles, ships, pipelines, and other infrastructure that transport the raw materials, processed materials, and subcomponents along the supply chain to manufacture the consumer product, and that transport the products to the consumer: iron ore ships, trucks carrying steel, engines going to an automobile assembly plant, trucks carrying the cars to dealers, trucks transporting gasoline, lubricating oil, and tires to service stations;

3. the factories that make each of the components that go into a car, including replacement parts, and the car itself;

4. the refineries and electricity generation facilities that provide energy for making and using the car; and

5. the factories that handle the vehicle at the end of its life: battery recycling, shredding, landfills for shredder waste.

Each of these tasks requires energy and materials. Reducing requirements saves energy, as well as reducing the environmental discharges, along the entire supply chain. Often a new material requires more energy to produce, but promises energy savings or easier recycling later. Evaluating whether a new material helps improve environmental quality and sustainability requires an examination of the entire life cycles of the alternatives. To make informed decisions, consumers, companies, and government agencies must know the implications of their choices for environmental quality and sustainability. Having good intentions is not sufficient when a seemingly attractive choice, such as a battery-powered car, can wind up harming what the manufacturer and regulator were trying to protect. This book provides some of the tools that allow manufacturers and consumers to make the right choices.

Systems Thinking in the Life Cycle

All of this discussion of increasingly larger scales of problems requires us to be more explicit in discussing an issue of critical importance in LCA studies that relates to system boundaries. Of course a **system** is just a collection or set of interconnected parts, and the **boundary** is the subset of the overall system that we care to focus on. Our chosen system boundary helps to shape and define what the appropriate parts are that we should study. Above we suggested that the entire life cycle boundary goes from cradle to grave or cradle to cradle. Either choice means that we will have a very large system boundary, and maintaining that boundary (as we will see later) may require a significant amount of effort to complete a study. Due to this effort requirement, or because of different interests, we may instead choose a smaller system boundary. If we are a manufacturer, perhaps our focus is only the cradle to gate impacts. If so, our boundary would include only the stages up to manufacturing. It is also possible that the boundary of our interest lies only in our factory. Constraining the system boundary in these ways means we no longer have a life cycle study.

Life cycle thinking is not restricted to manufactured products. Services, systems, and even entire urban areas can be better understood via life cycle thinking. Services are particularly interesting because such activities are typically considered as having very low impacts (e.g., consulting or banking) because there is no physical good being created, but in reality the same types of effects are uncovered across the life cycle through the service sector's dependence on fuels and electricity. Entire systems (e.g., a roadway network or the electric power grid) can be considered from building all of the equipment components and also then thinking about its design and disposition. At an even higher level, the life cycle of cities includes the life cycles of all of the resources consumed by residents of the city, not just the activities they do within the city's borders.

Finally, life cycle thinking is often useful when making comparisons, such as paper vs. plastic bags or cups, cloth vs. disposable diapers, or retail shopping vs. e-commerce. The relevant issues to deal with in such comparisons would be whether one option is more useful than another, whether they are equal, whether they have similar production processes, etc. In fact as we will see some of the great classic comparisons that have been done in the life cycle analysis domain were very simple comparisons.

A History of Life Cycle Thinking and Life Cycle Assessment

We will discuss the formal methods that apply life cycle thinking to real questions in future chapters (called life cycle *analysis or assessment*). In a life cycle analysis or assessment, the total and comparative impacts of the life cycle stages are considered, with or without quantification of those impacts. But to start, let us talk about some of the original studies that inspire the field of life cycle thinking (before we even knew there was a field for such things).

Most people attribute the first life cycle assessment (LCA) to Coca-Cola in 1969. At the time, Coca-Cola sold its product to consumers in individual glass bottles. Coca-Cola was trying to determine whether to use glass or plastic containers to deliver their beverage product, and wanted to formally support a decision given the tradeoffs between the two materials. Glass is a natural material, but Coca-Cola suggested switching to plastic bottles. They reasoned that this switch would be desirable for the ability to produce plastics in their own facilities, the lower weight of plastic to reduce shipping costs, and the recyclability of plastic versus glass at the time. No specific form of this study has been publicly released but we can envision the considerations that would have been made.

More recently, in the early 1990s, there were various groups of researchers debating the question of "Paper or plastic?" This simple question, which you might get at the grocery store checkout counter or coffee shop, turned into relatively complex exchanges of ideas and results. We may think that we know that the correct answer is "paper," because it is a "natural" product rather than some chemical based material like plastic. We can feel self-satisfied, even if the bag gets wet and tears, spilling our purchases on the ground because we made the natural and environmentally friendly decision. But even these simple questions can, and should, be answered by data and analysis, rather than just a feeling that the natural product is better. The ensuing analysis ignited a major controversy over how to decide which product is better for the environment, beginning with an analysis of paper versus polystyrene cups (Hocking 1991). Hocking's initial study was focused on energy use and estimated that one glass cup used and rewashed 15 times required the same amount of energy as manufacturing 15 paper cups. He also estimated break-even use values for ceramic and plastic cups. The response generated many criticisms and spawned many follow-up studies (too many to list here). In the end, though, what was clear at the time of these studies was that there was no single agreed upon answer to the simple question of "paper vs. plastic". Even now, any study using the best data and methods available today, will still conclude with an answer along the line of "it depends". This is a sobering outcome for a discipline (life cycle thinking) trying to gain traction in the scientific community.

Beyond these studies, other early analyses surprised people, since they found that paper bags, paper cups (or even ceramic cups), and cloth diapers were not obviously superior to their maligned alternatives (i.e., plastic bags, styrofoam cups and disposable diapers) in terms of using less energy and materials, producing less waste, or even disposal at the end of life.

- Paper for bags requires cutting trees and transporting them to a paper mill, both of which use a good deal of energy. Paper-making results in air emissions and water discharges of chlorine and biological waste. After use, the bag goes to a landfill where it gradually decays, releasing methane.

- A paper hot-drink cup generally has a plastic coating to keep the hot liquid from dissolving the cup. The plastic coating introduces the same problems as the foam plastic cup. The plastic is made from petroleum with relatively small environmental discharges. Perhaps most surprising, washing a single ceramic cup by hand uses a good deal of hot water and soap, resulting in discharges of waste water that has to be treated and the expenditure of a substantial amount of fuel to heat the water, although washing the cup in a fully loaded dish washer uses less soap and hot water per cup.

- The amount of hot water and electricity required to wash and dry cloth diapers is substantial. If water is scarce or sewage is not treated, washing cloth diapers is likely to cause more pollution than depositing disposable diapers in a landfill. The best option depends on the issue of water availability (washing uses much more water) and heating the water.

In short, it is not obvious which product is more environmentally benign and more sustainable. Such results are counterintuitive, but they reinforce the importance of life cycle thinking.

The analyses found that the environmental implications of choosing paper versus plastic were more similar than people initially thought. Which is better depends on how bad one thinks water pollution is compared to air pollution compared to using a nonrenewable resource. Perhaps most revealing was the contrast between plants and processes to make paper versus plastic. The best plant-process for making paper cups was much better than the worst plant-process; the same was true for plastic cups. Similarly, the way in which the cups were disposed of made a great deal of difference. Perhaps the most important lesson for consumers was not whether to choose one material over another, but rather to insist that the material chosen be made in an environmentally friendly plant.

The original analyses showed that myriad processes are used to produce a material or product, and so the analyst has to specify the materials, design, and processes in great detail. This led to another problem: in a dynamic economy, materials, designs, and processes are continually changing in response to factor prices, innovation, regulations, and consumer preferences. For example, in a life cycle assessment of a U.S.-manufactured automobile done in the mid-1990s, the design and materials had changed significantly by the time the analysis was completed years later. Still another problem is that performing a careful material and energy balance for a process is time-consuming and expensive. The number of processes that are practical to analyze is limited. Indeed, the rapid change in designs, materials, and processes together with the expense of analyzing each one means that it is impractical and inadvisable to attempt to characterize a product in great detail. The various dependencies, rationales, and assumptions used all make a great deal of difference in the studies mentioned above (for which we have provided no real detail yet). LCA has a formal and structured way of doing the analysis, which we will begin to discuss in Chapter 4.

Decisions Made Without Life Cycle Thinking

Hopefully you are already convinced that life cycle thinking is the appropriate way of thinking about problems. But this understanding is certainly not universal, and there are various examples of not taking a life cycle view that led to poor (albeit well intentioned) decisions being made.

A useful example is the consideration of electric vehicles in the early 1990s. At the time, California and other states were interested in encouraging the adoption of vehicles with no tailpipe emissions in an effort to reduce emissions in urban areas and to gain the associated air quality benefits. Policymakers at the time had a specific term for such vehicles – "zero emissions vehicles (ZEVs)". The thought was that getting a small but significant chunk of the passenger vehicle fleet to have zero emissions could yield big benefits. Regulations at the time sought to get 2% of new vehicles sold to be ZEVs by 1998. In parallel, manufacturers such as General Motors had been designing and developing the EV-1 and similar cars to meet the mandated demand for the vehicles (see Figure 1-3).

Figure 1-3: General Motors' EV-1
(Source: motorstown.com)

So why did we refer to this case as one about life cycles? The electric vehicles to be produced at the time were much different than the electric vehicles of today that include hybrids and plug-in hybrids. These initial cars were rechargeable, but the batteries were lead-acid batteries – basically large versions of the starting and ignition batteries we use in all cars (by large, we mean the batteries were 1,100 pounds!). Let us go back to Figure 1-1 and use life cycle thinking to briefly consider such a system. How would the cars be recharged? They would run on electricity, which even in a progressive state like California leads to various emissions of air pollutants. Similarly, the batteries would have large masses of lead that would need to be processed efficiently. Lead must be extracted, smelted, and processed before it can be used in batteries and then, old lead-acid batteries are often collected and recycled. None of these processes are 100% efficient, despite the claims at the time by industry that it was the case. Would these vehicles be produced in factories with no pollution? It is hard to consider that these vehicles would really have "zero emissions" – but then again, zero is a very small number! There would be increased emissions in the life cycle of these electric vehicles – the question was whether those increases would fully offset the potential gains of reduced tailpipe emissions.

Aside from the perils of considering anything as having zero emissions, various parties began to question whether these vehicles would in fact have any positive improvement on air quality in California, and further, given the need for more electricity and lead, whether one could even consider them as beneficial. In a study published by Lave et al. (to whom this book is dedicated) in *Science* in 1995, the authors built a simple but effective model of the life cycle of these vehicles that estimated that generating the electricity to charge the batteries would result in greater emissions of nitrogen oxide pollution than gasoline-powered cars. Eventually, California backed off of its mandate for ZEVs, partly because of such studies, and policymakers learned important lessons about considering whole life cycles as well as casual use of the number zero. The policymakers had been so focused on the problem of reducing tailpipe emissions that they had overlooked the back-end impacts from lead and increased electricity generation.

It is fair to say this was one of the first instances of life cycle thinking being used to change a "big decision". The lesson again is that life cycle thinking is needed to make informed decisions about environmental impacts and sustainability. Being prepared to use life cycle thinking and analysis to support big decisions is the focus of this book.

A more recent example of life cycle thinking in big decisions is the case of compact fluorescent lamps (CFLs), which were heavily promoted as energy efficient alternatives to incandescent bulbs. While CFLs use significantly less electricity in providing the same amount of light (and thus cost less in the use phase) as traditional bulbs, their disposal represented a problem due to the presence of a small amount of mercury in the lamps (about 4mg per bulb). This amount of mercury is not generally a problem for normal, intact, use of the lamps (and is less mercury than would be emitted from electric power plants to power incandescent bulbs). However, broken CFLs could pose a hazard to users due to mercury vapor – and the DOE Energy Star guide to CFLs has somewhat frightening recommendations about evacuating rooms, using sealed containers, and staying out of the room for several hours. None of this information was good news for consumers thinking about a choice of incandescent vs. CFL lighting choices.

The examples and discussion above hopefully reveal that you can think about life cycles quantitatively or qualitatively, meaning with or without numbers (more on that in Chapter 2).

Inputs and Outputs of Interest in Life Cycle Models

Above we have suggested that there is a need to think about products, services, and other processes as systems by considering the life cycle. We have also mentioned some popular examples of the kinds of life cycle thinking studies that have been done. It is also worth discussing the types of effects across a life cycle that we might be interested in tracking or accounting for.

By 'effects' we mean what happens as a result of a product being manufactured, or a service being provided, etc. There are likely economic costs incurred, for example by paying for the parts and labor needed for assembly. There are interesting and relevant issues to consider when focused purely on economic factors, and Chapter 3 discusses this type of thinking.

In many cases, the 'effects' of producing or using a product mean consuming energy in some way. Likewise, there may be emissions of pollution to the air, water, or land. There are many such effects that one might be interested in studying, and more importantly, in being able to detect and measure. Thus, we can already create a list of potential effects that one might be concerned about in a life cycle study. In terms of effects associated with **inputs** to life cycle systems, we could be concerned about:

- Use of energy inputs, including electricity, as well as solid, liquid, and gaseous fuels.
- Use of resources as inputs, such as ores, fertilizers, and water.

Note that our concern with energy and resource use as inputs may be in terms of the quantities of resources used and/or the extent to which the use of these resources depletes the existing stock of that resource (i.e., are we consuming a significant share of the available resource?). We may also be concerned with whether the energy or resources being consumed are renewable or non-renewable.

In terms of effects associated with **outputs** of life cycle systems, we could be concerned about:

- The product created as a result of an activity, such as electricity from a power plant.
- Emissions of air pollution, for example conventional air emissions such as sulfur dioxide, nitrogen oxides, and carbon monoxide.
- Emissions of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide.
- Emissions to fresh or seawater, including solid waste, chemical discharges, toxics, and warming.
- Other emissions of hazardous or toxic wastes to air, land, water, or recycling facilities.

In short, there is no shortage of energy, environmental, and other effects that we may care about and which may be estimated as part of a study. As we will see later in the book, we may have interest in many effects but only be able to get quality data for a handful of them. We can choose to include any effect for which we think we can get data over as many of the parts of the life cycle as possible. One could envision annotating the paper clip life cycle diagram created above with colored bars representing activities in the life cycle we anticipate have significant inputs or outputs associated with them. For example, activities that we expect to consume significant quantities of water could have a blue box drawn around them or to have a blue square icon placed next to them. Activities we expect to release significant quantities of air pollutants could have black boxes or icons. Activities we expect to create a large amount of solid waste could be annotated with brown. While simplistic (and not informed by any data) such diagrams can be useful in terms of helping us to look broadly at our life cycle of interest and to see where in the life cycle we anticipate the problems to occur.

Aside from simply keeping track of (accounting for) all of these effects across the life cycle, a typical reason for using life cycle thinking is to not just measure but prioritize. Another way of referring to this activity is **hot spot analysis**, where we look at all of the effects and decide which of the life cycle stages contributes most to the total (where "hot spots" appear). Our colored box or icon annotation above could be viewed as a crude hot spot analysis, because it is not informed by actual data yet.

For most cars, the greatest energy use happens during the use phase. Cars in the United States are typically driven more than 120,000 miles over their useful lives. Even fairly fuel-efficient cars will use more energy during use than at any other stage of their life cycle. Likewise hot spots for toxic air emissions for cars may appear in the use phase as well as in the refining of petroleum into gasoline. These examples illustrate why we use life cycle thinking – as we have shown above our intuition is not sufficient in assessing where effects occur, and only by actually collecting data and estimating the effects can we effectively identify hot spots. This use of life cycle thinking to support hot spot analysis helps us identify where we need to focus our attention and efforts to improve our engineering designs. If done in advance, it can have a significant benefit. If done too late, it can lead to designs such as large lead-acid battery vehicles.

Similarly, if we create a plan to generate numerical values representing several of these life cycle effects, we will eventually have to make decisions about how to compare them or prioritize them. Such a decision process will be complicated by needing to compare releases of the same type of pollution across various media (air, water, or land) and also by needing to compare releases of one pollutant against another, comparing pollution and energy, etc. While complicated, the process of making all of these judgments and choices will assist with making a study that we can use to help our decision process. Chapter 12 overviews the types of methods used to support such assessments.

From Inputs and Outputs to Impacts

It is appropriate early on in this textbook to briefly discuss the kinds of uses, emissions, and releases discussed above in connection with the types of environmental or resource use problems they create. The new concept in this section is the idea of an **environmental impact**. Unlike the underlying inputs and outputs of interest such as resource use or emissions, an environmental impact exists when the underlying flows cause an environmental problem. One can think of the old phrase "if a tree falls in the forest but no one is there to hear it, does it make a sound?" This is similar to the connection between environmental releases and environmental impacts. It is possible that a release of a specific type and quantity of pollutant into the environment could have little or no impact. But if the release is of sufficient quantity, or occurs in a location near flora or fauna (especially humans), it is likely that there will be measurable environmental impact(s). Generally, our concerns are motivated by the impacts but are indicated by the uses or releases because most of us cannot directly estimate the impacts. In other words, we often look at the quantities of inputs and outputs as a proxy for the impacts themselves that need to be estimated separately.

This brief section is not a substitute for a more rigorous introduction to such environmental management issues, and should be supplemented with external work or reading if this is not an area of your expertise. One could easily spend a whole semester learning about these underlying connections before attempting to become an expert in life cycle thinking.

Example Indicators for Impacts that Inspire Life Cycle Thinking

In this section, we present introductory descriptions of several prominent environmental impacts considered in LCA studies as exemplars and discuss how various indicators can guide us to the actual environmental problems created. If interested, there are more detailed summaries available elsewhere from agencies, such as the US Environmental Protection Agency, US Geological Survey, the Department of Energy, and we will circle back to discussing them in Chapter 12.

Impact: Fossil fuel depletion – Use of energy sources like fossil fuels is generally an easy way to measure activity because energy costs us to acquire, and there are billing records and energy meters available to give specific quantities. Beyond the basic issue of using energy, much of our energy use comes from unsustainable sources such as fossil fuels that are finite in supply. We might care simply about the finiteness of the energy resource availability as a reason to track energy use across the life cycle. As mentioned above, we might seek to separately classify our use of renewable and non-renewable energy. We might also care about whether a life cycle system at scale could consume significant amounts of the available resources. If so, the use of energy by our life cycle could be quite significant. In the context of our descriptions above, some quantity of fossil energy use (e.g., in BTU or MJ) may be an *indicator* for the *impact* of fossil fuel depletion. Of course, all of the energy extraction, conversion, and combustion processes may lead to other types of environmental impacts (like those detailed below).

Impact: Global Warming / Climate Change – Most people know that there is considerable evidence suggesting that manmade emissions of **greenhouse gases (GHGs)** lead to global warming or climate change. The majority of such GHG emissions come from burning fossil fuels. While we might already be concerned with the use of energy (above), caring more specifically about how our choices of energy sources may affect climate change is an additional impact to consider. Carbon dioxide (CO_2) is the most prominent greenhouse gas, but there are other GHGs that are emitted from human activities that also lead to warming of the atmosphere such as methane (CH_4) and nitrous oxide (N_2O). These latter GHGs have far greater warming effects per unit than carbon dioxide and are emitted from systems such as oil and gas energy infrastructure systems and agricultural processes. GHGs are inevitably global pollutants, as increasing concentrations of them in the atmosphere lead to impacts all over the planet, not just in the region or specific local area where they are emitted. These impacts may eventually manifest as increases in sea levels, migration of biotic zones, changes in local temperatures, etc. Our concern about climate change may be rooted in a desire to assess which component or stage of our product or process has the highest carbon footprint, and thus all else equal, the biggest contributor to climate change. The GHG emissions are indicators of the impacts of global warming and climate change.

Impact: Ozone Depletion – In the early 1970s, scientists discovered that human use of certain substances on the earth, specifically chlorofluorocarbons (CFCs), led to reduction in the quantity of ozone (O_3) in the stratosphere for a period of 50-100 years. This phenomenon is often tracked and referred to as "holes in the ozone layer". The ozone layer, amongst other services, keeps ultraviolet rays from reaching the ground, preserving plant and ocean life and avoiding impacts such as skin cancers. The Montreal Protocol called for a phase out of chemicals that deplete the ozone layer, but not all countries ratified it, not all relevant substances were included, and not all uses were phased out. Consequently, while emissions of many of these substances have been dramatically reduced in the past 30 years, they have not been eliminated, and given the 50-100 year lifetime, ozone depletion remains an impact of concern. Thus, releases of the various ozone-depleting substances can be indicators of potential continued impacts of ozone depletion. Note that there is also "ground level" ozone that is created by interactions of local pollutants and helps to create smog, which, when breathed in, can affect human health. This is an entirely different but important potential environmental impact related to ozone.

Impact: Acid Rain – Releases of various chemicals or chemical compounds lead to increased levels of acidity in a local or regional environment. This acidity penetrates the water cycle and can eventually move into clouds and rain droplets. In the developed world the key linkage was between emissions of sulfur dioxide (SO_2) and acidity of freshwater systems. One of the original points of concern was emissions of sulfur dioxide by coal-fired power plants because they were large single sources and also because they could be fairly easily regulated. Emissions of these pollutants are an indicator of the potential impacts of more acidic environments such as plants and aquatic life destroyed. While in this introduction we have only listed acid rain as an impact, acid rain is part of a family of environmental impacts related to acidification, which we will discuss in more detail later. In short, other non-sulfur compounds like nitrogen oxides can also lead to acidification of waterways, and systems other than freshwater can be affected. Acidification of water occurs due to global uptake of carbon dioxide and is of increasing concern in oceans where acidification affects coral reefs and thus the entire ocean ecosystem.

There are various other environmental impacts that have been considered in LCA studies, such as those associated with eutrophication, human health, and eco-toxicity, but we will save discussion of them for later in the text. These initial examples, though, should demonstrate that there are a wide variety of local and global, small and large scale, and scientifically relevant indicators that exist to help us to assess the many potential environmental impacts of products and systems.

The Role of Design Choices

The principles of LCA can help to build frameworks that allow us to consider the implications of making design (or re-design) decisions and to track the expected outcomes across the life cycle of the product. For example, deciding whether to make a car out of aluminum or steel involves a complicated series of analyses:

- Would the two materials provide the same level of functionality? Would structural strength or safety be compromised with either material? Lighter vehicles have been found to be less safe in crashes, although improved design and new automation technology might remove this difference (NRC 2002, Anderson 2014). A significant drop in safety for the lighter vehicles would outweigh the energy savings, depending on the values of the decision maker.

- Are there any implications for disposal and reuse of the materials? At present, about 60% of the mass of old cars is recycled or reused. Moreover, motor vehicles are among the most frequently recycled of all products since recycling is usually profitable; both aluminum and steel are recycled and reused from automobiles (Boon et al. 2000). It takes much less energy to recycle aluminum than to refine it from ore. The advantage for recycling steel is smaller.

- What is the relative cost of the two materials, both for production and over the lifetime of the vehicle? An aluminum vehicle would cost more to build, but be lighter than a comparable steel vehicle, saving some gasoline expenses over the lifetime of the vehicle. Do the gasoline savings exceed the greater cost of manufacturing? Of energy? Of environmental quality?

In this example, steel, aluminum, copper, glass, rubber, and plastics are the materials, while electricity, natural gas, and petroleum are the energy that go into making, using, and disposing of a car. The vehicle runs on gasoline, but also needs lubricating oil and replacement parts such as tires, filters, and brake linings. At the end of its life, the typical American car is shredded; the metals are recycled, and the shredder waste (plastic, glass, and rubber) goes to a landfill.

What Life Cycle Thinking and Life Cycle Assessment Is Not

The purpose of this chapter has been to motivate life cycle thinking, and why it should be chosen to ensure broadly scoped analysis of issues with potential environmental impacts – i.e., we have been introducing "what life cycle thinking is". We end the chapter by briefly summarizing what life cycle thinking (and, by extension, life cycle assessment) is *not* able to achieve.

First, life cycle thinking will not ensure a path to sustainability. If anything, thinking more broadly about environmental problems has the potential side effect of making environmental problems seem even more complex. At the least it will typically lead to greater estimates of environmental impact as compared to studies with more limited scopes. But life cycle thinking can be a useful analytical and decision support tool for those interested in promoting and achieving sustainability.

Second, life cycle thinking is not a panacea - a magic pill or remedy that solves all of society's problems. It is merely a way of structuring or organizing the relevant parts of a life cycle and helping to track performance. Addressing the economic, environmental, and social issues in the context of sustainability can be done without using LCA. To reduce energy and environmental impacts associated with product or process life cycles, we must want to take action on the findings of our studies. By taking action we decide to improve upon the current impacts of a product and make changes to the design, manufacture, or use of the current systems so that future impacts are reduced.

LCA is not a single model solution to our complex energy and environmental problems. It is not a substitute for risk analysis, environmental impact assessment, environmental management, benefit-cost analysis, etc. All of these related methods have been developed over many years and may still be useful in bringing to the table to help solve these problems. LCA can in most cases interact with these alternative methods to help make decisions.

Chapter Summary

Life cycle assessment (LCA) is a framework for viewing products and systems from the cradle to the grave. The key benefit of adopting such a perspective is the creation of a "systems thinking" view that is broadly encompassing and can be analyzed with existing methods. When a life cycle perspective has not been used, unexpected environmental impacts have occurred, some that may been anticipated with a broader view.

As we will see in the chapters to come, even though there is a standard for applying life cycle thinking to problem solving, it is not a simple recipe. There are many study design choices, variations, and other variables in the system. One person may apply life cycle thinking in one way, and another in a completely different way. We cannot expect then that simply using life cycle thinking will lead to a single right answer that we can all agree on.

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End of Chapter Questions

Objective 1: State (a) the concept of a life cycle and (b) its various stages as related to assessment of products.

1. Describe the major activities in each of the five life cycle stages of Figure 1 for a soft drink beverage container of your choice. Describe also the activities needed to support reuse, remanufacturing, and recycling activities for the container chosen.

Objective 2: Illustrate the complexity of life cycles for even simple products.

2. Draw by hand or with software a diagram of a life cycle for a simple product (other than a paper clip as shown in-chapter), with words representing the various activities in the life cycle needed to make the product, and arrows representing connections between the activities. Annotate the diagram with colors or shading to represent hot spots for two inputs or outputs that you believe are relevant for decisions associated with the product.

3. Do the same exercise as in Question 2, but for a school or university, which is providing a service not making a physical product.

Objective 3: Explain why environmental problems, like physical products, (a) are complex and (b) require broad thinking and boundaries that include all stages of the life cycle.

4. Power plants (especially fossil-fuel based coal and gas-fired units) are frequently mentioned sources of environmental problems. List three specific types of outputs to the environment resulting from these fossil plants. Which other parts of the life cycle of producing electricity from fossil plants also contribute to these problems?

Objective 4: Describe what kinds of outcomes we might expect if we fail to use life cycle thinking.

5. Across the life cycle of a laptop computer, discuss which life cycle stages might contribute to the environmental impact categories discussed in the chapter (global warming, ozone depletion, and acid rain). Are there other classes of environmental impact you can envision for this product?

Synthesis of Objectives

6. Suppose that a particular truck requires diesel fuel to transport freight (that is, moving tons of freight over some distance). In the process, carbon dioxide is emitted from the truck.

    a. In the terminology of life cycle thinking presented in this chapter, what does the diesel fuel represent?

    b. What do the freight movement and carbon dioxide represent?

c. What stage of the truck life cycle is being presented in this problem so far? What other truck life cycle stages might be important to consider?

d. In considering the environmental impacts of trucks, would it be advisable to expand our system of thinking to include providing roadways? Why or why not?