Environmental Life-Cycle Analysis: A primer

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A PRIMER

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FOREWORD

Sustainability actions are designed to reconcile two competing forces – environmental considerations on the one hand, and increasing population and rising demands on the other, in the context of finite resources. Resources comprise of 1) natural endowment which defines broader limits upto which it can sustain the population's demands, and 2) scientific and technological advancement, which defines how efficiently or inefficiently the resources are used. The sustainability agenda is pursued by trying to achieve a balance between the development agenda and societal goals and associated 'transformations' in physical, institutional, and governance structures. Life cycle analysis (LCA) provides a conceptual basis to understand how socio-economic development choices depend on – and interact with – the natural environment.

This book is truly innovative and lucidly written, with many illustrations to boot. It provides an easy understanding of the complex LCA concept to students, and will also be useful for students from non-science and non-technical backgrounds. The book explains the basic philosophy of LCA and argues, by providing examples, in its favour as a standard method for environmental decision-making.

During my teaching career which has spanned over two decades, I have seen young researchers struggling for guidance to fast-track their understanding of the LCA methodology and use it as an integral part of their research work. Students grapple with difficulties in defining system boundary, allocating environmental impacts of various interactive products or systems and analysing the life cycle inventory. All these are explained well in this book. Each section of the book starts with learning objectives, explains the concept with interesting case studies and ends with exercises to stimulate critical thinking. In addition to students, I believe that researchers and environment practitioners will also find the book useful.

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PREFACE AND ACKNOWLEDGEMENTS

This little book is a primer. Just as the word implies, it is the preparatory coat which one applies to the wall, before applying the final layers of paint. The final layers of paint will sharpen the student's skills, but the primer will help to advance quickly and retain the knowledge gained thereafter.

The target readership here is not necessarily only those who wish to undertake specialised courses in environmental life-cycle analysis (E-LCA) later on, in universities or research institutes around the world, but anyone and everyone who is curious to know what this well-entrenched acronym actually means. That includes even those studying to be lawyers, political scientists, administrators, business managers, etc. The environment is not just for scientists, after all, to understand, study, manage and maintain!

I have tried to used lucid language and have taken resort to analogies and 'cartoons' quite often in order to impress upon readers that E-LCA is not rocket-science. It requires a lot of attention to detail and a diverse understanding of systems being studied; that is all.

If this primer generates interest in the minds of some readers who would subsequently seek out more information, and also perhaps enrol for specialised courses offered in universities around the world, yours sincerely would consider that to be a reward unto itself. Having said that, I would just add that there is a lot of material on E-LCA available online and some excellent textbooks written by experts who have worked in this field – teaching, researching and publishing – for many years. If this primer serves as a modest aid to lead students on to the 'real masterpieces', it would have done its bit!

My sincere thanks to **Prof Dr Arun Kansal** of *The Energy Research Institute* (TERI), New Delhi, India and **Dr Geoffrey Guest**, Research Scientist at *Agriculture and Agri-Food Canada,* Ottawa (Ontario, Canada), for their insightful review-comments which helped me to improve the content; and also for the Foreword and the Afterword, respectively. Thanks, of course to Karin Jakobsen of BookBoon for her support all along, from 'concept to commissioning'

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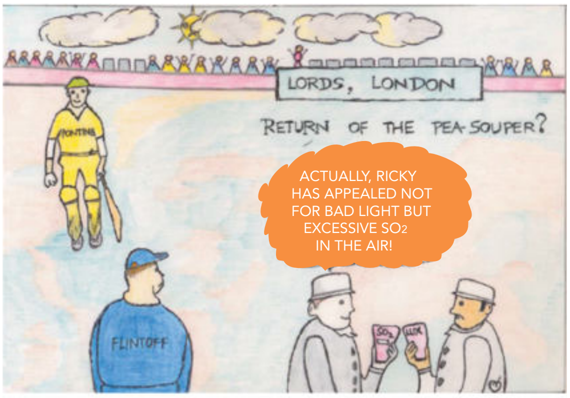
Karlstad, Sweden,
Year-2016

1 INTRODUCTION

Learning objectives: This chapter is to this book, what a trailer is to a movie. The purpose is just to get you interested in the chapters that follow this one…



By presenting grave concerns in a lighter vein, as in the self-explanatory lead picture, one hopes to, and often succeeds in attracting the attention of more people. Readers in the print media and viewers/listeners in the audio-visual media. A picture, as they say, is worth a thousand words! Likewise, a song or a short poem could also be worth a thousand or more. (Just try to prepare a short speech (5 minutes) based on the collage of three illustrations presented above; or some of you may be motivated to come up with sketches to depict some other challenges which humankind is trying to surmount). You can go on and on…

1.1 PHILOSOPHICAL AND FUNCTIONAL GOALS

We, humans, are dependent on the environment for our existence (yours sincerely hopes and prays that more and more of us will know and appreciate this, as soon as possible) and will continue to be dependent on it. As the 19th century Indian seer and philospher Swami Vivekananda said, '*We have to bear in mind that we are all debtors to the world and the world does not owe us anything. It is a great privilege for all of us to be allowed to do anything for the world. In helping the world, we really help ourselves.*' One may substitute the word 'environment' for 'world' in the message above. Dependence, instead of generating a feeling of gratitude, leads to mishandling and mistreatment and brings about a 'taking-for-granted' attitude in its wake…more often than not. That, we have been witnessing around us; and still do, when we encounter self-serving, materialistic narcissists in our daily lives who 'eat, drink and make merry, for tomorrow we die'. Such people do not really wish to think that they are here for much higher purposes. Sad indeed.

Now, while it is an indisputable fact that humankind has wreaked some havoc on the environment on which it depends, one may wish to measure this 'havoc' and try to understand what one can do, to hold back the rate at which the damage is occurring. If you can measure, you can manage. If you cannot, well…that is a different story. This is the philosophical basis of an environmental life-cycle analysis (E-LCA) – a basic understanding of our dependence on the environment and its vulnerability; and an ardent desire to play a role in setting things right. This is the answer to the primary 'Why' of E-LCA. Figure 1.1 shows the spheres of the environment – land/soil (lithosphere/pedosphere), air (atmosphere), water (hydrosphere) and the biosphere [the Flora (with all the plant-life) and the Fauna (the animal/bird/insect/reptile kingdom)]. Humans can be looked upon as comprising the Anthroposphere which has been responsible for the detrimental impacts on soil, air and water, and also on the flora and the fauna. The double-headed arrows indicate that humans extract valuable resources from the environment (making it the **source**), and also discharge wastes back into it (making it the **sink** also).

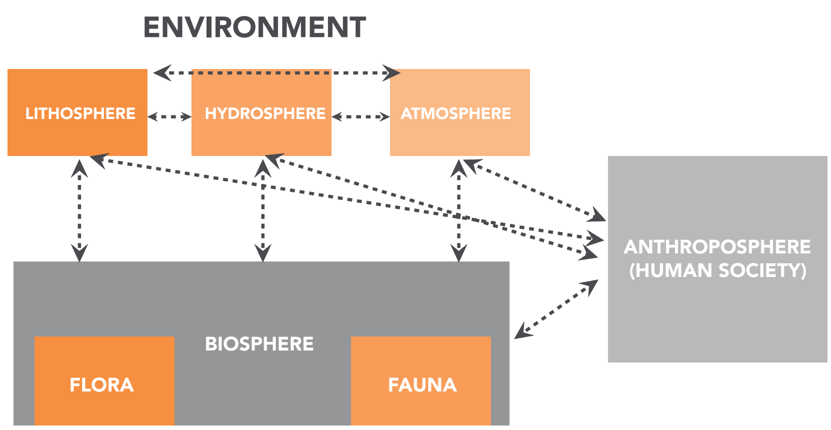


Figure 1.1: The different interacting 'spheres'

We do not need to be geniuses or prodigies to understand that if we need to continue using the environment as a source, we need to be aware of what we are doing to it when we use it as a sink and of course also how we are using it as a source. We can introduce the term 'carrying capacity' here, as the capacity beyond which the ability of a source to provide necessary services to humans (and for that matter, other living creatures as well) is irreversibly compromised. (Think for instance of how much a pack animal like a donkey can carry on its back. There is a limit. If you exceed this, the animal will collapse and perhaps suffer irreversible damage to its hauling-ability. It will then cease to be useful to its owner.) Each unit of the environment has its own carrying capacity, be that a lake, river, forest, or for that matter even animal species (in the last case, one could think more of the ability to endure). For example, if you are withdrawing raw water from a lake (to be treated and supplied for consumption), you would surely be careful about the wastewater you would be discharging into the lake! If you discharge trash and toxins, it will be you who will be (or may be) depending on the same water as a source of drinking water later on. Of course, you do not want to spread thorns under your own feet or throw a banana peel carelessly on the street without considering the possibility of stepping on it and falling and hurting yourself later on?

It is thus an indisputable fact that our actions have impacts on the environment – both adverse (which need to be reduced) and desirable (which need to be augmented). By bringing about the reduction and increase referred to in the previous sentence, we will be able to contribute to environmental sustainability. But how do we know if we are effecting a reduction or an improvement for that matter? To reiterate, *'You can manage what you can measure; or rather you cannot manage what you cannot measure!'*

Having answered the primary 'Why' of E-LCA, we will deal with the secondary *Whys* – the so-called functional goals – in Chapter 3.

1.2 THE JOURNEY

In the chapters that follow, you will be introduced to holistic (as opposed to 'narrow-minded' or 'tunnel-vision') thinking through the concepts of 'systems analysis' and 'life-cycle approach'. This knowledge will be seamlessly integrated with an introduction to the much-touted, well-entrenched tool/field of Environmental Life-Cycle Analysis (E-LCA, or simply LCA). Science, as opposed to art, obeys rules, sometimes very religiously. Hence, you will be taken through the steps which need to be assiduously followed while performing an E-LCA. This is where you understand the importance of defining the goal (the secondary *Whys* of E-LCA) and the scope of your analysis before starting. You also realise that E-LCA is data-intensive. You need to gather a lot of data in advance – either first-hand or from databases or published reports/papers/articles, before commencing on the assessment *per se*. There are some steps which are mandatory and some others which are obligatory. Now, the 'obligatoriness' would depend greatly on the goal you have specified for yourself.

Also included in this book are short chapters dealing with attributional/consequential LCA, rebound effect and problem shifting, allocation of environmental impacts, forecasting and backcasting. Attempting the exercises which appear at the end of every chapter will enable you to gain in confidence, which will be handy when you study and carry out E-LCA in much greater detail as a student or a professional later on in life…which I hope that many of you would like to do.

1.3 NOT α TO ω, JUST ABC

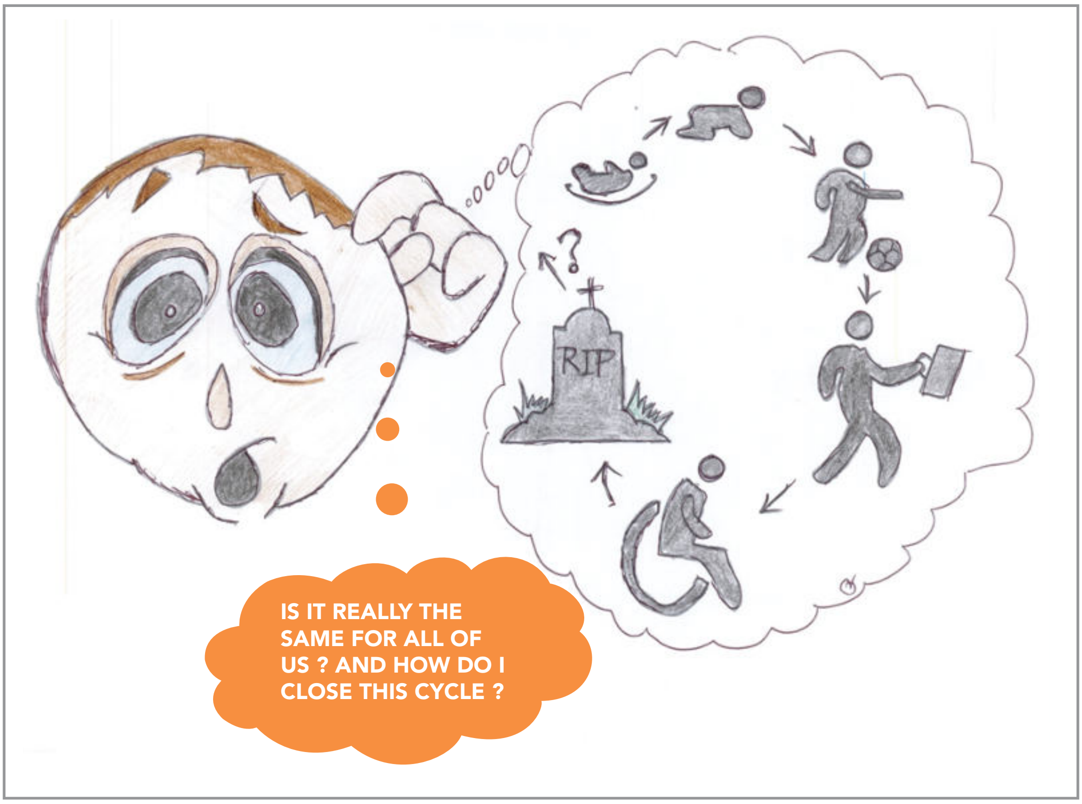
It must be emphasized here that the purpose of this book is obviously not to provide the alpha to omega of E-LCA, but rather just an ABC. It is just the starter, the appetiser… before the main course which you may wish to savour, and the satisfaction you would derive from the dessert which would follow thereafter!

Exercise

1. As you read in the chapter, if you are withdrawing raw water from a lake (to be treated and supplied for consumption), you would surely be careful about the wastewater you would be discharging into the same lake! If you discharge trash and toxins, it will be you who will be depending on the sink as a source of drinking water later on! But if your source for raw water is say, a lake in Sweden/Finland/Germany/Latvia/Estonia/Poland; and the sink for wastewater is the Baltic Sea for example, would that mean you do not need to worry at all?

2 SYSTEMS AND LIFE-CYCLE THINKING

Learning objectives: This is merely an introduction to what is meant by systems thinking and life-cycle thinking. These terms are, of course, self-explanatory to a great extent. Systems thinking is indispensable for understanding E-LCA. Readers must also bear in mind that life-cycle thinking and systems analysis encompass much more than just E-LCA. In other words, life-cycle thinking is definitely not synonymous with E-LCA!



2.1 SYSTEMS

A system is defined by the person studying it. In other words, what the system is depends on how one defines it. The definition entails setting up the boundaries for the same. For instance, if you wish to define your home as the system, the outer envelope of walls, ceilings and floors would become the boundaries of the system. Everything inside the home is a component of the system; and groups of interrelated components can be classified as sub-systems. You would thus understand the system at three different hierarchical levels – the entire system, its constituent sub-systems and the constituents of the subsystems (Figure 2.1). The constituents of the sub-systems may be labelled as sub-sub-systems or simply components. Components would figure right at the bottom of the hierarchy.

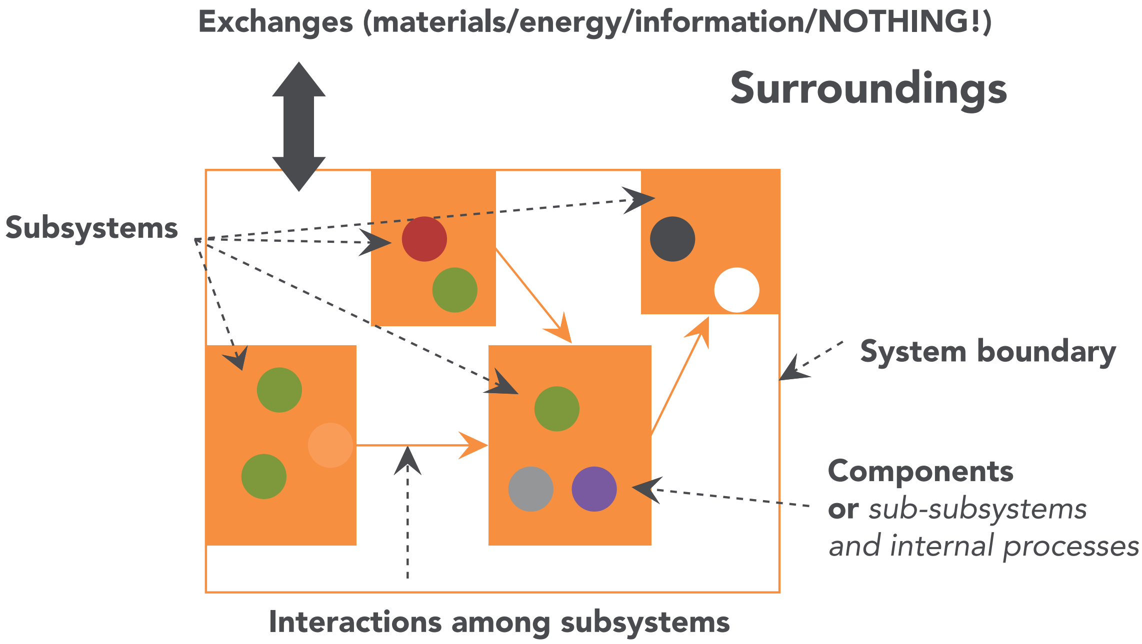


Figure 2.1: System, sub-systems, components and surroundings

Everything external to the boundaries of the system, comprises the surroundings of the system. Now, when you analyse a system, you ideally start by doing an 'internal' systems analysis, by studying the constituents of the sub-systems and the interactions (exchanges of materials, energy and information for instance) among the sub-systems within the system. Having understood the system fairly well – this is an indispensable first step – you go on to perform the 'external' systems analysis. This entails studying the interactions between the system (which could be considered as a black box for the sake of the 'external' systems analysis), and its surroundings. Now, you may opt to consider the atmosphere, hydrosphere, pedosphere and lithosphere as the surroundings, and carry out an environmental systems analysis. You may also consider the economy as the surroundings and perform an economic systems analysis; or you could perform a socio-cultural systems analysis by considering the surroundings as the society of which you or your system (the home in this case) is a part. You can compare two systems – A and B – on the basis of their interactions with the economy, environment and society. These have been depicted in Figure 2.2.

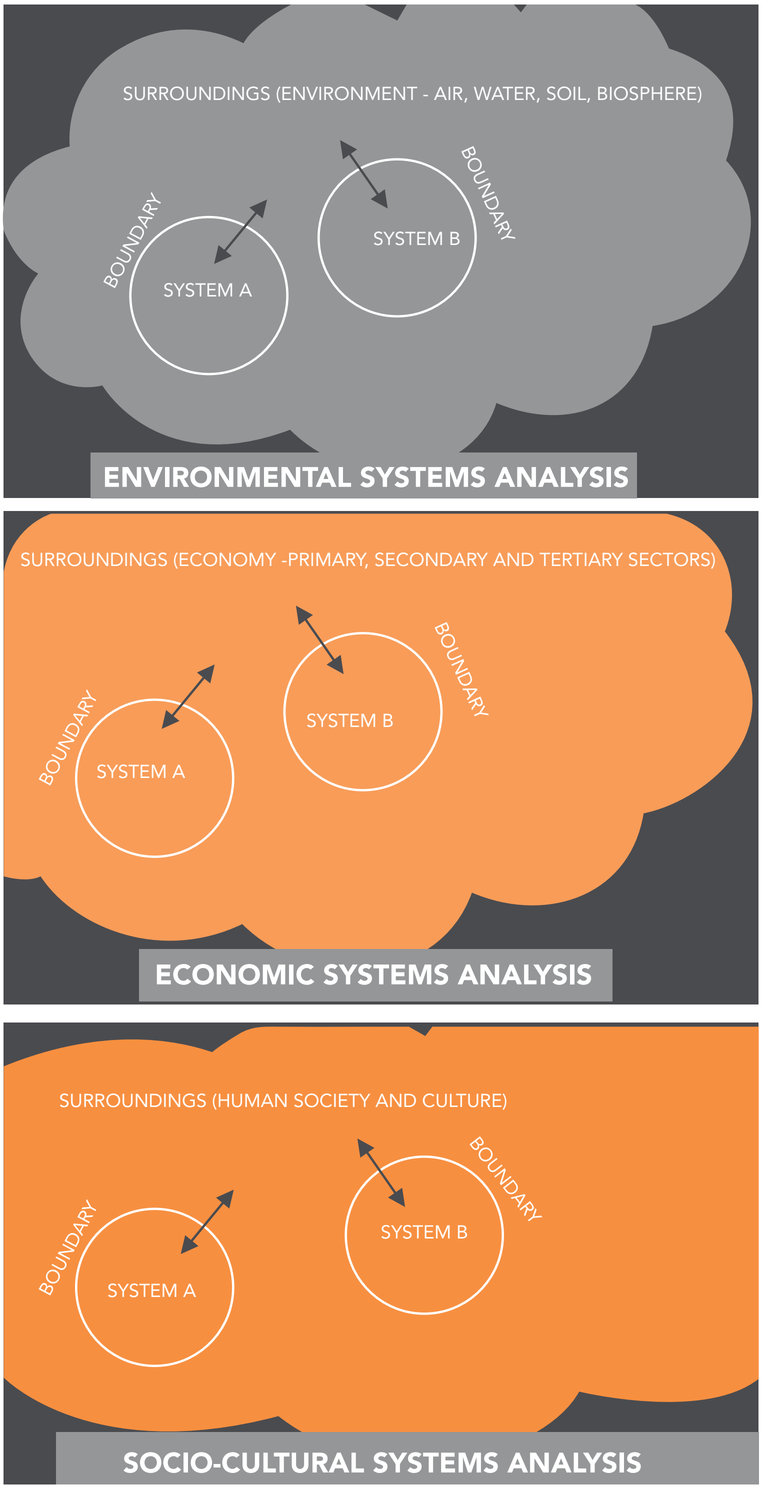


Figure 2.2: Economic, environmental and socio-cultural systems analysis

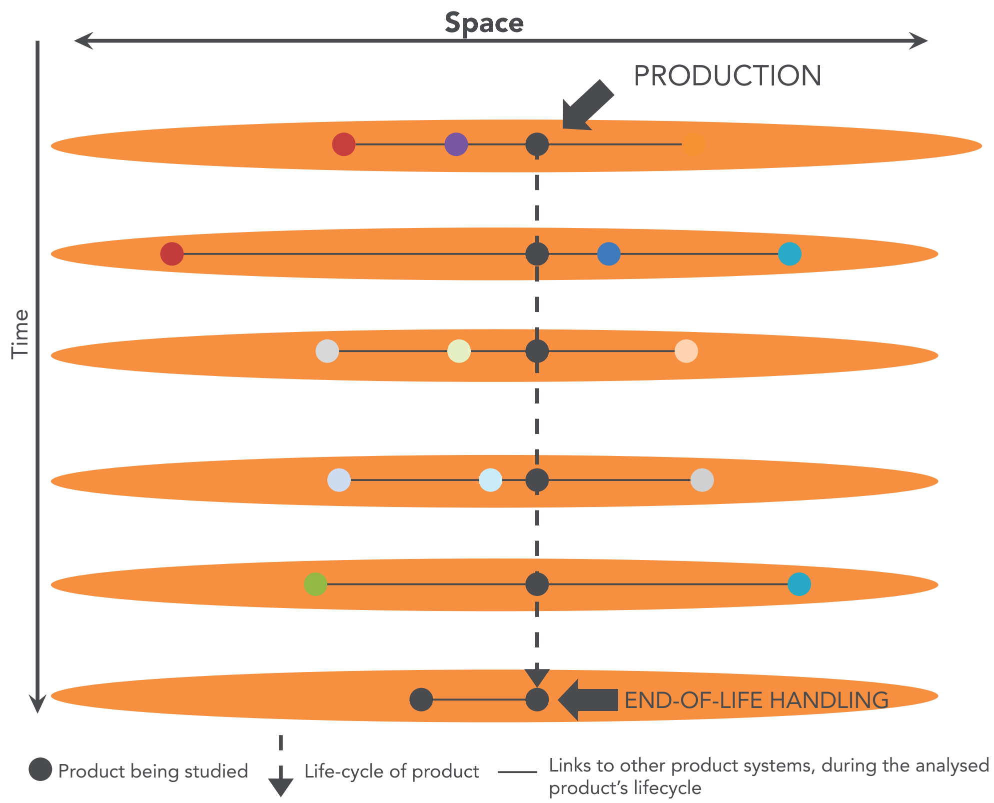


Figure 2.3: Systems and life-cycle thinking – of space and time

2.2 LIFE-CYCLE THINKING AND LIFETIMES

You would be analysing the interactions the system has with its surroundings at any given point of time. The system would have existed before you started your analysis, and will exist after you complete it. So, the analysis you are performing is a static one, carried out at the instant of time you are analysing it. How about studying the past and the future of this same system. In other words, right from when it came into being, and till the point of time when it would cease to exist (like for instance, the home you now inhabit, would have been constructed at some point in time in the past, and may be demolished perhaps, after a lifetime of hundred years or so). Now, instead of a system, think of a product – say your washing machine or dishwasher (these are components of two different sub-systems of your home!). Refer Figure 2.3 and think. The product you are analysing is shown as a filled black circle. This product has a lifetime – from production to end-of-life handling. Over this period of time, it interacts with other products/systems (shown as circles of other colours) and also with the environmental media – air, water, soil, land, fauna and flora. Its interactions with other products/ systems, are the causes for the interactions of the latter with the environmental media. Think of all the components of the washing machine and how they are fabricated (You would have guessed correctly that the fabrication of each of its components can be traced back in time, and across space to a complex network of processes). Thus, the product you are studying causes environmental impacts all through its life-cycle, directly and indirectly. If you club different products together to form a sub-system, you would be able to analyse the life-cycle environmental impacts of the sub-system. If you club different sub-systems together to form a system, you can analyse the life-cycle environmental impacts of the system. For instance, your car can be considered as a single product sold on the market. You could consider it to be a sub-system of the system of transportation in the city you stay in. You can also consider it to be a system, and break it down into different sub-systems, each performing a well-defined function – chassis, transmission, engine etc. The car as such, from 'birth' till 'end-of-life', interacts with several different kinds of systems – roads, gas stations, battery charging points (in the case of electric or hybrid vehicles), garages, automotive component suppliers, water supply systems, recyclers etc. When you disaggregate a system or sub-system, you at once realise that each of its component parts has a different lifetime.

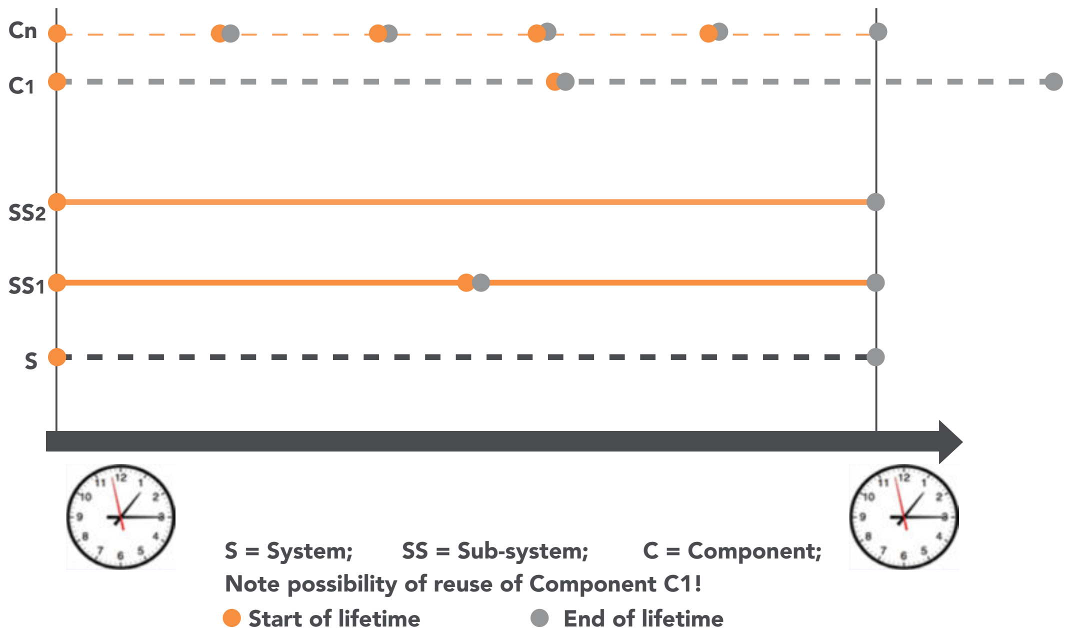


Figure 2.4: Life-cycles: System, sub-systems, and components

From Figure 2.4, which is a hypothetical example, it is at once seen that the lifetimes of the component parts of a sub-system would be less than or equal to the lifetime of the sub-system; and the lifetime of the sub-system may be equal to or less than that of the system of which it is a part. We know that, in general, there are component replacements which happen as part of repair and maintenance activities and sub-system overhauls as well. Of course, when the system itself reaches the end of its lifetime, as seen in Figure 2.4, there would be many components with residual lifetimes; and these can be reused. For that matter, entire sub-systems can be reused elsewhere! Components which reach the end of their lifetimes, are recycled for their material value – closed-loop (ending up in a similar product) or open-loop (ending up in a different product for which material quality requirements are less stringent – so-called downcycling). As an example, consider your own home. It would have a lifetime of say, 100 years. You would have a modular kitchen – a sub-system within your home – which would perhaps be changed after 20 years, when you would be selling your home for instance. Within this modular kitchen, you would have forks and spoons, which you would perhaps change every five years, sending the used ones to metal-recycling centres. Of course, when the home reaches its end-of-life after 100 years, and is about to be demolished, there would be sub-systems and components within it with residual useful lifetimes, which could be passed on to others in society who would find use for the same – either *gratis* or otherwise.

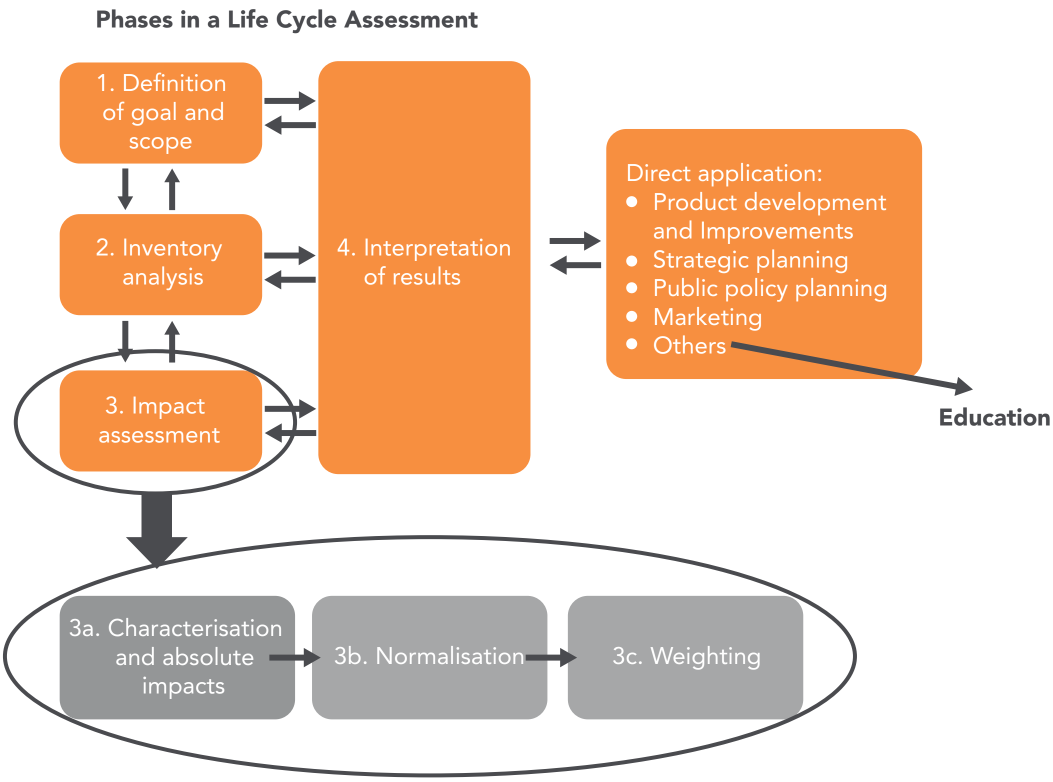
It is not advisable to miss the wood for the trees. But at the same time, it is also imperative that one does not get lost in the forest. The purpose is to understand holistically…and getting lost in the woods means ending up confused and not necessarily wiser than when you set out on the trek through the forest. Having understood what systems thinking and life-cycle thinking is, it is just right to move on to what this book is all about – environmental life-cycle analysis (E-LCA or simply LCA as it is called, of products and/or systems). In the chapters following this one, the acronym LCA will be used.

Exercises

1. Take the automobile. How does this interact with the environment over its life-cycle. Think of it as a system with a beginning and an end, and discuss. Of course, you would need to define what happens at the end (in terms of interactions with the environment). Sketch as detailed a diagram as possible to depict this. The diagram of course could have different 'sub-diagrams'! Now, would you say that all the interactions with the environment are adverse? Can the damages be mitigated? Discuss, from a life-cycle and systemic perspective.
2. Look at the lead picture very carefully. Can you prepare a write-up of 250 words describing the analogies you can draw from it? Think of the links with the environment/nature and pay special attention to the 'end-of-life'. You do not necessarily need to foray into the 'spiritual'.
3. Following up on Q1, look up the Internet for data regarding the lifetimes on the three levels discussed in the chapter, for the car. Of course, you can decide to what extent you would go, as far as comprehensiveness is concerned.
4. We referred to downcycling and recycling back into a similar product. Can one talk of 'upcycling'? If yes, what does that mean, and can that happen in practice? Do you know of any case where this happens? You can investigate and find out.
5. What do the expressions 'cradle-to-grave', 'cradle-to-cradle', 'field-to-fork', 'well-to-tank' and 'well-to-wheel' mean in the context of life-cycle analyses?

3 ENVIRONMENTAL LIFE-CYCLE ANALYSIS – *DE RIGEUR* PROCEDURE?

Learning objectives: Just an introduction to how this is carried out – formally, stepwise – adhering to rules and standards laid down by the International Standards Organisation



Well, the chapter heading is a question. I would answer 'Yes' and proceed to introduce the International Standards Organisation (ISO) standards to you…After all, if scientists and analysts around the world need to meet at conferences and understand each other, there needs to be some standardisation and harmonisation. Of course, one may wish to experiment and be creative within the frameworks of these standards!

In year 2006, ISO 14040:2006 and ISO 14044 came into being to supplant the standards drawn up in 1997-2000, viz.: ISO 14040–14043. These standards essentially form the framework within which analysts and practitioners in the world perform LCA. Those of you who are interested in reading the complete ISO documents, are encouraged to do so. As the lead picture on the previous page shows, LCA entails four major steps, with the ultimate goals being one or more of the following (also depicted in the said lead picture):

- Looking out for possibilities to reduce the environmental impacts of products at different stages in their life-cycles
- Conveying information to decision-makers in industry, government and NGOs, which will assist in strategic planning
- Identifying relevant environmental performance indicators
- Marketing and promoting products (through eco-labelling certificates and environmental product declarations)
- Education (the purpose which this book wishes to accomplish).

You will at once note that step 3 in the lead picture, has been split up into 3a, 3b and 3c and the last two boxes have dotted lines as their borders. This is to indicate that these two – 3b and 3c – are usually optional sub-steps, which need not (may not) be carried out. We will discuss more about the 'whats' and 'whys' of these in subsequent chapters.

3.1 GOAL AND SCOPE

Now, what is 'goal'? Well, I would refer you back to the previous section where five of them have been listed. Your goal could be one or more of these five. Usually it more than just one. Specifying what the goal actually is concentrates minds and enables the analyst to focus. Note very well that it is quite easy to get distracted when you set out to perform an LCA. You always need to remember the 'why' and the 'for whom'. The LCA has necessarily to fulfil a purpose – be it just conveying information to students in the classroom or communicating with a bureaucrat in the Ministry of Environment in your country's government. The ends, as they say, determine the means and also justify them.

Now, what is 'scope'? Here, I would like to refer back to Figure 2.1, in which you see a system boundary which separates the system defined, from everything outside it. Having done this, you also have indirectly decided on what the inflows (inputs) into the system across the boundary are (from other systems, or from the environment for instance) and what the outflows (outputs) from the system across this boundary are. You can either widen or narrow the scope, by fixing the boundaries to include or exclude more sub-systems respectively (Refer Figure 3.1). Eight different options have been depicted in Figure 3.1 for the LCA of a conventional urban water and wastewater system – the entire system with five sub-systems, each of the five individual sub-systems of this big system, the upstream which includes only water treatment and water distribution, and the downstream which includes only sewage transport and sewage treatment. Now, you would have got the point! When the scope is defined, one also needs to identify the so-called 'functional unit'. Now what is a functional unit? If I say, for instance, *'X kg of material A and Y kg of material B are needed to produce 1 kg of the product being analysed'*, I have decided to choose **1 kg of the product** as the functional unit and the material inputs of the LCA are X and Y. Or, if I say *' Y GWh of electricity (at grid; or in other words, delivered by the power plant to the transmission network) and Z litres of diesel are required to supply potable water to all the people in your city for one year'*, I can decide to use **'the action of supplying potable water to all the people in your city for one year'** as the functional unit; consequently, the electricity input for the LCA would be Y GWh and the diesel fuel input would be Z litres. Subsequently, all the environmental impacts are expressed as specific values, in terms of '*1 kg of product'* or *'Potable water supplied to the inhabitants of your city during one year'.* Or you may wish to compare different alternatives **'to travel 3 km from home to work daily'** – bus, bicycle, walking, car, two-wheeler etc.

Also, bear in mind that the definition of the scope itself is dependent on what the goal is! You would decide on which environmental impact categories you want to study, when you define the scope. An impact category is a type of damage done to the environment (air and/or water and/or soil and/or land and/or flora and/or fauna), by the processes and activities happening within systems – anthropogenic or otherwise. Some of them are listed hereunder (also refer to Appendix):

- **Global warming**
- **Eutrophication**
- **Acidification**
- **Marine ecotoxicity**
- **Freshwater ecotoxicity**
- **Human toxicity**
- **Photochemical ozone creation**
- **Ozone depletion**
- **Abiotic depletion**

These impact categories are termed as 'environmental mechanisms leading to the midpoint indicators'[1]. (The ReCiPe method to which you are directed via this footnote reference, will be useful in the future if any of you decide to study LCA in greater detail). The interactions of a system with the environment – by virtue of resource consumption and emissions – can be considered to be the direct causes of the midpoint indicators or environmental impacts which are a direct consequence of the environmental mechanisms triggered by the said interactions. Midpoint indicators acting in concert lead to the so-called 'endpoint indicators' or 'damage indicators'. The ReCiPe method referred to above identifies three such:

- ***Human health damage***
- ***Ecosystem damage***
- ***Resource depletion***

From 'potential impact' to perceptible/measurable 'damage' is of course a terrain laden with uncertainties. This is where one talks about the possible fates of the emitted pollutants and the probability of exposure of a given environmental medium (air, water, soil, land or the biosphere which includes human beings) to them. It is this uncertainty which sometimes makes analysts restrict their scope around the environmental mechanisms triggering the midpoint indicators. One may wish to either select one or more of the environmental mechanisms listed above, or opt for one or more of the endpoint indicators. These options are largely influenced by the scope, which in turn, is determined by what the goal is. The more uncertainty one introduces while defining the scope, the greater would be the need to carry out an uncertainty analysis[2]. Whatever the goal is, it is the analyst's responsibility to be honest and transparent, as there is a stark possibility that decision-makers who do not have much time to seek second opinions, may just follow the recommendations of the analyst. So, when you carry out an LCA and communicate the results, you are shouldering a great responsibility – your actions may influence changes and it is better if the changes would be for the better, so to say.

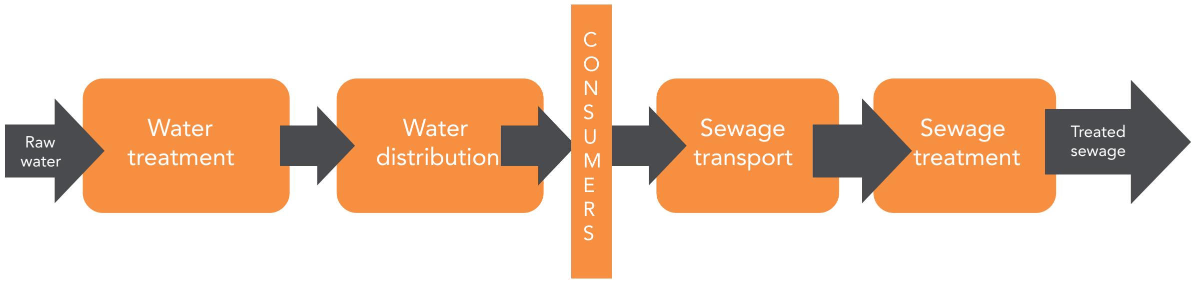


Figure 3.1: Scope and system boundaries – multiple options shown for an LCA of a conventional urban water and wastewater system as an example

3.2 INVENTORY ANALYSIS (LCI)

Let us understand this step with a diagram (Figure 3.2)

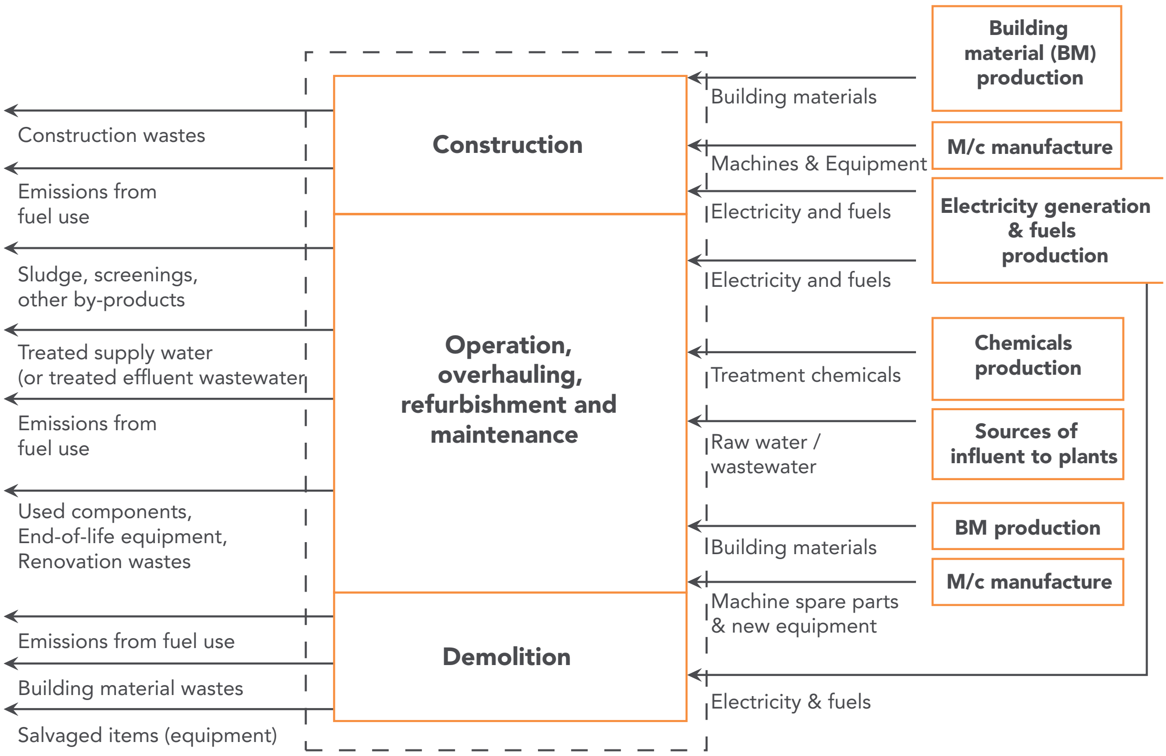


Figure 3.2: Inflows to conventional water treatment plants or wastewater treatment plants from other systems and outflows from them to other systems or the environment, during a complete life-cycle[3]

As we have used the urban water and wastewater system as an example in Figure 3.1 to understand setting the system boundaries, we will choose two of the eight options referred to in the previous section – water treatment and sewage treatment. The inventory – inflows/requirements of materials and energy, and outflows of products, by-products, reusables/recyclables and emissions, for either of these two, are shown in Figure 3.2. The life-cycle of this system is depicted with the dotted blue rectangle (Compare this with Figure 2.2).

The flows can be inventorised on a daily/weekly/monthly/yearly basis. The frequencies would vary depending on the type of flow (inflow or outflow). For instance, building materials for construction enter into the system at the beginning of the lifecycle and stay on usually, till the demolition of the structure and the creation of building material wastes towards the end of the life-cycle. Raw water into and potable water out of a water treatment plant; raw sewage into and treated sewage out of a wastewater treatment plant, flow on a continuous basis. So do chemicals and fuels and associated emissions. Interactions of the system we are studying in Figure 3.2, with other product systems upstream (on the right in the diagram) are the causes of indirect environmental impacts. To put it in other words, because the water treatment plant uses aluminium sulphate as a coagulant, a chemical plant upstream produces it, and during production and transport of the same to the point-of-use, itself has to interact with other systems (suppliers, power producers, transport companies etc.) and the environment, causing environmental impacts in the process. So, by including the aluminium sulphate in the inventory, one is attributing the environmental impacts associated with its production and transport to the water treatment plant. Now, if we expand the system boundary and include all the systems on the upstream, we would attribute the environmental impacts due to the production and transport of aluminium sulphate to the expanded system which now would include the producer of the aluminium sulphate and the transporter of the same.

3.3 IMPACT ASSESSMENT (LCIA)

Every product or service utilised by the system is essentially a culmination of a set of processes, each of which interacts with and impacts the environment – so-called indirect environmental impacts of the system under study. Further, there are processes within the system which, by virtue of the emissions to the environment, account for its direct environmental impacts.

There are some databases (which are dynamic in nature and are constantly being revised and updated[4]), which document the inputs and outputs of a range of processes and the production of a host of end-products and services (like transport in the previous section) of the primary, secondary and even tertiary sectors of the economy. These are referred to as the background data. These databases are used in concert with E-LCA software[5] to carry out the impact assessment. The software does it for you, essentially. For the software (the chef in Figure 3.3) to do it, one needs to identify the method (the recipe in Figure 3.3) which the software would use on the 'background data' from the database and the 'foreground data' from your inventory analysis (both the raw materials needed). The final assessment is the food. Digesting it is akin to interpreting the results.

The most commonly used methods are as under:

1. **The CML methodology** (Institute of Environmental Sciences at the University of Leiden in the Netherlands)
2. **Eco-Indicator** (also developed by the Institute of Environmental Sciences at the University of Leiden in the Netherlands)
3. **TRACI** (or the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, developed by the US Environmental Protection Agency)
4. **ReCiPe** (created by the National Institute for Public Health and Environment, CML-Leiden, PRè Consultants and Radbound Universiteit, Nijmegen, all from the Netherlands).

The choice of method for the impact assessment is strongly influenced by the goal specified – what you wish to convey and how and why. Now, the steps 3a, 3b and 3c shown in the lead picture of this chapter, are all embedded in the methodology you choose to carry out your LCA. You feed data to the software which has the support of an extensive database, and specify the methodology you want the software to adopt (depending on the options available to you, generally speaking), and it does the impact assessment for you. But even as just an end-user of the LCA software, it is of utmost importance to have some idea about what exactly the software does with the data and the method you want it to follow.

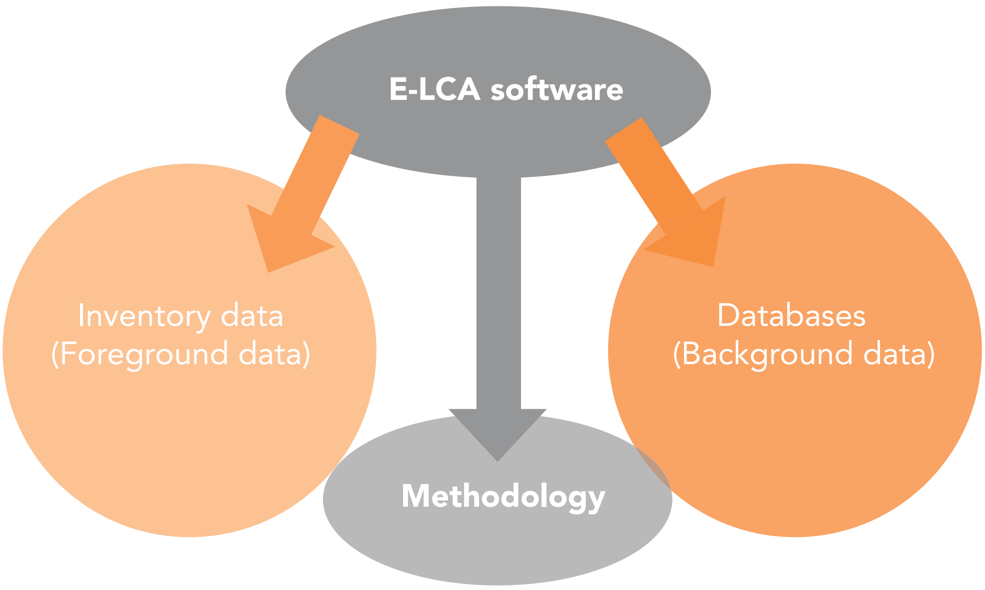


Figure 3.3: Impact assessment – raw materials, recipe and the chef

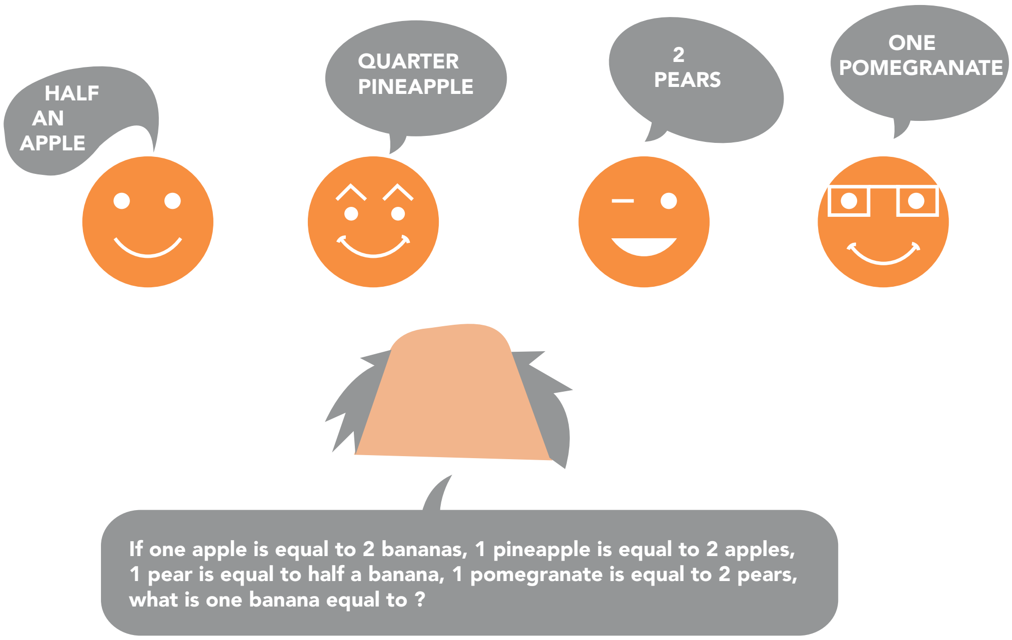
So, you move from an LCI (Life-Cycle Inventory analysis) to an LCIA (Life-Cycle Impact Assessment) to the last stage of interpretation to accomplish a 'complete E-Life-Cycle Analysis'. It is very important to understand the differences among these acronyms. Often, when these acronyms are used by experts and practitioners, beginners may fell a bit confused. But no longer…as now, you know.

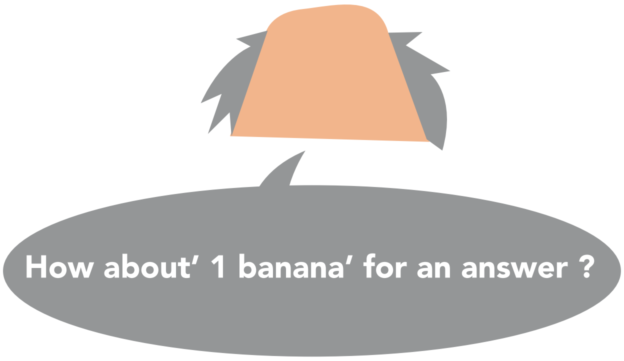
Exercises

1. Attempt an inventory analysis of any one day in your life. (Note that one day is a very small part of your life-cycle). You, as a system, interact with many other systems over 24 hours – including the environment. Remember that along with the inflows and outflows, you can also document the stocks. Try to find the environmental impacts associated with the inflows and outflows.
2. In the above exercise, you performed a kind of an environmental systems analysis, with yourself as the system, right? Now, try economic and social systems analyses likewise, with yourself as the system, for the same period of time – one day. Find something interesting? How about expanding the time period of study now to one week/month/year? Now stand back and take stock of your findings, and discuss the importance or otherwise of holism in thinking – in other words, the importance of considering all the three aspects of sustainability (social, economic and environmental).

4 CHARACTERISATION

Learning goals: Characterisation is a necessary step in the LCIA of E-LCA and this chapter tries to make the understanding of the same, a little lucid, by resorting to analogies.





This was 'step 3a' in the previous chapter. Characterisation is LCA jargon which you will come across very often if you are studying/discussing/listening to lectures on Life Cycle Analysis. This can be busted using the following analogy. Assume that you have with you currency notes in GBP (Great Britain Pounds), INR (Indian Rupees), EUR (Euros), CNY (Chinese Yuan Renminby) and JPY (Japanese Yen). You are in New York and wish to convert all these to USD (US Dollars). On the day you enter the FOREX office, the rates at which the FOREX sells US dollars to you are as under[6]:

- 1 GBP – 1.296 USD
- 1 INR – 0.0149 USD
- 1 EUR – 1.114 USD
- 1 CNY – 0.1506 USD
- 1 JPY – 0.00986 USD

If you have 100 GBP, 200,000 JPY, 90 EUR, 5000 INR and 5000 CNY, you would get a total (in USD equivalence) of **3129.4 USD**. If you revisit the USA after 2 years with the same amount of money in the said currencies, let us assume that the dollar buying rates for you have changed to the following[7]: (You appreciate of course, that these rates do not remain the same always!)

- 1 GBP – 1.3 USD
- 1 INR – 0.013 USD
- 1 EUR – 1.113 USD
- 1 CNY – 0.16 USD
- 1 JPY – 0.01 USD

You would then get a total of **3095.2 USD.** Small difference, considering the exchange rates we have taken into account for these calculations – a drop of 1.08%.

Thus, you have assigned a 'characterisation factor' or exchange rate for each currency. The equivalent unit in this case is the USD. If you land up in South Africa, the equivalent unit would be ZAR (South African Rand). If you land up in Mumbai, you would not need to exchange the money you have in INR. The others would then be converted to the equivalent unit – INR; and what you already have in INR would be added on to the converted amount.

Now this is all about money. Let us replace money with an environmental impact category – say global warming. Remember the analogy as we proceed. Understanding exactly how the factors are determined is beyond the scope of this primer. It will suffice now to understand that just as 1 GBP is not the same in terms of US dollars, as say 1 CNY is, unit mass of one type of greenhouse gas is not necessarily as effective as unit mass of another. And just as we have replaced money with global warming, we can also replace 'USD-equivalents' with 'kg-carbon dioxide-equivalents'. The equivalent unit for money will change as we saw, depending on which country you find yourself in, when you intend to exchange currencies. But the equivalent unit for global warming for instance is considered to be fixed – 'kg CO_2-eq'. This has come to be so, because, carbon dioxide is the most abundant greenhouse gas responsible for global warming…and it seems intuitively obvious to have that which is abundant (or most dominant) as the unit of equivalence – quite like the US dollar has been for a long time now.

4.1 SOME CHARACTERISATION FACTORS

Table 1 lists the characterisation factors for a clutch of GHGs (sourced from IPCC (2007)[8]). Do not forget however that just as the exchange rates keep fluctuating for currencies, the characterisation factors may be revised up or down, as new knowledge is obtained. For instance, the presently-considered factor for methane is greater than what it was before. Tables 2 and 3 likewise, present the characterisation factors for substances causing two other kinds of environmental impacts – acidification and eutrophication. You will note that in Table 3, we also include oxygen depletion. You would already have guessed why, as you know what actually happens when eutrophication takes place. Surfeit of nitrogen and phosphorus (nutrients) stimulates oxygen depletion in the waters which consequently affects aquatic life-forms adversely (Also refer to Appendix A). Tables 1, 2 and 3 provide the factors for some selected substances for just three environmental impact categories. There are obviously more substances and more environmental impact categories to consider and curious readers are encouraged to seek out other sources of information[9]. To lead you on, here are the units for some of the other impact categories referred to in Chapter 2:

- *Marine ecotoxicity (kg dichlorobenzene-eq)*
- *Freshwater ecotoxicity (kg dichlorobenzene-eq)*
- *Human toxicity (kg dichlorobenzene-eq)*
- *Photochemical ozone creation (kg ethylene-eq)*
- *Ozone depletion (kg chlorofluorocarbon-eq)*
- *Abiotic depletion (kg antimony-eq)*

Greenhouse gas	CO_2-equivalence (GWP)
Carbon dioxide, fossil	1
Methane, fossil	27.75
Methane, regenerative	25
Nitrous oxide	298
Tetrafluoromethane	7390
Hexafluoroethane	12200
Halon 1301	7140
R22	1810
Tetrachloromethane	1400
Trichloroethane	146

Table 4.1: Global warming potentials (GWP) for selected greenhouse gases; kg CO_2-equivalent values for the 100-year perspective[10]

Acidifiers	SO_2-equivalence (AP)
Sulphur dioxide	1
Nitrogen oxides	0.7
Hydrochloric acid	0.88
Hydrogen sulphide	1.88
Hydrogen fluoride	1.6
Hydrogen cyanide	1.6
Ammonia	1.88
Nitric acid	0.51
Sulphuric acid	0.65
Phosphoric acid	0.98
Sulphur trioxide	0.8

Table 4.2: Acidification potentials (AP) for selected substances; kg SO_2-equivalent values[11]

Eutrophicating substances	PO_4^{3}-equivalence (AEP)
Phosphate (PO_4^{3-})	1
Nitrate (NO_3^-)	0.1
Total phosphorus (P)	3.06
Ammonium (NH_4^+)	0.33
Chemical oxygen demand (COD)	0.022
P as phosphorus pentoxide (P_2O_5)	1.34

Table 4.3: Aquatic eutrophication (and oxygen depletion) potentials (AEP) for selected substances; kg PO_4^{3-} equivalent values[12]

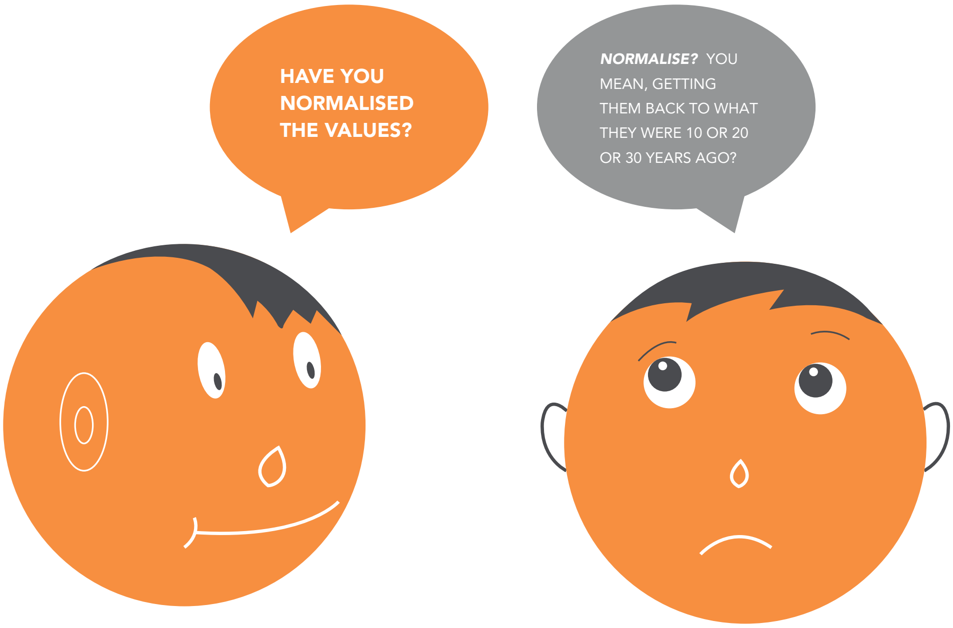
Exercises

1. Look up the Internet for characterisation factors like the ones given in Tables 1,2 and 3 for common substances causing the following environmental impacts:
   a. Photochemical ozone creation
   b. Ozone depletion
   c. Marine eco-toxicity

4. In a wastewater treatment plant's anaerobic sludge digester unit, sludge is digested and methane leaks out. You are an engineer there and are asked to analyse the situation. You can suggest plugging leaks followed by methane capture and use (for energy generation) or blocking leaks and flaring all the methane out as carbon dioxide. You have to prepare a detailed report on the situation and what must be done (if at all, something needs to be done) to change it. How would you do it and why?

5 NORMALISATION

Learning goals: This is an optional step in an LCA. But there are reasons why one may wish to perform it. It is imperative to understand why you are normalising and whether you really need to do so. What is the information you get from the normalised value? The student, after reading this chapter, will have a good understanding about the what, why and why-not of this step in an LCA.



I must confess that the confusion illustrated in the lead picture was a personal one when I was first introduced to the term 'normalisation'. Let us start off with a short anecdote.

I once advised a not-so-little boy who kept the faucet running while brushing his teeth. He would have used up (or wasted) several litres, without having brought more than 95% of the water in contact with his hands, face, teeth or brush. His retort was, 'Well, everyone does it and this is just an infinitesimal percentage of the total. How does it matter?' Does this ring a bell? Perhaps yes. Perhaps not. This dismissive attitude can be extended to electricity usage, solid waste generation, compulsive shopping…the list is endless. Now, what was the 'not-so-little' boy doing in this short story? He was normalising (personally of course, he was trying to make his behaviour seem like the most normal thing to do). He normalised and established that his contribution to the total water wasted by all boys and girls of his age in the city/state/country/region/world was extremely small and so negligible. You are getting the line of thought? A million negligibles added together, will become significant, right? A drop of water is negligible, but when trillions and trillions of them get together, you see a body of water – stagnant pool/lake or flowing stream/river!

Now, what does this mean in LCA lingo? Surely not what the tyro in the lead picture is thinking. It simply means, expressing, for instance, the aggregated equivalent greenhouse gas emissions from the life-cycle of a product in kilograms-CO_2 equivalents (refer chapter on Characterisation), in terms of some reference value. (Note that we are talking about global warming only here…you can do this for any environment impact category you consider). The reference value could, for example, be the total greenhouse gas emissions from all activities and processes, in a given period of time, from the city, state, province, country, region or even the whole world. We can then say that we have normalised the emissions, by adopting a spatial/geographical approach. A temporal approach can also be adopted, for that matter. In this case, the normalisation is carried out with reference to the corresponding emissions during some period of time in the past – the previous year, the year before that, or 10 years ago for example.

In the spatial approach, you get an idea of how small/ big, important/negligible the contribution from the process / product life-cycle is, when you widen your perspective, geographically. In the temporal approach, you get an idea of the degree of improvement or worsening over time. You may, for instance, conclude that the process being studied, contributes 0.001% to the total global warming impact caused in the city in a given year. Or you could, by adopting the temporal approach, conclude that the annual greenhouse gas emissions from the process being analysed have decreased by 1% with respect to the previous year, but still is 10% higher with respect to 10 years ago. If the 0.001% result makes you feel like the not-so-little boy did, that you need not care, perhaps, normalisation is evil! Well, that is an exaggeration. I am just joking. On the other hand, if you conclude that the emissions have increased by 2% with respect to the previous year, and that knowledge rankles your brain, and you start thinking of possible improvements, it is a wonderful thing, indisputably. Well, does this mean that normalising with respect to time (in other words, dividing by the corresponding value from the past), is a more constructive and therefore meaningful approach? I would leave that to you to decide…

5.1 SUBJECTIVITY

Now, when you choose the denominator value for the normalisation (temporal or geographical), your normalised value – a fraction without units – is purely subjective. It will change, depending on what you wish to compare the emissions you calculate, with. Thus, the element of subjectivity appears in the actual LCA results you get…and there is more subjectivity heading your way, in the next chapter. You thus see, that LCA, like life, is a mix of subjectivity and objectivity, certainty and uncertainty. But we cannot eliminate subjectivity by adding some objectivity. We cannot root out uncertainty by adding in some certainty. Of course, the degree of subjectivity/uncertainty can surely be reduced.

Exercises

1. You undertake an exercise where you need to perform a time-series analysis of two environmental impacts – acidification and global warming – caused within a small area you are studying.

   The emissions are as shown below:

Year	CO_2 fossil	CH_4 fossil	N_2O
2013	100,000 kg	250 kg	125 kg
2014	120,000 kg	245 kg	100 kg
2015	90,000 kg	210 kg	150 kg

Table A: Greenhouse gas emissions

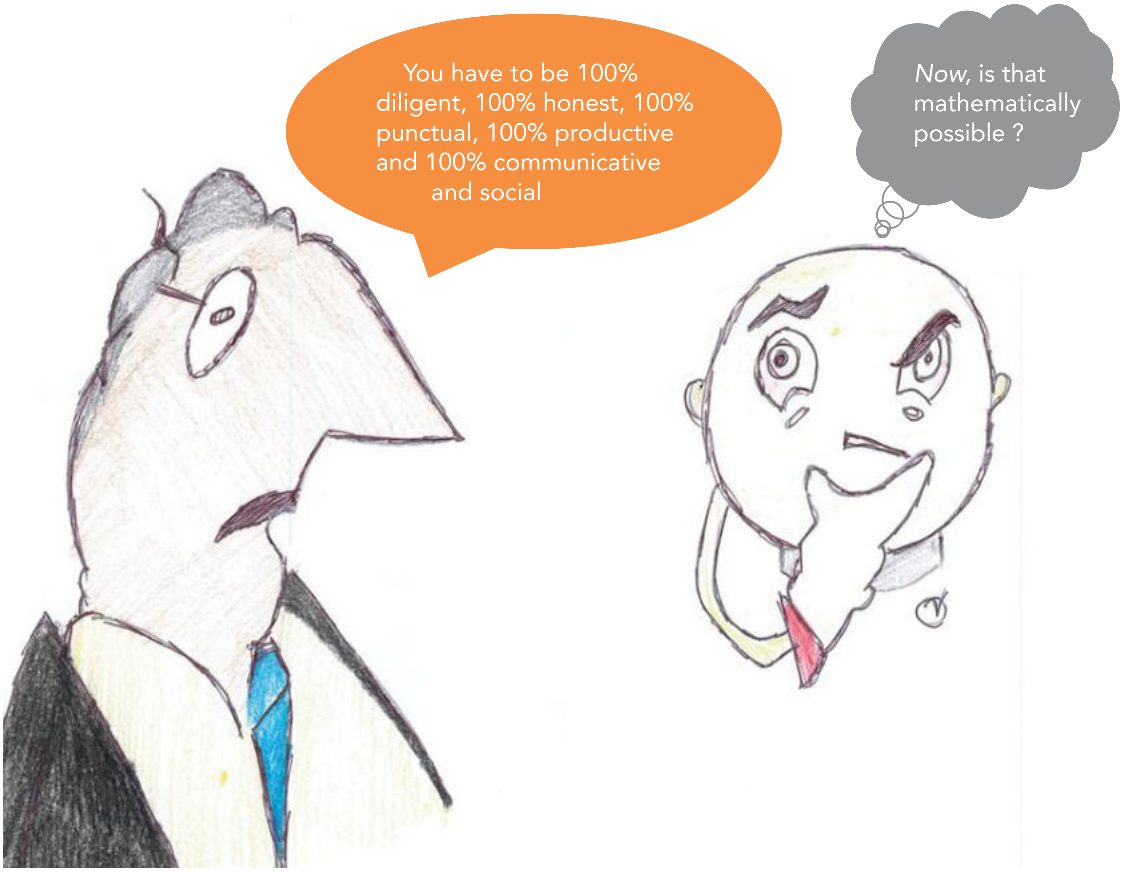
Year	SO_2	Nitric acid	Hydrofluoric acid
2013	1500 kg	1950 kg	100 kg
2014	1550 kg	2000 kg	75 kg
2015	1750 kg	2100 kg	200 kg

Table B: Acidifying substances

Use characterisation factors from the previous chapter…normalise the emissions in years 2014 and 2015 with respect to year-2013, for both these impact categories. Discuss your findings…

6 WEIGHTING

Learning goals: Weighting is an optional step in LCA. Why must it be done if someone wishes to do it? Why can it be skipped if someone wants to skip it? Using simple analogies to more mundane daily 'thought processes' which we often engage ourselves in, the student is encouraged to come to his/her own final conclusion on what/why/why-not/how of weighting.



You will learn in LCA courses (if you sign up for one) that weighting is not mandatory. You will be told that this introduces a lot of subjectivity to the results. Well, that does not mean that you do not need to understand what weighting entails (To use an extreme analogy, you need to know how thieves think to be able to catch them, even though you would yourself not become one). Perhaps such understanding will help you to clearly appreciate the adjectives 'subjective' and 'not mandatory' which are often used for this step in an LCA.

6.1 PRIORITISATION, RANKING AND WEIGHTING

The environmental impact categories undergo prioritisation. This manifests itself as ranks accorded to the categories, in order of importance or significance or relevance. Prioritisation and ranking may be followed by weighting. Weighting takes ranking up to a greater degree of detail. Instead of simply saying that impact category A is ranked above category B which in turn is ranked above category C, one may wish to specify 'how much above'. If I am 5 feet 9 inches tall and you say that you are taller than I am, your height may be anything upwards from 5 feet 9.1 inches, right? If A, B and C are the only three categories and if A is twice as important as B and B is twice as important as C, the weighting factors for A, B and C are respectively 57.12%, 28.56% and 14.28%. How? Well, if the weighting factor for C is x%, that for B is 2*x% and that for A is 4*x%. We then have the condition, 'x + 2*x + 4*x = 100'. This gives us a value of x equal to 14.28. The rest follows…Now let us try to understand what ranking/weighting actually means, with the help of an analogy.

6.2 ANALOGY

Assume that you have got 4 job offers and find yourself in an enviable position. Well, is it really as enviable as you think? Having to make decisions every now and then is not so comforting for the human mind, you will agree. You may perhaps just have wished you got only one offer and had to take it as the Hobson's choice. But, now you have 4 and you need to make a good decision at the end of which you may have to politely decline 3 offers and accept one. You decide to analyse the opportunities on the basis of a set of criteria which you define:

a) Salary
b) Proximity to residence
c) Presence of good acquaintances at the workplace
d) Ability to use your formal training and education well

You sub-consciously have your own priorities as regards these four criteria. Priorities imply ranks and ranks may lead to weighting factors if you intend to be very scientific in your decision-making (but you and I agree that none actually goes through all this rigmarole prior to decision-making!). Gut instinct always rules over mathematical evaluations. Of course, if you have two children to take care of, you would prioritise a good salary over all the others and if you decide to assign weighting factors, would assign a very high value to 'Salary'. Now imagine yourself two decades and a little more down the line – in your mid-50s. Your children are now independent and earning well. You now feel that the workload you are shouldering is a bit too much and that you need to take care of your health and spend more time with your partner/spouse. You wish to change your job, making way for someone younger to take over your position. You may perhaps assign a much lower priority (weighting factor) to 'Salary' and focus more on 'Proximity to residence'. You may also decide to change the criteria in the first place. Criteria (c) and (d) will now not be relevant and can be replaced by say 'Number of working hours per week' or 'Workload/ Job responsibilities'. A job which gives you flexibility as regards daily/weekly working hours and does not involve too many responsibilities at the workplace may seem more suitable to your needs, even if the salary decreases. Of course, if you have saved up for a rainy day, you would comfortably go ahead with such a plan. With this analogy, we have seen that both the criteria and the weighting factors thereof are likely to change with time.

6.3 RELATIVE IMPORTANCE – VARYING WITH SPACE AND TIME

Likewise, when an environmental LCA is done, some impact categories may lose their relevance with time, and others which were never a concern earlier, may become more significant. 'Totally irrelevant' can be considered to be equivalent to having a weighting factor of zero. How must one prioritise and rank environmental impact categories, before assigning weighting factors? It is not easy. Any ranking can be questioned. Even if a ranking is acceptable, the weighting factors can surely be questioned. Why 40% and not 35%, for instance? This makes weighting, if not the ranking, purely subjective, to a very great extent.

You will come across terms like 'Distance to Policy', 'Distance to Target', 'Monetisation' etc., when you search for the different approaches adopted to assign weighting factors. Let us cut the jargon and try to think aloud, using analogies. Say you have to pay two bills – an electricity bill and a piped gas bill. How would you prioritise? In other words, what would be the logical order/ sequence in which you would make the payment? Though this may not always be true, you would opt to pay that bill first, which has the earlier deadline, to avoid having to pay a fine/penalty. Likewise, if you know that there is a governmental mandate or a general rule which states that annual acidification impacts have to be reduced by 30% over a period of 10 years, while annual global warming impacts need to be cut by 10% over the same period of time, you would automatically prioritise acidification over global warming, and thereby assign the former a greater weighting factor. Greater by how much, is another question altogether!

Now there are reasons why policies are set the way they are. At times, they may be questionable and politically motivated and may irk experts and scientists in academia and research institutes. The status quo may be dangerously close to the carrying capacity of the environmental media in question (say emissions of nitrogen and phosphorus to water bodies causing eutrophication)[13]. This may necessitate quick and drastic action and in the said instance, eutrophication will tend to get prioritised over many other impact categories. It is also possible that one government will be motivated by governments in neighbouring countries to 'keep up with the Joneses' (used in a positive sense here). It may also be so that direct/indirect monetary damages incurred by the aggravation of a given environmental medium (atmosphere, lake, river, soil etc.), owing to a given environmental impact category may be very high, necessitating a greater weighting factor to be assigned to this category.

You will also read/hear that weighting factors are often determined by a panel of experts. How many members the panel has, and what their educational and professional backgrounds are, will influence the final 'averaged' weighting factors which are obtained. It is also possible to think of a 'weighted average' of the weighting factors assigned by the members. The weights for the averaging may be determined by factoring in seniority, educational and professional background etc. That is what you may call, 'subjectivising the subjectivity' itself. Perhaps, what you arrive at eventually is what ought to be…but we would never know!

Exercises

1. Consider the two Tables below. The first one rates four alternative transport options which are being compared for sustainability along three different dimensions – environmental, economic and social. Scores are between 0 and 1; with 1 indicating the best among the four. The second table, presents the results of a survey conducted over the e-mail in which five people (experts from academia and government) were asked to give their priorities in terms of percentages. Note that the sum of the percentage values for each person sums to 100%. Using these numerical data,
   a. Determine the consolidated sustainability score for each of the alternatives and decide which one would thereby be chosen as the most sustainable one. (Hint: The weighting factors are to be averaged)
   b. Why do you think people think so differently when it comes to priorities and even if they all stay in the same city and work at the same place, and perhaps all belong to the same country?
   c. Suppose you decide to delete the responses of the men from the second table, and use only the three sets of responses provided by the women, what changes do you see in the overall ranking of the alternatives? So, now, do you think that this approach to making a selection for sustainability, makes you feel confident about your decision? Why?

Scores for the three dimensions for the four alternatives

Category of sustainability	Alternative A (Score between 0 and 1)	Alternative B (Score between 0 and 1)	Alternative C (Score between 0 and 1)	Alternative D (Score between 0 and 1)
Environmentally sustainable	**1**	**0,75**	**0,6**	**0,7**
Economically sustainable	**0,7**	**1**	**0,8**	**0,4**
Socially sustainable	**0,9**	**0,86**	**1**	**0,65**
Overall sustainability score	**????**	**????**	**????**	**????**

Weighting factors collected from five respondents

Experts providing weighting factors	Environmentally sustainable	Economically sustainable	Socially sustainable
Mr P	40%	40%	20%
Mrs Q	55%	25%	20%
Mr L	0%	35%	65%
Mrs M	25%	70%	5%
Mrs N	75%	10%	15%
Average weighting	??	??	??

2. Consider the two Tables below. These are excerpts from the paper: *Venkatesh, G. & Bratteboe, H. (2013). Typifying cities to streamline the selection of relevant environmental sustainability indicators for urban water supply and sewage handling systems: a recommendation. Environment Development and Sustainability, 15: 765–782.*

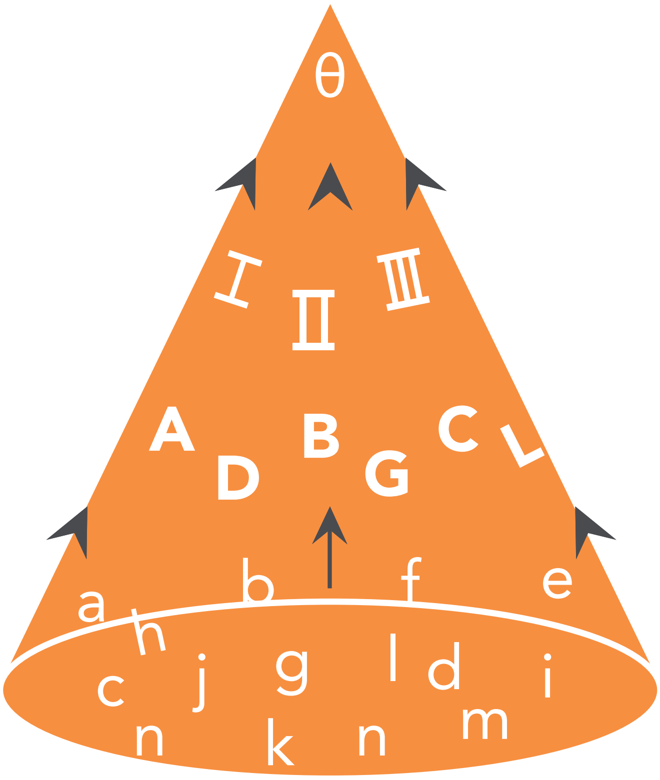
City (country)		Oslo (Norway)-year 2011	Trondheim (Norway)-year 2010	Turin (Italy)	Tel Aviv (Israel)	National capital Territory of Delhi (India)	Male (Maldives)	Sacramento (USA)	Sao Paulo (Brasil)	Beijing (China)
City type: attributes		CT8: 1-5-8 10	CT8(with a difference); 1-(1a)-5-8-10	CT31; 2-3-5-8-9	CT23 (with a difference); 1-1A-5-7-7A-9	CT51; 2-4-5-5A-7-9	CT1; 1-5--7-9	CT7; 1-5-8-9	CT26; 2-3-5-7-10	CT59; 2-4-4(a)-5-7-7a-9
Source of data/information Environment indicator		Elmi and John sen (2012)	Slagstad (2012)	Guiseppe (2012)	Opher (2012)	Kansal (2012)	Mujthaba (2012)	Dale (2012)	Ricardo (2012)	Pei (2012)
Freshwater eutrophication potential (kg $PO4^{3}$ equivalents per capita serviced per year)	A	Not relevant	Not relevant	**Yellow**	Not relevant	**Red**	Not relevant	Not relevant	**Red**	**Yellow**
Marine eutrophication potential (kg $PO4^{3}$ equivalents per capita serviced per year)	B	(0.65) **Yellow**	Not relevant	Not relevant	Not relevant	**Red**	**Red**	**Yellow**	Not relevant	Not relevant
Acidification potential (kg SO2 equivalents per capita per year)	C	(1.84) **Green**	(0.04) **Green**	**Green**	**Red**	**Yellow**	**Red**	**Not known**	Not relevant	**Green**
Global warming potential (kg CO2 equivalents per capita per year)	D	Not relevant	Not relevant	**Green**	**Red**	**Yellow**	**Red**	**Green**	Not relevant	**Yellow**
Intensity of water stress (qualitative indicator)	E	Not relevant	Not relevant	Not relevant	**Red**	**Red**	Green	Not relevant	**Yellow**	**Red**
Mass of solids in sludge generated per capita serviced per year (kg per capita per year)	F	(20) **Green**	(17.3) **Green**	**Yellow**	(22) **Green**	**Yellow**	**Red**	**Green**	**Red**	**Green**
Heavy metal content in sludge (kg metal/kg solids in sludge generated: can be calculated for different heavy metals seperately)	G	Not relevant	Not relevant	Not relevant	**Not known**	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

Assume that you are a World Bank consultant and are presented these two Tables, which encompass 9 different cities and 13 different environmental performance indicators for the urban water and wastewater systems. Further, you also know that 'Green' implies very high environment-friendliness and proximity to desirable performance, 'Red' indicates a critical situation which needs to be attended to with expediency (this may mean that the carrying capacity of environmental media is very close to being breached) and 'Yellow' is somewhere in between. So, it is not wrong if one says that the prioritization is somewhat clear for each of the cities. Do you think this information will help you to get to grips with the weighting process? Perhaps, just as a starting point which you could build on?

City (country)		Oslo (Norway)-year 2011	Trondheim (Norway)-year 2010	Turin (Italy)	Tel Aviv (Israel)	National capital Territory of Delhi (India)	Male (Maldives)	Sacramento (USA)	Sao Paulo (Brasil)	Beijing (China)
Percentage of solid in sludge generated annually, used in agriculture (%)	**H**	Not relevant	Not relevant	Not relevant	(0) **Red**	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Volume of biogas captured and utilised per kilogram of solids in sludge generated (cubic metres per kilogram per year)	**I**	(1.22) **Green**	Not relevant	**Green**	(0) **Red**	**Red**	**Red**	**Red**	**Red**	**Green**
Total energy (head plus electricity) recovered and used, from biogas per kilogram of solids in sludge generated (kWh per kilogram per year)	**J**	(6.22) **Red**	(248) Yellow	**Yellow**	(0) **Red**	**Red**	**Red**	**Red**	**Red**	**Green**
Percentage of treated wastewater reused (%)	**K**	Not relevant	Not relevant	**Red**	(100%) **Green**	**Yellow**	**Red**	Not relevant	**Red**	**Green**
Heat energy recovered from wastewater per capita per year (kWh) per capita per year)	**L**	(0) **Red**	(0) **Red**	**Red**	(0) **Red**	**Yellow**	**Red**	**Red**	**Red**	**Yellow**
Depth of groundwater from crust (mertres)	**M**	Not relevant	Not relevant	Not relevant	(650) **Red**	Not relevant	Not relevant	**Green**	Not relevant	**Red**

7 AGGREGATING TO A SINGLE SCORE

Learning goals: Well, this just brings everything together as a summary; and a quick read will enable the reader to know what he/she is supposed to do after normalising and weighting, while performing simple LCA studies.



Consider the two Tables hereunder. The emissions from a system in a calendar year, say year-2015 are given.

Number	Mass of GHG emitted (kilograms)	Characterisation factor (kg CO_2 –eq per kg emitted)
1	m_{GHG1}	c_{GHG1}
2	m_{GHG2}	c_{GHG2}
3	m_{GHG3}	c_{GHG3}
4	m_{GHG4}	c_{GHG4}
5	m_{GHG5}	c_{GHG5}
6	m_{GHG6}	c_{GHG6}
7	m_{GHG7}	c_{GHG7}

Table 7.1: Greenhouse gas (GHG) emissions and global warming

Number	Mass of acidifying substance emitted (kg)	Characterisation factor (kg SO_2 –eq per kg emitted)
1	m_{ACID1}	c_{ACID1}
2	m_{ACID2}	c_{ACID2}

Table 7.2: Acidification

Now, the total global warming potential of the emissions listed in Table 7.1, in kg-CO_2-equivalents, would be:

$$\sum_{k=1}^{7} m_{\text{GHGk}} * c_{\text{GHGk}}$$

Likewise, the total acidification potential of the emissions listed in Table 7.2, in kg SO_2-equivalents would be:

$$\sum_{k=1}^{2} m_{\text{ACIDk}} * c_{\text{ACIDk}}$$

Assume that you would like to express the aggregates of the characterised emissions from the system, for the two environmental impact categories, in terms of the total respective emissions on a national level, for the same calendar year – $M_{\text{GHG, national}}$ & $M_{\text{ACID, national}}$.

The normalised values would then be:

For global warming, N_{GW}: $(\sum_{k=1}^{7} m_{\text{GHGk}} * c_{\text{GHGk}})\ /\ M_{\text{GHG, national}}$

For acidification, N_{ACID}: $(\sum_{k=1}^{2} m_{\text{ACIDk}} * c_{\text{ACIDk}})\ /\ M_{\text{ACID, national}}$

Now, if you are able to assign weighting factors to these two environmental impact categories – say W_{GW} and W_{ACID} (both in %), the final score, which is used to communicate information about the environmental footprint of the system studied for the given year would be:

$$(N_{\text{GW}} * W_{\text{GW}} + N_{\text{ACID}} * W_{\text{ACID}})*0.01$$

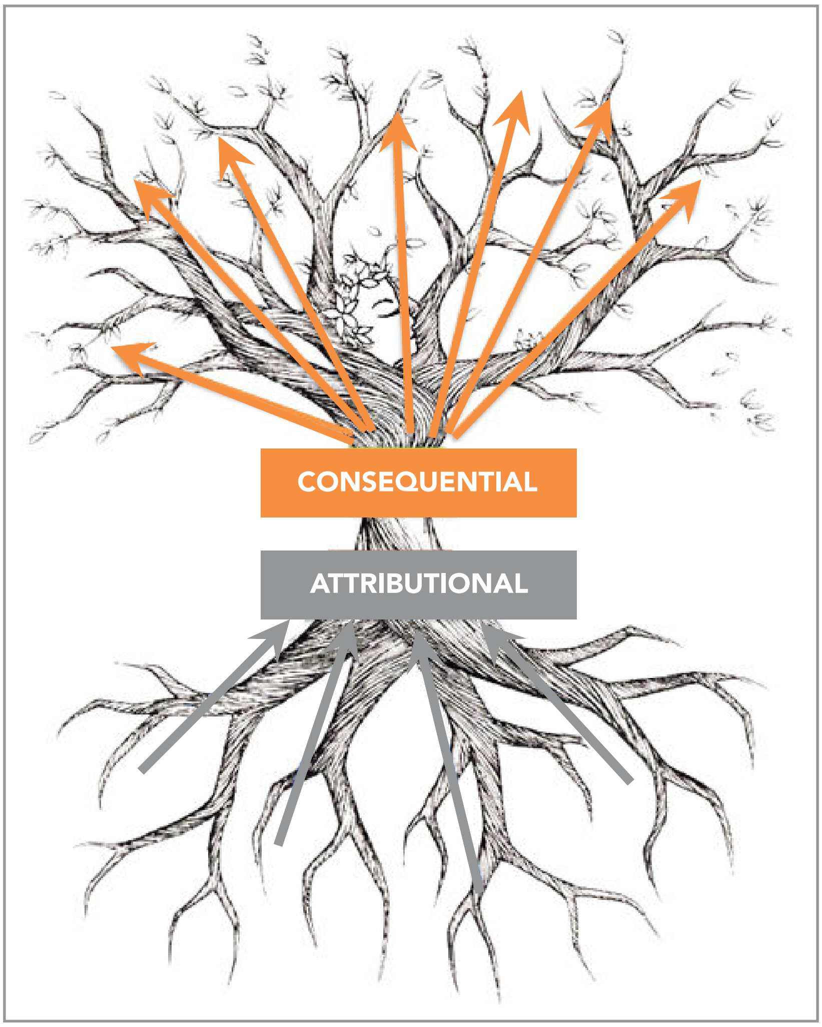
Now, you can add on more environmental impact categories and thereby more terms in the summation above, to make the final score more comprehensive and inclusive of a plethora of environmental impacts. However, accuracy will be compromised in the process. The single score is good, as long one is aware of how it came to be. It is quite like the apex of a cone (refer to the lead picture); knowing the base and understanding the convergence all the way to the single point on the top, is indispensable for the person seeking to understand what the single score is trying to tell him/her. The journey from the 'measurable-objectives' to the 'simplified-subjective'! The latter has a story hidden behind it.

Exercises

1. Go back to the exercise in the chapter on Normalisation. Consider some random combinations of weighting factors for the two environmental impacts studied. Apply these to get the single score which has been written about in this chapter. How do the weighting factors you have chosen, affect the final results and the inferences you draw from them? Depict the sensitivity to weighting factors graphically.

8 ATTRIBUTIONAL AND CONSEQUENTIAL LCA

Learning objectives: You will come across these two adjectives quite often. This chapter explains what these terms imply. You will then know exactly what you are doing, when you perform an E-LCA.



To put it simply, *attributional* is the 'what-is' or 'what-has-been' for the product or process being studied, and *consequential* is the 'what-will-be' if the attributional LCA results lead to some action which would bring about changes[14]. Surely, you would have guessed that the former is quite simple and straightforward. The goal in this case is to study the life-cycle environmental impacts associated with the product as it is now – production to maintenance/operation to end-of-life handling – or the process as it happens now. It is, to use another word, descriptive (or 'historical') in nature. You would be able to account for all the resources directly consumed and impacts directly caused by the product right from cradle to grave (or cradle to cradle).

Consider the case of a flat plate solar collector (FPC) for instance. The supplier would need to source its component parts from different places and then assemble them together to form the FPC unit. Each component part may have required several sub-components and thus one can track the flows to the FPC manufacturer back to the mines/oil rigs/forests… the ultimate sources of the raw materials. All along, from the points of extraction of these raw materials to the assembly of the FPC unit, there are interactions with the environment and thereby impacts of various kinds. Now, the FPC is transported to the point of use, and the transportation entails environmental impacts. During the use phase (which may be a few years long, variable though from case to case), the FPC requires some maintenance and also part replacements from time to time, and this would again imply that environmental impacts are caused. In a given country, one would know how the FPC is handled at the end of its operational lifetime – recycling/reuse of component parts/landfilling/incineration etc. Different end-of-life handling approaches have different environmental footprints – both with respect to the impact categories and the sizes of the impacts. Thus, one can, based on average values obtained from published case studies, databases, and interactions with suppliers, users, recyclers, incinerators etc., arrive at a reasonably-reliable estimate of the environmental impacts of the FPC over its life-cycle. When you have done this, you can pat yourself on the back, as you have successfully carried out what they call an attributional LCA. But this does not give you the complete picture. You have, on the basis of the attributional LCA, just determined that the life-cycle of the FPC has an environmental footprint, as all life-cycles do.

Now, you must ask yourself this question: What could happen as a consequence of adding an FPC life-cycle into the global energy-supply system? Well, if you are adding on more heat energy generation capacity, were there other options available and did the FPC replace something which would otherwise have been the obvious choice? In that case, what was it that the FPC replaced? Would it have caused greater environmental impacts, or lesser for that matter? Or, did the FPC totally or partially replace some other way of generating heat, from the system? By expanding the system to include the alternative which was replaced or avoided, we talk of 'net environmental impacts'. The FPC does cause impacts as you determined from the attributional LCA, but they may be much less than what the alternative (now a part of your expanded system) would have caused. So, if they are less, you could rightly say that the FPC contributes to a reduction in the system's environmental impacts, **with respect to what prevailed before the FPC was introduced!** The consequential LCA would thereby tell you that as a consequence of introducing an FPC into the system, you manage to reduce the environmental impacts of the system.

Fine, but it can get more complex, if you keep expanding your system boundary. Your system has truncated its environmental footprint by say, cutting down on its use of natural gas or diesel as the case may be. But does that lead to a drop in the production of natural gas or diesel? Of course, the oil and gas companies will try to look for new markets for their products, and not let their sales dip. Now, if new markets which did not exist earlier are discovered, and these turn out to be in countries which use fossil fuels indiscriminately in the absence of any stringent top-down control, can your system take the blame for that? After all, the new markets were discovered as a 'consequence' of the fact that you decided to use FPC instead of natural gas/diesel? Let us consider a geopolitical analogy to elucidate this – *The author was attentively listening to the presidential debate in September 2016 between Hillary Clinton (Democrat) and Donald Trump (Republican) and the latter said that the ISIS may not have been born if the Democrats had not pulled the US military out of Iraq. The US soldiers were pulled out for a host of well-thought-out and sound reasons. When the pull-out was being planned, none would have predicted the formation of ISIS. Further, can one directly attribute the formation of ISIS – 100% – to the decision of the USA to pull out of Iraq?* Complex, right? One can go on arguing back and forth over several cups of coffee! A consequential LCA is complex indeed and also characterized by greater uncertainties. It falls within the realm of forecasting and predicting the possible effects of the change. As Albert Einstein famously said, *'When the number of factors coming into play in a phenomenological complex is too large scientific method in most cases fails. One need only think of the weather, in which case the prediction even for a few days ahead is impossible.'*

Now, if you consider using biofuels instead of natural gas/diesel, the consequences here are not limited to what would happen to the natural gas/diesel markets, but also to what would happen to the way land-use is managed globally! By including these systems within yours – expanding the scope and system boundary – and creating a Grander System, you make sure that you do not simply shift the problem (refer Chapter 10). Another consequence of a shift to biodiesel which must also be factored in is the so-called rebound effect (see Chapter 10 again). Does the shift to biodiesel simply imply replacing 'x' joules of energy from diesel with 'x' joules of energy from biodiesel, or will it result in much more vehicle-kilometres than before, because of the perception that bio-diesels are cleaner and greener than fossil-diesel? If the latter is true, what may be an improvement for the city, may cause larger-scale environmental damages elsewhere in the world – one man's meat becoming another's poison, as the Roman poet Lucretius wrote.

Exercises

1. Attributional LCA of a flat plate solar collector used for heating

Solar thermal energy has the potential to substitute other sources of heat energy like electricity (high exergy and thereby not really recommended for applications like heating), natural gas and oil (fossil fuels contributing to greenhouse gas emissions and thereby candidates for use-reduction).

A flat plate collector can be visualized as being assembled with the following range of components (quantities expressed in terms of per square metre of area of the collector):

1. Copper sheet in absorber: 2.82 kg
2. Low iron solar glass in absorber: 9.12 kg
3. Corrugated board in absorber: 3.68 kg
4. Aluminium (castings) in framework: 3.93 kg
5. Rock wool in framework: 2.43 kg
6. Stainless steel in framework: 4.14 kg
7. Propylene glycol as heat transfer fluid: 1.01 kg

Let us assume that the transport distances from the component suppliers to the FPC assembly unit are quite small and thereby the emissions associated with the use of transport fuel to get them to the plant can be ignored. (However, we know, in reality, that this may not be so.) Electricity consumption within the plant per square metre of FPC is 4.2 MJ.

The components referred to above, have their own life-cycles which go back to the basic raw materials needed (like iron ore, nickel ore mining for stainless steel; bauxite mining for aluminium, etc.). There are several stages upstream linked by transportation. When the greenhouse gas emissions related to a fabricated flat plate solar collector are to be determined, the individual contributions of all these components which make up the FPC are added together. In other words, shares of the total carbon footprint are 'attributed' to the different components which make up the FPC!

1. Copper sheet in absorber: 11%–15%
2. Low iron solar glass in absorber: 6%–10%
3. Corrugated board in absorber: 3%–4%
4. Aluminium (castings) in framework: 45%–55%
5. Rock wool in framework: 2%–4%
6. Stainless steel in framework: 10%–13%
7. Propylene glycol as heat transfer fluid: 3%–5%
8. Electricity use for assembly at plant: ???

Assume that these 8 inputs together account for about 98% of the total greenhouse gas emissions associated with an FPC. There of course are other smaller contributions from relatively smaller quantities of material (or energy) inputs.

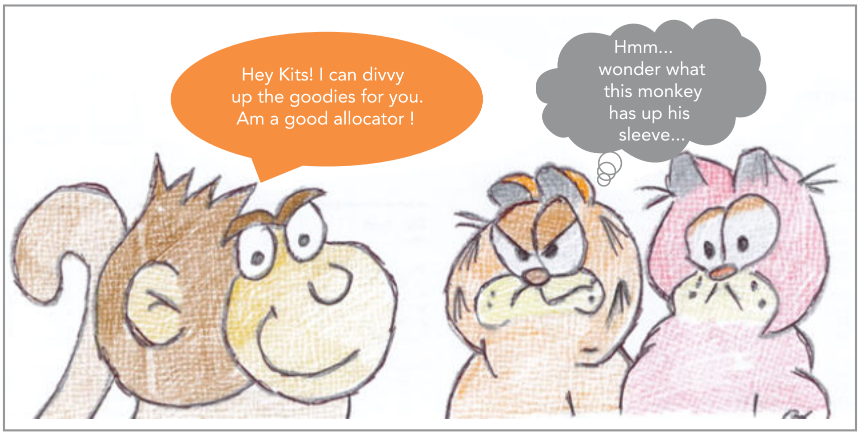
Thus, you see that there are variations (ranges) for the percentage contributions, indicating a dependence on the suppliers the assembler (FPC manufacturer) sources components from. These suppliers may also be located abroad and some components may have to be imported (Note that there can be significant transportation-related emissions in that case!)

- Now, we do not know what the carbon footprint of the FPC is. But using the data above, and by referring to literatures (library, Internet, textbooks etc.), can you estimate an approximate range for GHG emissions related to just the upstream production/assembly of 6 square metres of flat plate solar collector?
- Test the values you get from your searches with the approximate percentage ranges provided above.
- Now discuss the impact of sourcing most of these or all of these from abroad – necessitating transport by sea or road over several hundreds of kilometres. Do you think the carbon footprint will increase significantly? By what approximate percentage-range do you think it will rise?
- Also sketch a rough flow diagram starting back at the sources of the respective raw materials, indicating the intermediate processes in each of the chains (and the main inputs of materials/energy into each of these), and culminating at the FPC which is fabricated and ready for shipment.

2. Consequential LCA – replacing natural gas with solar heating
Having done an attributional LCA to find out the environmental impacts upstream for a flat plate solar collector, think now of a consequential LCA – what are the environmental impacts created and avoided due to the replacement of natural gas heating with solar heating using a flat plate solar collector. You can make your assumptions and carry out rough calculations!

9 ALLOCATION OF ENVIRONMENTAL IMPACTS

Learning objectives: Who/What is responsible for how much? That is the question you ask when you try to allocate. You would be dealing with a single process with multiple outputs and industries with a palette of saleable products here, and also with countries which trade with each other (as producers/exporters and consumers/importers).



The lead picture talks about allocating goodies. However, just as bounties must be shared, penalties must also be. If you want to partake of the 'goods', you need to be willing to partake of the 'bads' too.

I was thinking of a suitable analogy but then decided to come to brass tacks directly. Let us say that you decide to manufacture a product P sensing a good demand for it in your country. You find out that you would be needing ΣX of materials and ΣY of energy to produce a ton of P. Let us say that the carbon footprint associated with the upstream processes – production and transport of raw materials and fuel elements and the generation and transmission of electricity – and the emissions from the production process of P per se, is C kg-CO_2-eq, for 1 ton of P. You also realise that alongwith P, you get two by-products Q and R (a few kilograms of each) in the process. (Figure 9.1 (A))

Now, if Q and R can be sold on the market to add to your revenues, would it be fair to say that the main product P, to produce which, you set up your business, is responsible for all the C kg-CO_2-eq of greenhouse gases emitted? No, right? I understand if you say that it is not easy to answer this question. After all, the purpose was to produce P. Q and R just happened to be co-produced as byproducts with some economic value in the market. However, if you agree that P must not be held wholly accountable for the carbon footprint, you can proceed in two different ways:

1. Allocation of the total carbon footprint among the main product (P) and the byproducts (Q and R) either proportional to their economic values or masses
2. System expansion (explained later in the chapter)

9.1 ALLOCATION AMONG THE PRODUCT AND BYPRODUCTS

It is reasonable enough to consider that the 'contributions' of P, Q and R to C, are proportional to the contributions of the same to the revenues earned by selling them. In other words, if for every ton of P, you put 100 kg of Q and 150 kg of R on the market, and sell them for 10,000 USD, 950 USD and 2000 USD respectively, you would allocate 77.2% of the carbon footprint C to product P. Q would take up 7.3% and R, 15.5%. You may, if you are not sure of the economic values of Q and R (in a case where you are trying to create a market for them, to augment your profitability), simply wish to allocate on the basis of the masses of P, Q and R. Economic value now gets replaced by mass. P would then get 0.8C, Q will be allocated 0.08C and R, 0.12C. The allocated shares increase for P and Q and decrease for R, vis-à-vis the shares you got when you allocated on the basis of economic value. It is easy to see the reason – the specific value of R (13.33 USD/kg) is higher than that of P (10 USD/kg) and Q (9.5 USD/kg).

9.2 SYSTEM EXPANSION

Now, if you decide to attribute the entire carbon footprint – C – to the main product P, and thereby nothing to Q and R, you make P take up all the blame for C. even as Q and R go scot-free despite contributing to your bottomline. But you know this is unfair and will not let it happen. However, even if you decide to attribute all of C to P, as a starting point, you can work around the supposed unfairness and set things right. How?

Consider the possibility of Q replacing D in performing some end-use function; R replaces E likewise. So, Q becomes the reason behind D not being needed, and R becomes the reason behind E not being required. And P becomes the reason behind the existence of Q and R. So P indirectly becomes the reason behind D and E not being required. So, if you have decided to penalise P by assigning all of C to it, it is just fair to also give it credit for being the cause behind the existence of Q and R and thereby the avoidance of production of D and E. If D and E had been produced, and if they would then have had carbon footprints equal to C_D and C_E respectively, P can be credited with truncating the 'expanded system's' carbon footprint by an amount equal to $C_D + C_E$. The expanded system here includes the sub-systems in which Q replaces D and R replaces E (Figure 9.1 (B)).

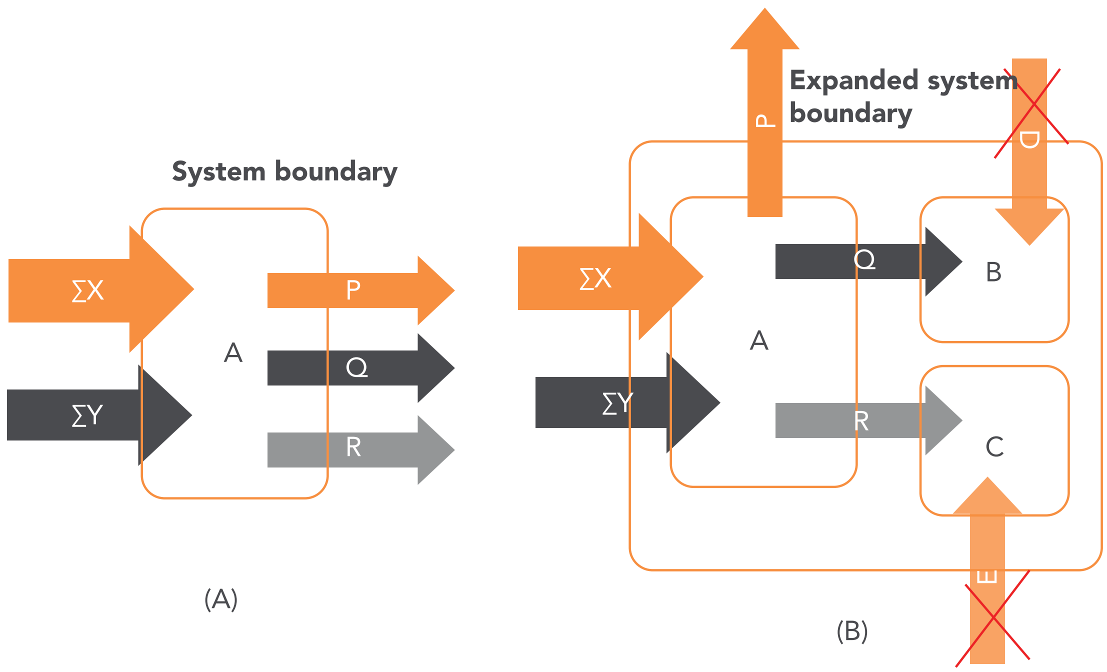


Figure 9.1: Products and byproducts from a process and system expansion

The effective carbon footprint of P in the expanded system would now be C – (C_D + C_E). Now, this value can certainly be different from 0.8 C and 0.772C. It may be greater than 0.8C or less than 0.772C or in between the two. And if it is less than 0.772 C, it could even be zero or negative for that matter, implying in that case that the replacements, respectively, just offset or even more than offset the emissions from the process producing P, Q and R. Despite the uncertainty you are now confronted with, system expansion or for that matter allocation on the basis of mass or economic value is more appropriate than just assigning the entire carbon footprint C to product P. Yet, when the carbon footprint of P is documented, this uncertainty – *what should it be? 0.8C, 0.772C or C – (C_D + C_E)?* – is bound to linger.

9.3 TRADE AND ALLOCATION

Consider this issue. If you are paid by someone to ghost-write for him/her, the credit goes to that person, and you pocket the *moolah*, stay silent and remain cryptonymous. But if someone paid you to do some harm – contract crime – there may be every chance that you shoulder the responsibility and also be paid for taking the risk. The payer remains *incognito*. Double standards! In either case, you accept the money and remain silent.

From writing and crime, to trade and environment – If people staying in the USA placed a demand for some products being manufactured in Vietnam and paid up for the same, who would be responsible for the environmental impacts caused by the manufacturing processes? USA or Vietnam? In other words, when one calculates national carbon footprints (or national environmental footprints for that matter), would the aforesaid impacts be listed under Vietnam or the USA? (This has also been discussed in Chapter 10.) Must one follow the maxim, 'What happens indoors stays indoors', and hold the producers in Vietnam responsible for the impacts in exchange for the payment they receive from the consumers in the USA? Or must it be deemed that the manufacturing process itself was stimulated because of demand from somewhere else and hence the consumers must be considered accountable for the impacts? Well, we do not know how it should be, what is fair and what is unfair.

But we can surely understand and agree on one thing – we have one earth, one *terra firma*. No matter where impacts happen, it is parts of 'our earth' which tend to get affected. If the hands are severed and the legs are not (or vice versa), it is still a handicap, isn't it? Perhaps this thought would enable you to decide what is fair and what is not?

Exercises

1. A production process has product A as the main output, with B and C as byproducts. 1000 tons of A are produced every year, with 50 tons of B and 150 tons of C resulting. The economic value of A remains constant (in constant 2016 USD) at 20 USD/kilogram. However, the values of B and C keep changing over time, annually, over a five-year period starting from year-2016, as under:

Year	2016	2017	2018	2019	2020
B (USD/kg)*	19	21.5	25	35	36
C (USD/kg)*	24	26	28	32	37

*constant 2016-USD

How would you allocate a carbon footprint of 'G' among A, B and C over this five year period, both on the basis of mass and economic value?

Now consider a different scenario. The yields of B and C (which as you see are more valuable products than A), are increased gradually over time. The carbon footprint however can be assumed to remain unchanged, as some clever process modifications are made to increase the yields and these do not add to the carbon footprint. The increase in yield (in % with respect to the previous year) are given below:

Year	2017	2018	2019	2020
B	3%	2.1%	1.3%	1%
C	6%	6%	1%	0.5%

Now, redo the allocations for every year. Both mass-wise and on the basis of economic value.

Can you discuss the results you obtain in brief? Any new learnings you can derive from these?

10 PROBLEM SHIFTING AND REBOUND EFFECTS

Learning objectives: The 'traps' one may fall into if one is not careful with the way one uses the results of an E-LCA must not be overlooked. If you would get ensnared in one of them, often it is very difficult to undo what has been wrought. Again, the student's appreciation of the importance of holism and systems-thinking is reinforced through this chapter.

Big brother west of the border,
built four hydropower plants,
checking the free flow of the rivers,
into the neighbouring lands.

'Electrify, my dear friends,
buy some power from us.
Keep in step with changing times.
Embrace the wave of progress.'

'That is fine, dear big bro,
but our fist are dying in shoals.
Less water to irrigate our crops,
we are becoming dust bowls.'

'No worries, my little brothers,
no worries at all, you see!
We can also sell you fish and food,
they are already *en route*, by sea!

15

I'm OK, you're OK…well, are you really okay? With sincerest apologies to the Thomas Harris book of 1969 and the more-recent Jason Falkner album (2007), the question to be asked to understand problem shifting, is precisely this one. My room is clean, but is my home clean? My home is clean, but is my lawn clean? My lawn is clean, but is the street running past my home clean? Well, that is clean too, but is my city on the whole clean? Of course, you would say that all that you can do is to adopt a NIMBY (Not In My BackYard) attitude… or even a NIMR (Not In My Room) one and expect everyone else to do the same and automatically hope that the world would be a better place! Will this work? Most certainly, if I am OK but you are NOT, it is quite possible that your condition is the effect and mine is the cause? One needs to conscientiously ponder over such things. You would say that I am taking you to a philosophy or a spirituality classroom…but well, no. In fact, we are still talking E-LCA!

Refer back to the lead picture/poem, and at once you realise that while hydropower could be 'green and renewable energy' and may help China (the Big Brother in the poem) to hold back the expansion of its carbon footprint to some extent, grave problems are being shifted to the countries in South East Asia ('the little brothers')! Now, a problem may either be shifted from one environmental medium (say the atmosphere) to another (say the lithosphere) by way of alleviating one type of environmental impact while aggravating another. It could also simply mean shifting the occurrence of the impacts temporally (so that the generations to come may be at risk of exposure to the same) or geographically (so that the developing countries with less-stringent regulations may 'soak up' most of the adverse impacts.) Sometimes, it really does not make any difference – the impacts occur in the same country, only away from the hubbub of populated cities[16, 17]. Now, the problem shifting may occur either because of the wanton NIMBY attitude referred to above ('*I will have the cake and eat it too*') or an absence of systems-thinking and holistic approach in planning. The latter can be rectified by some awareness generation.

We say that there is a rebound effect – also referred to as recoil effect or boomerang effect – when the efforts made to mitigate the problem, oddly become the cause of reappearance of the problem or even its aggravation. Quite like striving to get out of the frying pan, but landing in a hotter oil fire, though not intentionally of course! We shall look at examples later on in the chapter.

10.1 PRODUCTION AND CONSUMPTION

Researchers have been discussing and debating for some years now, about the allocation of responsibilities for environmental impacts[18], when goods are produced in one part of world for consumption in another. Whose environmental footprint expands when something is produced in China and exported to Sweden? China's or Sweden's? The environmental impacts related to the use, maintenance and end-of-life handling phases of the lifecycle of the product may well be attributed to Sweden, but what about those related to the production and transportation phases? If the latter would be attributed to China, can one say that Sweden is shifting the environmental problems upstream to China? Maybe yes, perhaps not. But of course, socio-economically, the Chinese labourers do incur some benefits. So when analysed holistically from a sustainability perspective, perhaps the problem shifting is offset by the socio-economic benefits which are generated.

Consider another example. Your national government mandates that the percentage of biofuels in transportation must be increased steadily to 25% by 2030. The goal is to truncate the carbon footprint of the transportation sector. Fair enough, you would get it done for your country. But where do the raw materials for the biofuels come from? Imported? In that case, do the imports trigger a food-fuel-fibre debate? Do they lead to a rise in food prices in the developing world? Or do they encourage mono-cropping and affect the fertility of the soils? Does the cultivation of the fuel-crop lead to a stress on water resources? Does the use of more pesticides and fertilisers lead to eutrophication? Hope the message has been driven home? While attempting to solve one problem within your country – greenhouse gas emissions from transport – you may unwittingly be responsible for a host of others elsewhere. So, when you do an LCA, where do you want to set your system boundaries? Do you see the subjectivity of your final results?

10.2 REBOUND EFFECT

Consider a city in which only 20% of the families depend on the automobile for transportation. Assume that all the cars driven in the city are gasoline-, or diesel-powered. The remaining 80% abstain from owning and driving cars, because they would like to hold back their individual (of familial) carbon footprints from expanding. Now, plug-in hybrid electric vehicles are introduced into the city and roads widened at the same time to combat congestion and traffic jams. The car-averse 80% are now attracted to the greener credentials of hybrid electrics, and suddenly, the automobile count on the roads in the city shoots up. Now, you know well that hybrid electrics are not zero-emission vehicles. Thus, by introducing something into the marketplace which was posited as being greener than what existed (the diesel and gasoline-powered cars), one ends up contributing to a perceptible increase in greenhouse gas emissions and the carbon footprint of the anthroposphere of the city. That is a rebound effect for you!

Figure 10.1: Rebound with a spatial problem shifting element to it[19]

Now, let us say, instead of plug-in hybrids, a sizable fleet of electric cars were sold to the first-time car owners of the city. Will there be a rebound now? It depends. You could have a rebound with a spatial problem-shifting element to it. Refer Figure 10.1, and I believe that it is quite self-explanatory (*also read the article 'D-EV-il in the Detail' in the Appendix*). There is a study from 2004 conducted by researchers at the Umeå University in Sweden[20] which shows that an increase of 20% in energy efficiency in Sweden will, courtesy the rebound effect, increase greenhouse gas emissions in the country by 5%. The rebound/recoil/boomerang effect generally comes into play when cutting down on expenses on or energy consumption for one activity frees up time and money for other activities which are as environmentally-damaging (or more), than the former[20].

10.3 EXPERIENCES[21]

Seven years ago, in Singapore, as a student at the Nanyang Technological University, I was having lunch at one of the university eateries. A Chinese colleague of mine seated opposite me, got up leaving a half-full plate of food on the table (which was duly consigned to the trash can by the cleaner woman later). I looked at the plate and up at his face and made a futile attempt to conceal my annoyance, as thoughts of famished, ill-nourished children in sub-Saharan Africa flashed across my mind.

What? He challenged me arrogantly.

Why have you wasted food? I said with the utmost self-restraint.

Singapore has a very efficient food-waste handling system. You should know that. They make biogas out of all this food waste. He smirked and walked away.

I did not want to wrestle with the smart Alec. I let the matter rest.

Yes, that is right. The food yields a lot of biogas. But it also takes a lot of effort and energy (both manual and fossil) to make it. Also, more importantly, there are others who would need it for its primary purpose – nutrition. Some would say that they are using their money to buy food which they waste, and not someone else's – so it is not anyone else's problem. It may not be anyone else's problem, but a problem it is, for sure, for the earth/world. This also could be termed as some kind of a rebound effect, you will agree?

In 2013, in Trondheim, at the Norwegian University of Science and Technology, where I was employed at that time, I asked a colleague who was about to throw away a stack of papers, one side of each of them plain and not written or typed upon, to hand them over to me. I have developed a habit of using paper optimally and writing on both sides of each sheet with pencil (which aids in the reduction of chemicals usage during the recycling process). The proclivity to writing first, before typing matter onto a laptop screen, has come in handy. The colleague studied me with a *where-has-this-guy-come-from* look and quipped – *We all know that there is 100% paper recycling in this country. So, do not bother. Sending more and more waste paper to the paper mills is a good thing!* The rebound effect again!

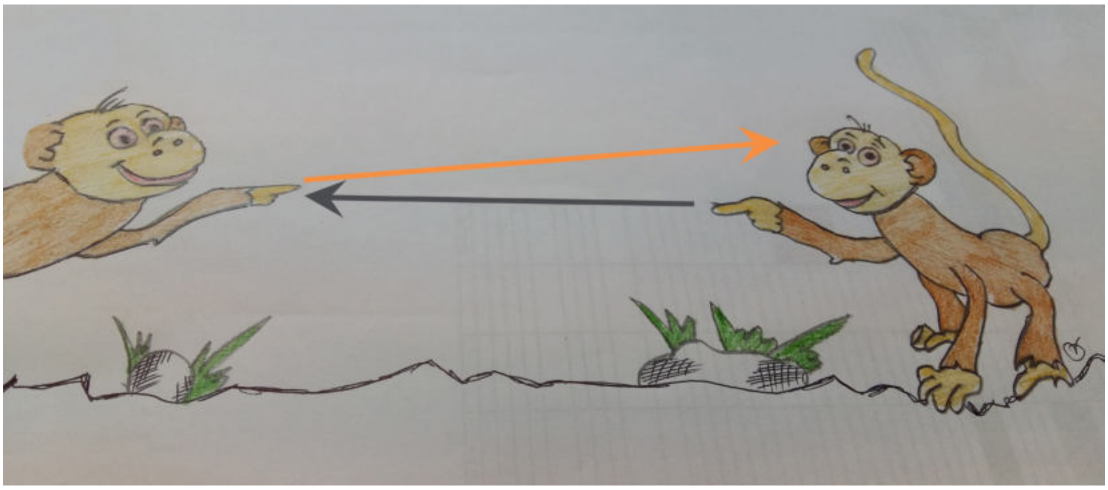
One talks about the rebound effect when it comes to consumption or purchase of goods. It is rarely talked about when the end-of-life is in focus. One needs to get to the root of these misunderstandings and effect a permanent healing. These two real-life observations prove that changes which *prima facie* are deemed to be good are sometimes not so, when one acts on impulse, spurred by emotions and force of habit. You cannot be blamed if you feel that we are fighting for a cause which has already been lost. Human behaviour, you agree, is the key factor here. Managing and influencing it is an 'indispensable' tool in the toolbox, along with E-LCA and the like. Understanding that knowingly or unwittingly, one may end up shifting problems and ignoring the rebound effects, while setting the goal and scope of an E-LCA and defining the system boundaries, is very necessary. Oftentimes, after implementing a decision to bring about a change, one is left wondering whether it was the right thing to do. Faith in E-LCA can only be augmented if such an understanding is reinforced.

Exercises

1. Think of other examples of problem shifting, which may make the results of an E-LCA questionable if the system boundaries are not expanded. Any instances of the rebound effect which you may have witnessed in your city/country?
2. Over a period of three decades, the specific end-user energy consumption (kWh per person) increases at a compounded annual growth rate of 1.2% for the first 10 years, 1.5% for the next 10 years, and 1% for the last 10 years. The population rises at a uniform annual rate of 1.5% over this period of time. The efficiency of conversion from primary energy to end-use energy remains the same for the first 7 years; then increases at a CAGR of 3% for the next 10 years, remains constant for the following 5 years, and then increases at a CAGR of 1.2% over the remaining part of the period. Plot the curves depicting the changes over these 30 years. Is the rebound effect perceived here? What are your views, when you look at the graph then, about the ability to technology alone to help man surmount the challenges ahead in this century?

11 FORECASTING AND BACKCASTING

Learning objectives: You will understand what these terms mean and also how E-LCA is effective in forecasting and backcasting for decision-making purposes



The lead picture is not to suggest that forecasting and backcasting are monkey-businesses. Rather, it emphasizes the contrary. One cannot monkey around with E-LCA, as big decisions are sometimes made on the basis of the results of such analyses. Forecasting and backcasting are what one does by using a mix of attributional and consequential LCA, and considering a whole lot of external influential factors. Decision-makers responsible for setting targets and tweaking financial instruments like taxes, subsidies and penalties need to make forecasts based on a business-as-usual scenario (no systemic changes…things go on as they are). They then set targets for themselves – reduction of environmental impacts for instance – and try to find out how to reach those targets. Just wanting to reach somewhere does not take one there! And the distant target is often broken down into several nearer ones *en route* to the former. There could be several paths leading to the final target…many roads leading to Rome, so to say.

Now, you know what entropy means. You also know that the total entropy in the universe keeps increasing. Entropy is disorder. Environmental damage or lack of environmental upkeep is also a disorder. Any disorder needs to be curbed and if it is increasing, the rate of increase has to be decreased. Let us use entropy as a proxy for environmental damage (see Figure 11.1) and try to understand forecasting and backcasting…understanding something with the help of something else often makes understanding gloriously easier.

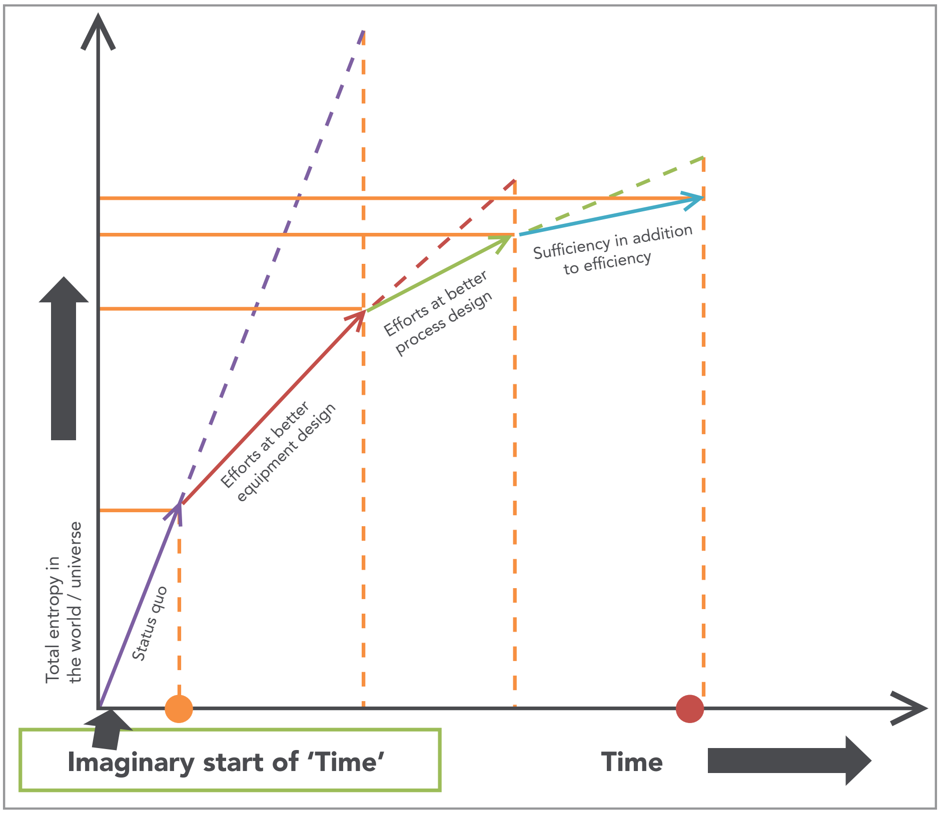


Figure 11.1: Entropy is rising…can we do something about it?

Let us assume an imaginary start in time, at which entropy in the universe/world was zero. We assume a linear increase in entropy with time (though this is a gross oversimplification, and it is also questionable if entropy can actually be measured and recorded thus) – the violet line in the Figure 11.1. The blue circle on the X-axis represents the time when you decide to sit up and take stock – forecast and back-cast in other words. You fix a time in the future represented by the red circle on the X-axis. If you extend the violet line upwards, you would have a measure of the entropy if current trends continue unabated. Now, you wish to bring the total entropy down in the year depicted by the red circle, to a value corresponding to the tip of the blue arrow. That is a daunting task, as you see right away! When you made the forecast, you assumed a linear increase in entropy with time. You know where you will be if you did nothing at all. You know where you wish to be, and for that, you have to do something, or actually, several things! Now, it is time for back-casting. You see the farthest target in terms of two nearer ones, as shown – the tips of the green and red arrows in Figure 11.1. You have now fixed three time intervals and three target-points to aim for. The paths traced within these intervals may not be straight lines…they also need not be smooth curves. Having done this, you would decide the *modus operandi*. Often, you may find that it is impossible to just resort to better equipment design to bring about the drastic change represented by the difference in slopes of the violet line and the red line. You may have to add doses of 'better process design' and 'sufficiency' to the recipe. And this may apply for the next two intervals as well. But as you will agree, stronger the enemy, wiser it would be to fight it as a team. The more daunting the challenge, wiser it is to surmount it with a 'team of solutions' and not any one in isolation.

Now the three means we have identified to hold down the rate of rise of entropy, are very much applicable to environmental damage as well. You would forecast and back-cast for different environmental impact categories, setting relatively more challenging goals for those categories which demand greater attention. For instance, if the water bodies in the region are nearing their carrying capacity and there are clear signs of the habitability of the same being eroded over time, eutrophication should figure prominently on the table. If the energy mix of the region is by and large made up of renewable resources and the forecast suggests that this would not change appreciably over the time period considered, global warming need not be prioritised as highly as eutrophication in this case at least. E-LCA while enabling one to forecast the impacts at current trends, will also enable one to identify the reduction potential of efforts made to improve equipment and process design/efficiency and to inspire consumers to understand the meaning and value of sufficiency. To understand, appreciate and embrace sufficiency, one has to go back to the philosophical premise of environmental systems analysis, which we alluded to in the first chapter. Back to Godhead…or rather back to having a 'good head'.

Exercises

1. Can you try to measure your own environmental footprint? Say, just your carbon footprint to begin with (your contribution to global warming, that is). Now, is it possible for you to forecast how your cumulative contributions would increase with time – say over the next decade? Having done that, can you set some target for yourself (of course, you should want to reduce pull the curve down vis-à-vis the forecast 'Living-As-Usual' scenario. Then back-cast and decide how you would go about truncating your carbon footprint. You can work in groups of two and then compare your analyses. Figure 11.1 could serve as a base to start working from…

12 APPENDIX : ENVIRONMENTAL IMPACT CATEGORIES

12.1 ENVIRONMENTAL MECHANISMS – MIDPOINT INDICATORS (IN ALPHABETICAL ORDER)

1. **Abiotic depletion** (of non-living – fossil fuel and mineral – stock resources)
   This is calculated by using the equation Σ (ADP_i * $\mathbf{m_i}$)[22]**,** where m_i is the mass of the abiotic resource ‘i’ used. ADP_i or the abiotic depletion potential of the resource ‘i’ is calculated using the formula in Figure A.1. The reference resource indicated with the subscript ‘ref’ is antimony, which explains the unit for ADP – **kg-antinomy equivalents**. (Check for yourself with the units in the quantities in ‘ADP_i * m_i’. ‘Ultimate reserve’ refers to the total recoverable crustal content of the resource in question (usually always greater than the economic reserve and the reserve base). Economic reserve refers to that proportion of the ultimate reserve which can be economically extracted at the time of recording/documenting. Reserve base is that fraction of the ultimate reserve which has the potential of being technically and economically extractable in the foreseeable future. The reserve base is greater than the economic reserve.

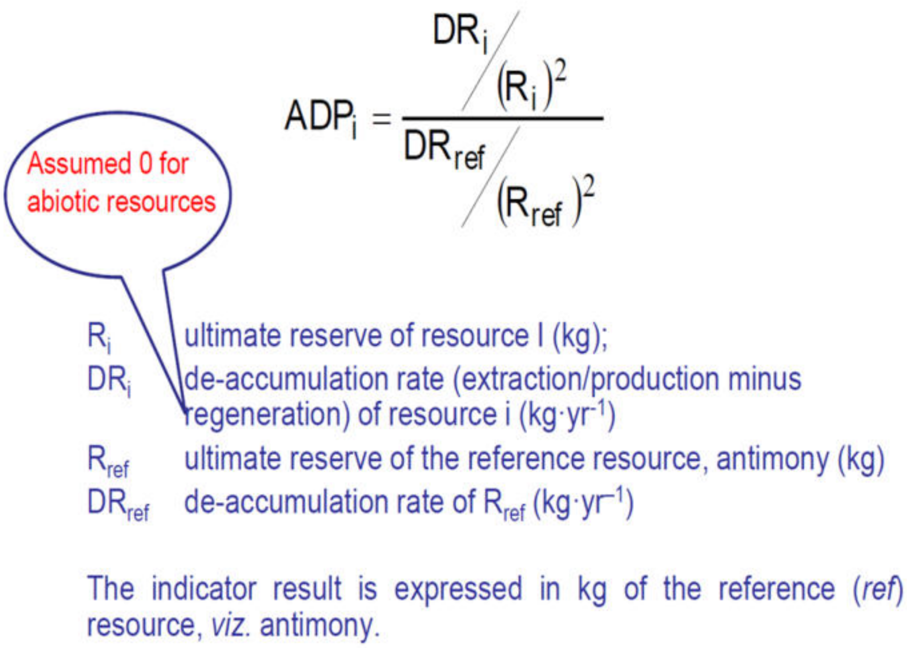


Figure A.1: Abiotic depletion[22]

When resources which have high de-accumulation rates as well as low ultimate reserves are a part of a process for which an LCA is being carried out, the ADP needs to be given a high-enough weighting factor. A comment here would be in place for those who may have started wondering about the terms 'depletion', 'scarcity' and 'criticality' of resources. The former is the reduction in the ultimate reserve over time. The second-named happens when the availability of the resource is less than the demand for it. The last-named occurs when a particular resource is indispensable for the society/economy and is scarce at the same time. Also to be remembered is the fact that on an elemental or atomic level, nothing is destroyed. It is only the exergy (degree of usability) which keeps decreasing, reducing the quality of the resources. This is when we talk of downcycling (recycling in a cascade).

Depletion and scarcity can be tackled by investigating the possibility of alternatives (with much greater ultimate reserves), so that the de-accumulation rate of those resources which are getting depleted at a brisk clip, can be controlled. As far as criticality goes, the situation is a bit more challenging than this. Also note that the consumption of fossil fuels (coal, oil and gas) which in effect are regenerated but extremely slowly (the rates being numerous human lifetimes), also contributes to abiotic depletion and the transition to renewable energy is a solution to this depletion, which may lead to scarcity and criticality over time in some parts of the world, if the said transition is not effected. (You will agree that abiotic depletion of fossil fuels is linked to climate change/global warming and acidification and thereby to the endpoint damage categories Human Health Damage[1] and Ecosystem Damage[1]; and thus also realise that different environmental impact categories may be somehow interlinked.)

(As an exercise, try to get data for the ultimate reserve and de-accumulation rates of arbitrarily selected abiotic resources…and understand the situation that prevails…)

2. **Acidification**
   The poem and the cartoon may make you smile and wonder if such a thing would ever happen. Of course, let us hope it does not. Here, I would like you to also refer back to Table 4.2, in which some acidifying emissions with their characterisation factors have been listed. As you know by now, the unit for acidification potential is kg-SO_2-equivalent. Sulphur dioxide, which combines with water and settles down in the hydrosphere as sulphuric acid, or gets oxidised to sulphur trioxide, is a strong acidifier, though as you will see in Table 4.2, there are stronger ones as well.

One rainy morning in 2024,
the laboratory ran out of H2SO4.
Class starts at quarter to nine.
It is already eight thirty-nine.
Jack looked out wondering,
at the dark sky thundering.
He sought and found a way out.
Acid rain from heaven's spout.
'Every cloud has a sulphur lining,'
he smiled sarcastically at the modified saying.

Figure A.2: Acidification in a lighter vein[23]

Acidification links up all the spheres of the environment in a way. Here we talk of the 'fate' of the acidifying substance emitted from the anthroposphere. Of course, acidification happens naturally as well – like for instance when organic acids in plant litter like acetic acid, humic acid, oxalic acid etc., get mixed with the soils or when silicic acids from granites and igneous rocks get added to the soil due to weathering over time – but here we are interested more in what humans have been doing to upset the natural balance in the 'intra-spherical' environmental flows. What is released to the atmosphere is likely to settle down in the soil, or for that matter get dissolved in river water or sea water.

When acid rain (acids like sulphuric acid, nitric acid formed in the atmosphere when nitrogen oxides and sulphur dioxide combine with rain water) falls on the soil, the free hydrogen ions (protons) thus donated to the soil, displace the essential nutrient cations – calcium, magnesium, sodium and potassium necessary for plant growth. This reduces the fertility of the soil, and thus affects the yield of this category of 'fund resources', being instrumental along with other mechanisms for the endpoint 'Resource Depletion'.[1]

Interestingly, even carbon dioxide (a global warming agent) is an acidifier – when it gets dissolved in the oceans and forms carbonic acid. The ocean, quite like the forests, can soak up a lot of carbon dioxide (natural carbon capture and storage), but it too has its own carrying capacity, or in other words, marine organisms have their own tolerance limits. Ecosystem damage as an endpoint indicator, thus has acidification as one of its causes. It is estimated that about 40% of the carbon dioxide released by anthropogenic activities dissolves in the oceans.

3. Eco-toxicity (terrestrial and freshwater/marine) and human toxicity

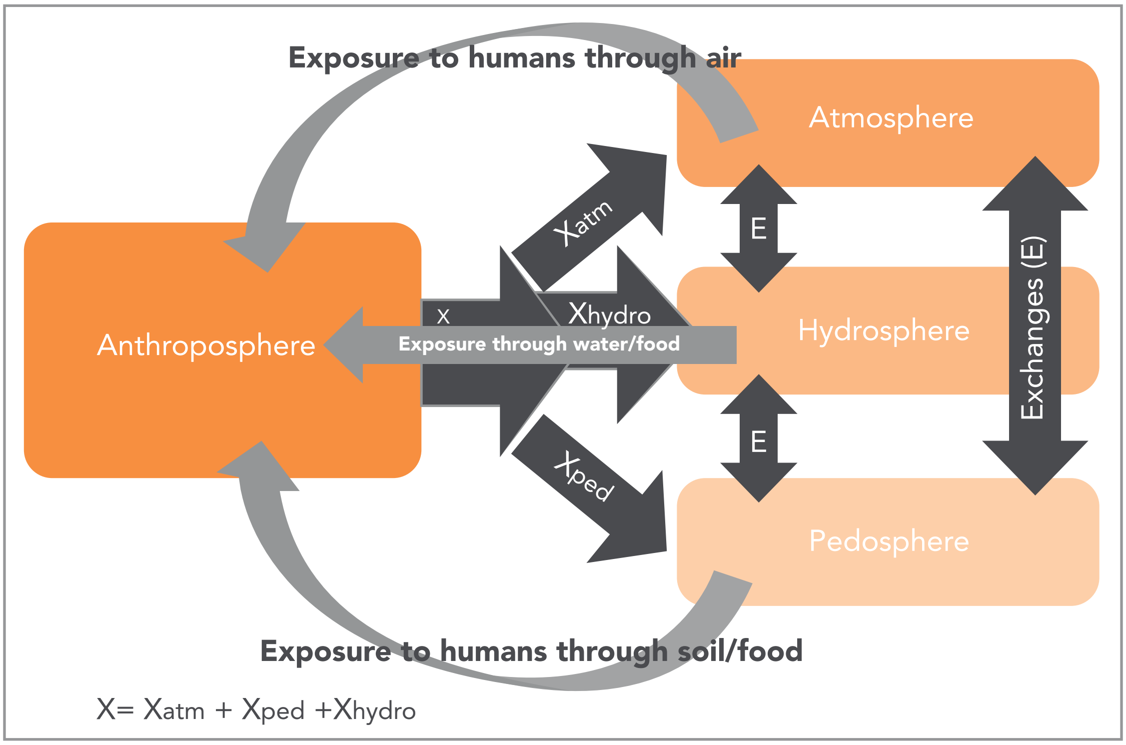


Figure A.3: Eco-toxicities and human toxicity: Release, fate and exposure

Any xenobiotic substance (foreign to an ecosystem), is likely to have disturbing/adverse effects on some or all of the components of the same. It would take a long time for the system to get acclimatised to the presence of such a substance (to become immune to it, in other words). If not toxic, perhaps, such a substance may just be non-biodegradable and may interfere with some functions within the system. Natural systems do have some buffering capacity – like the white blood cells in the blood – to counter the intrusion of toxic substances. But this capacity is not unlimited. Further, different components of a system have different levels of tolerance to toxic intrusions.

Toxic pollutants adversely affect freshwater/marine ecosystems as well as terrestrial ones. Human beings get exposed to pollutants through contact with air (atmosphere), soil (pedosphere), water (hydrosphere) and food (sourced from the biosphere which could be a part of the lithosphere/pedosphere – plants and terrestrial animals, atmosphere – birds, or hydrosphere – fish and other aquatic creatures). The fates of the molecules released from the anthroposphere, determine whether they will cause terrestrial eco-toxicity or freshwater/ marine eco-toxicity. What gets deposited on the soil/rocks/land can also land up in water in the future, courtesy weathering, erosion and rainfall run-off. Terrestrial and freshwater/ marine eco-toxicity lead in the medium-term to resource depletion and ecosystem damage. The probability of exposure of human beings to toxic substances (to be more precise, substances which cause human toxicity) determines the degree of human health damage that could occur. We delve into a new discipline here – eco-toxicology – which describes the chain of processes from the actual emissions of the toxic substances to their fates in the environment, exposure of living beings in the biosphere and anthroposphere to the same, and the effects these have on different aspects of human health – ranging from tiredness and fatigue to cancer and death.

Anthropogenically-released toxic substances essentially can be grouped into four different categories:

a) *Chemical toxicants* like lead, mercury, chlorine gas, hydrofluoric acid, methyl alcohol, cyanides, aromatic hydrocarbons etc.
b) *Physical toxicants* like coal dust, asbestos fibres, silicon dioxide and asphyxiant gases.
c) *Nuclear radiation* from radioactive materials

Of course, disease-causing pathogens are 'toxic' to living beings (humans included), but those are components of the natural environment.

4. **Eutrophication**

The interactions among the different spheres of the environment play a key role when one tries to understand eutrophication. As the word suggests, it indicates a surfeit of nutrients (nitrogen and phosphorus) in the hydrosphere which result in uncontrolled algal growth on the surface of the water bodies. (Of course, the algae trap some of the carbon dioxide in the atmosphere, as they bloom.) When the algal blooms, as they are called, die, they sink to the bed of the water body, are decomposed by microorganisms which consume oxygen dissolved in the water at a rapid rate (causing hypoxia of the waters) and release carbon dioxide. The surface being covered by the living algal blooms, dissolution of oxygen from the atmosphere is hindered to some extent. Oxygen depletion which results in the process, has a detrimental effect on sub-surface aquatic life, causing ecosystem damage and resource depletion (fund resources in this case – fish which may be a source of nutrition for humans, animals and birds in the system of which the water-body is a sub-system). Refer back to Table 4.3 in which a list of some common emissions causing eutrophication has been provided, alongwith characterisation factors – relative strengths with respect to the trivalent phosphate ion.

The pathway of the 'eutrophicating' emissions can be directly to the hydrosphere from point sources (as in the case of treated wastewater with some unremoved nitrogen and phosphorus being discharged to the sink), or indirectly from the atmosphere (when ammonia and nitrogen oxides released to the atmosphere during industrial processes dissolve in water), or pedosphere (when rainfall erodes and carries nutrient-rich soils into seas, lakes and rivers). A point to be borne in mind here is that a discharge of nitrogen and phosphorus into the open sea does not cause as much cause for concern (owing to the fact that *'the solution to pollution is dilution'*, or is it?), as discharge into a landlocked stagnant water body of a considerably smaller surface area and volume.

Also to be remembered is that one can also have eutrophication of the soils! Terrestrial eutrophication in other words. Excessive nitrate content in the soil is also not good for plants. Nitrogen fixing by bacteria in the soil, is Nature's way of fertilising it to the right extent. Human interference (sometimes to get the most out of arable land in a short period of time) often upsets the balance. A question to you then is, 'Can eutrophication happen because of the natural biogeochemical nitrogen cycle alone?'

5. **Global warming**

Figure A.4: Global warming at its worst?[23]

Just like the natural nitrogen cycle referred to in the previous section, there is a natural carbon cycle, which keeps things in a more-or-less perfect balance. This is courtesy the 'self-regulating nature of Nature', so to say[24]. It is human interference with this balance, that has caused global warming and the associated climate change effects of late. Of course, natural processes release greenhouse gases continuously – methane, carbon dioxide, nitrous oxide etc. – but as mentioned before, Nature does keep things in a more-or-less perfect balance. Of course, even naturally, things could go wrong…but that does not mean that humans can look away from their contribution to global warming.

As Table 4.1 shows, there are several greenhouse gases with different 'potencies' – expressed with respect to carbon dioxide (therefore, the unit – kg CO_2-eq.); and the sources (causative agents) are diverse. As is known to you, the greenhouse gases in the atmosphere trap the low-frequency infra-red radiations that emanate from the earth's surface, and radiate this back to the earth, raising the temperature in the process. Rising temperatures lead to several 'climate change' issues, but interestingly one sees interlinkages among global warming, eutrophication and acidification when it comes to the self-regulating behaviour of the earth[23]. According to the Gaia theory, when the sea levels rise, the waters would inundate more of the land on the shores, providing nutrients therefrom for the aquatic life-forms. Phytoplanktons proliferate, and during their growth emit dimethyl sulphide (DMS) to the atmosphere. DMS subsequently forms a host of sulphur-bearing compounds, which are then able to form aerosols which serve as cloud condensation nuclei. The more the clouds in the sky, more solar radiation is reflected back from the atmosphere into space. In effect, the warmer it gets, if this effect is to come into play, there is a wonderful negative feedback mechanism which reflects back more of the incoming solar radiation.

6. O**zone depletion**

We are talking of the stratosphere here – the part of the atmosphere above the troposphere and below the mesosphere. The ozone layer in the stratosphere prevents most of the harmful ultraviolet (UV) wavelengths (280 to 315 nm) from passing through the stratosphere-troposphere and reaching the earth. The ozone in the stratosphere can be depleted by several free radical catalysts – the strongest of them being the hydroxyl, nitric, chlorine and bromine radicals. While most of the nitric and hydroxyl radicals in the stratosphere are of natural origin, we must say '*mea culpa*' for the chlorine and bromine radicals which have proliferated in that zone of the atmosphere. Halocarbons, which are stable organic compounds, make their way up when they are emitted from the surface of the earth into the stratosphere, encounter electromagnetic radiations and dissociate into highly-reactive chlorine/bromine radicals. They then get to act on the ozone molecules they come across. It is alarming to note that a single chlorine atom can react with hundreds of ozone molecules before being removed from this catalytic cycle.

Adverse health effects owing to ozone depletion include sunburn, skin cancer, and cataracts. Interestingly, there is a link between ozone depletion and photochemical ozone creation. As more UV light manages to penetrate the atmosphere and reach the surface of the earth, tropospheric ozone levels rise (owing to the role played by UV light in the reactions among VOCs and nitrogen oxides to form photochemical smog – read the next section). Human health damage is thereby aggravated with respiratory tract ailments being added in. In addition to human health damages, ozone depletion also affects plant and animal life, thereby resulting in ecosystem damage and fund-resource depletion.

7. **Photochemical ozone creation**
Ozone is produced photo-chemically (in the presence of sunlight) in the troposphere when nitrogen oxides and volatile organic compounds (VOCs) react. It is a part of what is called photochemical smog – a mixture of aldehydes, nitrogen oxides (NO and NO_2), peroxyacyl nitrates, ozone and other VOCs. The reactants – VOCs and nitrogen oxides – by and large originate in the exhausts of automobiles and this impact thereby is conspicuous in big cities in the tropics, with a large automobile density. Now, with gasoline and diesel being the precursors of the VOCs and NO_x emitted to the atmosphere, it follows that there is a correlation between global warming caused by the combustion of fossil fuels and photochemical ozone formation! Photochemical ozone formation has direct adverse impacts on human health, with the respiratory system being affected. Fatalities have also been linked to excessive ozone levels in the troposphere. The same ozone, however, is a blessing further up in the stratosphere! While levels of ozone in the troposphere must not be allowed to rise, stratospheric ozone ought not to get depleted.

12.2 ENDPOINT INDICATORS (DAMAGE CATEGORIES); IN ALPHABETICAL ORDER

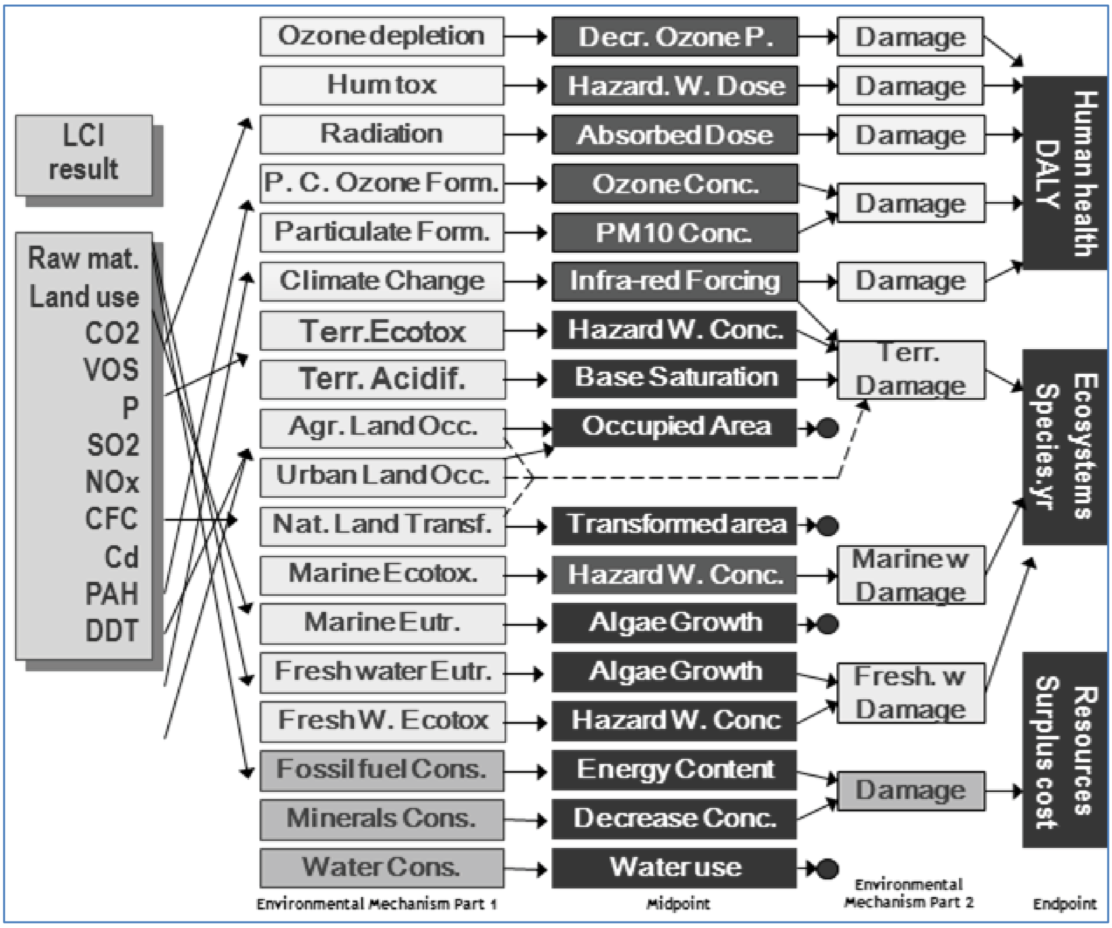


Figure A.4: The ReCiPe method: Emissions to endpoint indicators[1]

Figure A.4 depicts the interrelations between the emissions on the far left and the endpoint damage indicators on the far right. The environmental impact categories are identified in the Figure as Environmental Mechanism Part I. Of course, you see many more 'mechanisms' than the nine referred to earlier (Toxicity – nr. 3 is essentially three impact categories bundled up together). Also note that minerals consumption and fossil consumption are essentially parts of abiotic depletion. Land use change figures in Figure A.4. Water consumption (water is of course a flow resource and ideally always renewable but certainly not available in the form and quantity needed, where needed) is a prominent addition in Figure A.4.

13 APPENDIX: PUBLISHED ARTICLES ON INTERESTING FINDINGS FROM LCA STUDIES

13.1 PACK A PUNCH[25]

G Venkatesh[33], Fredrik Wikström[26], Helen Williams[27]

How to save the world, 10 grams at a time…

It is all in the packaging, my dear Watson. Sherlock Holmes would have said this, if he had been assigned a case involving a 'mountain of food waste.' Too much of focus on something often makes one miss the wood for the trees. The very purpose of the focus seems to have been defeated thereby. This is what could happen if the environmental impacts associated with the materials and manufacturing of packages for food, get a disproportionate share of the attention. Of course, the firm supplying the packaging (or the food processing industry using the packaging) may go overboard with how it managed to reduce the mass of the packaging significantly (dematerialisation) and use a very environment-friendly material instead of the conventionally-adopted less-environment-friendly ones (transmaterialisation). The undiscerning or callous among us, may get latched on to what we hear and read…and overlook what we see (but do not notice) later on…more food being wasted! This piece is a wake-up call to look beyond the obvious…beyond the wool drawn over our eyes. To quote from the Bible, ignoring the 'large indirects' and paying a lot of attention to the 'small directs' is very much like straining the gnat but swallowing the camel. The 'indirects' here refer to consumer behaviour triggered by (or exacerbated by) 'inconveniences' in the packaging if one may say so. Of course, the inconveniences are mere pinpricks to the 'green brigade' committed to sustainable development. The study on which this article is based was done in Sweden, and hence, the common item of food chosen was minced meat. Of course, one could select a different food item for a different country, and compare the different types of packaging used to sell the same in supermarkets/groceries. The minced meat is available in two types of packaging – one, a polyethylene terephthalate (PET) tray with a film made of PET and low density polyethylene (LDPE), an LDPE label and a paper label (together weighing 20 grams; and holding 508 grams of foodstuff); and two, a tube made of polyamide with aluminium clips and LDPE label (together weighing 5 grams; and half a kilo of foodstuff).

The heavier tray (made of PET) can be easily emptied fully onto a plate/utensil without leaving any foodstuff behind in it; zero food waste and the PET tray available for recycling without needing to be washed with a lot of water before disposal. On the other hand, foodstuff sticks onto the insides of the polyamide 'tubing' and even after some effort to scrape it all off the insides onto a plate/utensil, about 10 grams of food are wasted anyway. Well, 10 grams out of 500 grams may seem like 'small change', but add on all the consumption (and thereby wastage) of minced meat packed in such a manner, and over a period of 12 months, the waste would cumulatively add up to become conspicuous enough. And if it is minced meat, it does have a large environmental footprint (carbon footprint, water footprint etc.) In addition to the food wasted anyway, if the polyamide sheet has to be made recycling-ready, so to say, one would need to use tap water (and perhaps some soap), and this entails additional resource consumption. And the food waste wends its way into the sewer network and into the wastewater treatment plant (in Sweden).

Packaging performs several functions, and these are known to readers. It has resulted in bringing suppliers from around the world closer to consumers anywhere on the surface of the earth. Distances have been shrunk, so to say. Packaging keeps foodstuffs durable for a longer time. It serves as a cushion and absorbs mechanical shocks during transport, shielding vulnerable foodstuff from damage. But can it and should it be made to perform one more? To contribute to improved user behaviour and thereby reduction in or elimination of food waste and a greater degree of recycling? Yes, why not? And how can this be brought about? By imparting the following attributes to the packaging: Easy to empty, easy to clean, easy to separate into different fractions, easy to fold, having clear information on how to sort. To put it in a lighter vein, if it is well-equipped to run 3 miles, it can always be made to run an extra mile!

If only the direct environmental impacts of the packaging are considered, the tube wins hands-down! However, if food waste is also factored in (the 10 grams which are wasted per polyamide sheet), the tray emerges as the better alternative environmentally, despite the fact that it is much more massive (over 20 grams) and made of another fossil-fuel-sourced plastic material. 'Easy to empty' becomes the trump card here! However, it must be pointed out here that the meat does remain more durable within the polyamide tubular packaging vis-à-vis the PET tray. So if a consumer is absent-minded and forgets that he has purchased meat in the tray for many days, he may have to throw away all the meat. Of course, the PET tray would still be easy to empty – but all the 508 grams of spoiled meat will go into the food-waste bin instead and not into a utensil! The meat inside the polyamide packaging may still be edible…and only 10 grams may end up being wasted (perhaps along with the polyamide sheet also). However, in different countries and cultures, behaviour may be different. In India for instance, people are aware of the fact that foodstuffs do remain edible for some time after the 'Best Before' date stamped on the package. In India, one may still be able to feed stray dogs or birds…the food is not wasted, but consumed by some living beings – albeit ones with two wings or four legs. And as the food still remains edible (though not best), it is often also given away as alms to the impoverished slum-dwellers in the vicinity. Perhaps, the clouds of 'a yawning gap between the rich and the poor' and 'very high populations' can be looked upon as having silver linings – opportunities for the environment-friendly citizens to reduce wastage. Religion plays a strong role in India too – there are strong cultural traits which make people believe that feeding the poor and the animals/birds cohabiting with mankind, is an act which is dear to God.

So, it is not mere eco-design we are talking about here…but as explained, many other socio-cultural-religious influences need to be clearly understood to study, and thereafter positively influence consumer behaviour. And most importantly, this cliché must also always be borne in mind by designers and sustainable development professionals – *If it ain't broken, do not fix it!*

13.2 D-EV-IL IN THE DETAIL[28]

G Venkatesh[33]

Rob Peter to pay Paul/Pay Peter by robbing John/Plug a leak at Vauxhall/And end up flooding Wimbledon

Those lines of the doggerel above allude to the nature of problem shifting. Some would do it consciously; while some others may simply not be aware. The devil, as they say, is always in the details. Details of the sequence of causes/events leading to the manifested effect; details of everything that sustains this end-result while it lasts; details of everything that lies beyond the obvious.

This is true for just about everything that is bandied about these days in the name of the environment. As with bio-fuels, so with electric vehicles (EVs). These two, *prima facie,* may be silver-bullet solutions to the mushrooming concerns about carbon dioxide and the concomitant climate change. But if one would think laterally and scratch the surface, and go on doing it, to get to the devil(s) in the details, a little (or even a big one sometimes) Pandora's box is opened.

It may be difficult for readers to accept, but EVs which are usually heralded as messiahs of the environment, may even turn out to be wolves masquerading as sheep. The stress here is on the word 'may'. These are not ramblings of skeptics with an *idèe fixe*, but findings from analyses meticulously conducted by industrial ecologists at the Industrial Ecology Programme of the Norwegian University of Science and Technology in Trondheim.

Did you know that an EV, if analysed for its interactions with the environment, from cradle to grave, (or back to the cradle, where there is appreciable recycling of the materials or reuse of component parts after end-of-life), may turn out to be much less 'greener' than one would think it is? The global warming potential of the production process of an EV, for instance, can be over twice of that of its conventional IC-engine counterpart. And if you own and drive an EV in say Warsaw (Poland), throughout its lifetime (where a good deal of the electricity is sourced from coal), it should not surprise you if someone came over to you and told you that you would end up being responsible for anything between 17% and 24% more greenhouse gas emissions than what you would have if you had been loyal to your IC-engine car.

If you would cast off your blinkers and look around and about for environmental impacts other than global warming, you would also realise that IC-engine vehicles fare either better or as bad as electric vehicles do, in a host of environmental impact categories like freshwater eco-toxicity, mineral (abiotic) depletion, particulate matter formation, freshwater eutrophication and human toxicity.

Here is some more food for thought. It is actually good to be possessive of your EV and use it longer; for the longer you use it, the greater may be your potential contribution to the mitigation of the global warming menace. But there is a caveat here…and thereby the use of the word 'may'. Find out where the electricity you use to recharge your batteries comes from. Greater the renewable energy content in the electricity mix, you can pat yourself on the back more, for being a responsible citizen of Planet Erath – though of course, not as much as someone who walks, or cycles, or uses buses and trains throughout his life!

Morals of the story:

1. What is good for the goose, may not always be good for the gander!
2. If this has piqued you, you ought to find out more about this…

13.3 MEATY ISSUES[29]

G Venkatesh[33]

According to Wikipedia, in 2007, the United Nations Food and Agriculture Organisation (UN-FAO) had gone on record that Indians had the lowest rate of meat consumption in the world. Studies (which now are dated, and perhaps need to be carried out again) have put the percentage of vegetarians in India at between 20% and 42%. Impressive, one would say, at least on a percentage basis…relative to almost all the other countries of the world, where non-vegetarianism is almost the *sine qua non* for survival and happiness! Yet, this means that over 50% of Indians – that is over 600 million people – is meat-eating. In terms of the quantity of meat (would include chicken, beef, pork and mutton here; and exclude fish) consumed annually, India may really not be that low down on the list. In the light of the fact that serious environmental concerns (impacting water, air and soil) can be attributed in part to non-vegetarianism which augments the demand for meat products as people ascend the ladder from poor to middle class to upper middle class to upper class, one needs to seriously pause and re-evaluate one's food habits – all over the world for that matter. This applies more to countries where a significant percentage of the population would consume meat almost every day.

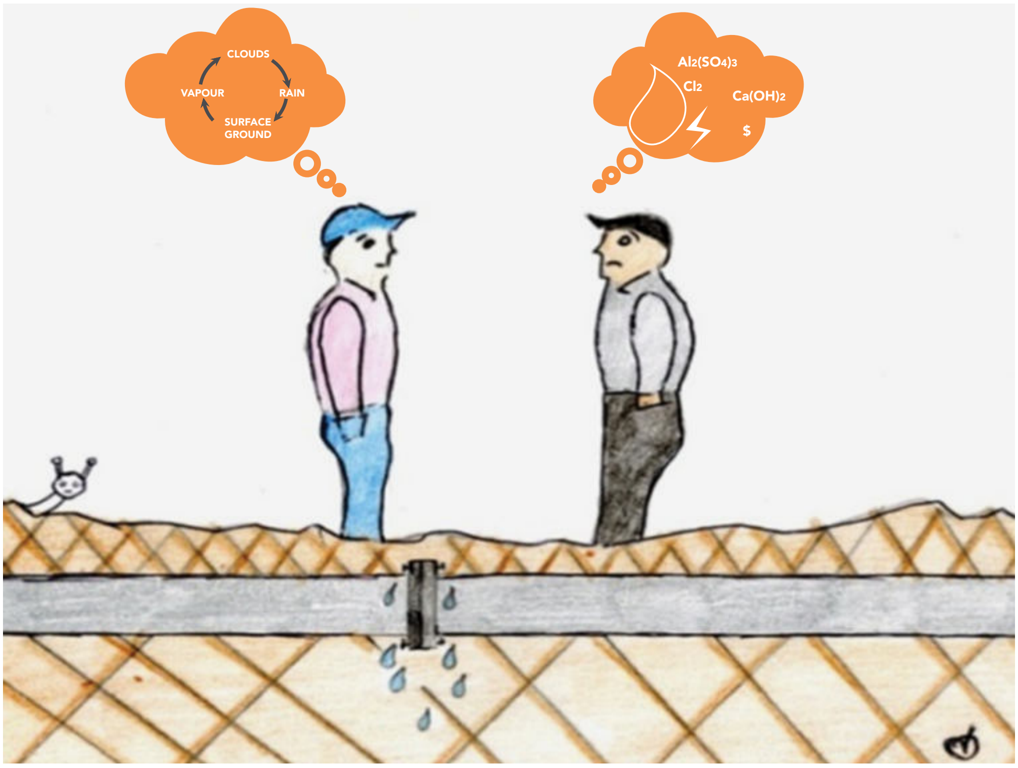
As reported in the Feb-2014 issue of the magazine Water[21] (published by the International Water Association, UK), food production consumes around 75% of global water withdrawals, 38% of the earth's land area is devoted to agriculture, conversion of forest to agricultural or pasture land generates 15% of global greenhouse gas emissions, while agriculture directly contributes to a further 20%, and agriculture uses about 30% of global energy. It is also important to remember here that it takes three vegetable calories to produce one animal (meat) calorie, according to the said article. So, a rise in demand for meat is certainly going to stress water, energy and land a lot more! Water, land and even energy to a great extent (as on date, considering the existent conversion technologies) are limited resources, as we all admit. In the western world (or in general, in richer countries), animal feed and biofuels production are slowly encroaching into crop/fruits/vegetables production territory. Demand for biofuels would keep rising, and the transportation sector (private and public) would feel that it is getting greener. Owners and users of cars which avail of biofuels would like to feel that they are contributing greatly to the environment. This may have a disastrous rebound effect. They would just be making it difficult for poor people in many parts of the world to get food! Perhaps, with more and more people using public transportation more often, and resorting to walking and biking, the world would benefit a great deal. If governments around the world do their level-best to make public transportation affordable and accessible to more and more people, this would be a good combination for the future. Well, alongwith developing a penchant for public transportation – no matter how taxing and tedious it may be, relative to private transport – and walking and biking as frequently as possible, can one expect man (and woman) to reduce and eventually give up their liking for meat? What we actually need now is a step-change and not a slow transition – so, more of giving up by more and more people, would perhaps lead to much greater benefits for the world on the whole, than following a phased approach. This certainly would be a sterling sacrifice by man (and woman) and a wonderful contribution to the sustenance of human welfare on earth – in other words, for the generations to follow, also of the people who would be making these sacrifices for that matter! It is very difficult, of course, for someone who has clung to a habit for too long to admit that he/she was not doing the right thing all this while, and suddenly change. But as the old adage goes, *'It is never too late to mend.'*

Consumer attitudes and demand for goods and services are affected by higher incomes, they say. But is it necessary that higher incomes should, *de rigeur*, lead to an increase in meat consumption and a deviation away from public transport to use of private cars? People associate a rise in status and an increase in personal wealth, invariably, with these two things, *inter alia*. Well, some introspection here would be of great help. Of course, 'to each person his own; to each dog his bone'. None for that matter wishes to comment on the food habits of others. This is usually sensitive territory which one wishes not to tread (and be angels) and refrain thereby from being fools and making enemies. On the website www.happycow.net, readers can find a list of famous vegetarians. If this list is inspiration enough and if one would find one's idols therein; and is that is good food for thought, it is worth a *dekko!*

EPILOGUE

This sketch is a favourite one which I often use in my lectures. Of course, the poem which it illustrates is not used so often. I present both hereunder and leave it to you to ponder on the importance of life-cycle thinking – all complexities and subjectivities notwithstanding – in the 21st century. Think about the E-LCA of a litre of water delivered to you at your tap and subsequently used (for bathing) and discharged into the sewer…

MORE THAN JUST WATER IS LOST[23, 30]



‘Water leaks out every day, from pipes below the ground.
Age-old conduits of iron and steel, rusted, damaged, unsound.’
‘Is not it true that water, is never really lost?
Ground-to-sea-to-cloud-to-rain; is not that what we were taught?’
‘There is more to every drop, leaking out along the way.
Think of the treatment processes, and you’ll question what you say.
Aluminium sulphate and chlorine, calcium hydroxide and UV-radiation.
Lots of electricity goes into making raw water suitable for consumption.
With every drop lost, you lose value; the water comes back later as you say,
but chemicals and energy must be added again, and isn’t it that for which we pay?’

AFTERWORD

(Dr Geoffrey Guest)

I sincerely hope that you have enjoyed Venkatesh's unique, light-hearted though philosophically-deep introductory piece on E-LCA as much as I have. To those who are planning to take the next step into this fascinating subject, I commend you, and I'd like to tell you that the LCA community is heading towards exciting times. The discipline of E-LCA (or just LCA) is still relatively young. The initial seeds of LCA's conception reach back as far as the 1950s when ideas about bio-economics and systems ecology were formalized in Samuel Ordway's 'Resources and the American Dream' and Eugene and Howard Odum's 'Fundamentals of Ecology'. However, most LCA practitioners track LCA's beginnings back to 1969 when Coca Cola hired the Mid-Western Research Institute (MRI) to conduct a material and energy flow study of their packaging alternatives. The study consisted of a comparative analysis between returnable glass bottles, primary aluminium and plastic alternatives. Harry Teasley, the Coca Cola executive who initiated the study was conscious of the need for environmental knowledge for both internal planning purposes and public relations. Findings from this pioneer study suggested that plastic measured far better than the other alternatives. However, it took many years before Coca Cola began the switch to the plastic bottles that we know today. The MRI defined their technique as a 'Resource and Environmental Profile Analysis' and it was based on a cradle-to-grave systems analysis of the production chain of the investigated products.

The E-LCA tool soon became widely recognized as a methodologically-rigorous approach to quantifying how eco-friendly a specific product pathway actually is and the approach now has seven ISO standards dedicated to either E-LCA or more specifically, the carbon footprint of a product, service or organization.[31] As you can imagine, E-LCA is now taken very seriously by a great number of institutes, governments and companies. For instance, Walmart had conceived a dream of undertaking 10,000 or so LCAs in order to attain a detailed LCA of every single product that they sold. In 2009, they announced their 'Sustainability Index' that would cover a product's entire life cycle, from resource extraction to final disposal. This led to what is now termed the Sustainability Consortium which currently boasts more than 80 corporate members, operates on four continents and since late 2012, has worked with the much larger Consumer Goods Forum to establish 'a globally-harmonized, science-based approach to measure and communicate life cycles.' There are a number of similar green initiatives around the world where E-LCA has gained a high degree of popularity. What was once a rather unpopular, academic and, if I may dare to say, geeky system of accounting turned into the go-to approach for corporate and government initiatives to measure, disclose, inform policy and improve the 'cradle-to-grave' environmental impacts of existing products. The corporate supply chain itself has become a breeding ground for the knowledge and insight of a company's operations and its big-picture implications.

For the majority of LCA's existence, it has, for the most part, been situated in a place where academics told industry – *LCA will benefit you and therefore you should utilize it.* With the initiatives of Walmart, it really helped to open the flood gates of the application of LCA, where it is now industry that inquires with LCA consultancies that they need that tool. LCA has reached a renaissance where even the big four – Deloitte, PwC, Ernst & Young, and KPMG – have adopted it into their toolbox along with many other specialized consultancies where they are finding a growing demand. LCA in industry has not been a total success however. The methodological rigour required to undertake a detailed LCA brings upon several challenges with industry: LCAs can be time-consuming and cost a lot of money to undertake; they can become too complicated for the public and results do not always turn out in favour of the companies' best financial interest; more supply chain transparency can lead to greater vulnerability and potentially moral disquiet. These challenges can lead to misuse of LCA in the industry, which in turn harms its reputation. A notable quote from Oscar Wilde is apt at this juncture – *The truth is never pure and rarely simple* – and many LCA practitioners struggle to avoid the muddy waters of complexity, data gaps and what the funding corporations want to hear.

Nevertheless, the tool of E-LCA has already proved itself to be a popular discipline in both the corporate and governmental arenas. There are a great number of signs that LCA is thriving and will only keep getting better. Companies like Dow Chemicals, Apple, Google, and Facebook have all sought out LCA experts to work in their firms. All companies face rising resource costs, and many are dealing with growing pressures for transparency requiring that they account for, and manage better, both the environmental and social impacts throughout their supply chains. LCA is one of the best tools to provide this transparency and it also protects companies from the accusation of 'greenwashing'. European Union regulations now require lawmakers to apply life-cycle thinking when undertaking waste management decisions. Many European governments have looked to LCA to inform them about key policy decisions covering key sectors like recycling, public transport, food labeling and renewable energy production. In the United States, both federal and California biofuel standards draw on LCA results. It is common practice for greenhouse gas emission reduction initiatives to require an LCA framework for quantifying the same. China, Chile, New Zealand and others are investing in LCA research programmes and LCA database development, not only for their own benefit, but in anticipation of an encroaching need to better inform global corporations of their upstream impacts. Similar to the nutritional content label of foot products, hundreds of companies are utilizing LCA to substantiate their products' environmental product declarations in a certifiable and third-party-verified fashion.

As you continue learning about LCA and hone your skills as a practitioner, I urge you to keep abreast with the Open LCA movement. With a contributing data and programming community the openLCA Project[32] has the potential to have a big impact on how to undertake the most innovative and scientifically sound E-LCA approaches. The openLCA Project offers a freely-available software for E-LCA which is opening many different, new application fields in science, education, training, and peer-review. Moreover, publishing the source code will allow in-depth comparison of calculation procedures. This peer-to-peer environment will demand high-quality coding from practitioners, and it will enable any user to implement an additional module as required or modify the source code where needed. If and when you become a dedicated LCA practitioner, I recommend that you take the effort to understand the Leontief Inverse and its practical usefulness to LCA. The most fundamental currency of the life-cycle inventory used to power an LCA is the unit process. The material and energy inputs and outputs required to produce a unit of a product from a process should be accounted for in a standardized way that should be replicated across all processes in your system. Always appreciate the simplicity of the unit process, and the high resolution of insight that can be attained when several thousand unit processes are weaved into an integrated system that is representative of our globally-connected economy. If you then move on to gain an appreciation for Wassily Leontief's work, which won him the 1973 Nobel Prize in Economics, you will achieve a deeper understanding of how your life-cycle case study connects with processes in the wider economy. This extra insight will also allow you to appreciate how the approach of hybrid LCA can connect a process-based LCA to an economic sector-by-sector input-output framework, which is considered a far more complete approach to compiling a life cycle inventory.

Lastly, I recommend that you gain an appreciation for the methodological differences that often create heated debates in the LCA community. Things like allocation, consequential versus attributional approaches, indirect land use change and recycling are some of the main areas where practitioners might feel strongly, for the utilization of one approach over another. My advice here, is to be polite and open, and try your best to gain a working proficiency in all of the available methodological choices and to understand the strengths and the weaknesses of each. We live in fast changing times. May your work in the field of E-LCA allow humanity to choose the best options for change that provide optimal benefit for both people and the planet.

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ENDNOTES

1. http://www.lcia-recipe.net/project-definition
2. A chapter on uncertainty analysis has not been included in this primer. Those of you who would be motivated to study E-LCA in greater detail will surely be able to access useful material on this topic within E-LCA
3. Sourced from **G Venkatesh**. PhD thesis – Systems Performance Analysis of Oslo's Water and Waste-water System (Page 27). Norwegian University of Science and Technology, Trondheim, Norway-7491. ISBN 978-82-471-2623-3, 2011. <http://urn.kb.se/resolve?urn=urn:nbn:no:ntnu:diva-12664>
4. GaBi databases, US LCI, ecoinvent etc.
5. Simapro, GaBi, TEAM, BEES, Umberto, ECO-IT etc.
6. www.xe.com. Accessed on 10th July 2016
7. Values assumed by the author
8. IPCC (2007). IPCC Fourth Assessment Report – Contribution of Working Group I: Technical Summary 2007; 31.03.2008.
9. https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

10. This refers to the amount of heat trapped by a constant mass of any of the greenhouse gases over a period of 100 years. The characterisation factors simply tell you how much more heat a given mass of a particular greenhouse gas traps, than the same mass of carbon dioxide over a 100-year period. Now, for example, the average lifetime of methane molecules in the atmosphere (about 13 years) is much less than that of carbon dioxide molecules. So a given mass of methane would last as methane only for about 13 years, and trap 27.75 times more heat than the same mass of carbon dioxide would do in 100 years. If 13 years is considered as the time period instead of 100 years, then the heat trapped by a given mass of carbon dioxide during 13 years is much less than what it would be in 100 years… resulting in a much higher characterisation factor for methane!
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26. Associate Professor, Department of Chemical and Engineering Sciences, Karlstad University, Sweden
27. Senior Lecturer, Department of Chemical and Engineering Sciences, Karlstad University, Sweden
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