Sustainable mechanical engineering guide

A guide to sustainable design in the field of mechanical engineering

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Green mE
Duurzaam onderwijs op 3mE

Sustainable mechanical engineering guide

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Preface

This manual is the result of the hard work of the Green-mE student innitiative. Green-mE was set up in 2016, after two students found that improvements could be made with regard to the level at which sustainability was a part of the mechanical engineering curriculum at the Delft university of technology. Green-mE took on the following goal:

“Green-mE wants the faculty of 3mE of the Delft University of Technology to educate students to be engineers that actively contribute to the transition towards a sustainable society. The education should incorporate comprehensive technical knowledge in the discipline of the development and application of sustainability in engineering.”

In the founding year Green-mE consisted of 4 students. The goal of that year was to find whether the consensus that sustainability should be a more prominent part of the education was broadly recognised by different stakeholders in the education. Thus the Green-mE board engaged in conversations with lecturers, education management staff, relevant businesses and relevant sustainable organisations. The results from the meetings and research that had been performed was documented in a report. One of the major findings in the report was that all the different stakeholders agreed that education should play a more important role in education. It was however unclear who would take on the task of implementing this vision. Thus the second year of Green-mE took a shot at it.

A student that has acquired a degree in mechanical engineering will have spend 58% of their time on theory in physics and mathematics, and 23% of their time on projects. The remaining time is spend on an elective minor and ethics. Because projects are such a major part of the curriculum and the place where everything that engineering embodies comes to together, they seemed like the most suitable place to start with the implementation of sustainability. In order to provide students with the pragmatic expertise necessary to improve their designs, with regard to sustainability, we set out to write this manual. We sincerely hope that people will enjoy working with this manual and that it will provide them with some of the insight that will be necessary for our generation to perform the major transition ahead of us.

The authors gratefully acknowledge the helpful comments of Regine W. Vroom of the Delft University of Technology on a draft of this paper. All errors and omissions remain the responsibility of the authors.

Introduction

Introduction

An essential question to ask yourself before beginning to read this guide on sustainable design, why bother? Well first of all, sustainability is a hot topic these days and you may personally be wondering how you can be a part of the transition to a more sustainable society. A second argument is company intent, your future or current employer is likely to want you to be able to perform a sustainability analysis of the good or service that the company delivers. This intent could be driven either by a desire to decrease material and energy cost or because it may increase revenue through product innovations. The final argument is that more and more regulations are being implemented in order to force a transition to a more sustainable economy. This could very well affect your industry of interest and it is thus important that you have a grasp of the basic concepts and tools that enable you to design in a sustainable manner.

Let us continue by defining what sustainability is so that you know what goal to strive for. The world commission on environment and development defines sustainability as follows; "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". From the laws of thermodynamics the following four conditions have been derived for a sustainable society by Broman and Robert [2015]. In a sustainable society, nature is not subject to systematically increasing…

- concentrations of substances extracted from the earth's crust,
- concentrations of substances produced by society,
- degradation by physical means
- and, in that society people are not subject to conditions that systemically undermine their capacity to meet their needs.

From this definition and description of a sustainable society it becomes clear that sustainability encaptures much more than just global warming and CO_2 emissions. Even though this might currently be the biggest threat to the survival of mankind and many other species that inhabit our planet, we should not lose sight of the many other hazards that accompany a poorly designed product.

Another major misconception that we would like to eliminate right out the gate is that improving efficiency per say makes a product more sustainable. Looking back on history we have made major steps in improving the amount of energy that it takes to transport and produce anything. The first step was taken by Thomas Savery, through the invention of the steam engine. This initiated the first industrial revolution which gave us live as we know it today. People have never been wealthier and healthier than the society is at this very moment and we have our ancestors to thank for that. However at the same time this improvement in efficiency has allowed us to surround ourselves with a lot of products. Products that are often made from scarce materials, containing toxic batteries and in many other ways negatively impact our environment.

If improving efficiency is not the way to go than what is it we should change in order to continue our current lifestyles? Should we just stop living altogether? Well luckily we have the sun. The sun is the very reason life has started on earth, and it is also the reason we will be able to sustain life on earth. In fact earth receives a dazzling 174 petawatts of solar radiation at the upper atmosphere [Mandruss, 2018]. Currently we are trying to satisfy our energy demand by harvesting this energy using wind turbines, solar panels, tidal power and so on.

Generating energy in a sustainable way is however only one facet of the problem. Another facet of the problem is the way that goods and services negatively impact the environment. In order to target this part of the problem engineers will need to change the way they design. That is what this guide will enable you to do. So let's get crackalackin and solve the current sustainability crisis together!

How to use this guide

How to use this guide

This manual for sustainable design describes several tools and methods necessary to design and assess products for a smaller, neutral or positive impact on the environment. This chapter starts with guidelines that help find suitable tools and methods for your project followed by a small summary of each of them. The Frame of Reference chapter provides readers with the foundation necessary to work with these tools and methods. The intended audience for this guide are the mechanical engineering undergraduate students at the Delft University of Technology. However, this guide can be applied to many other fields of engineering. The authors of this guide aimed to make it both as comprehensive and compact as possible.

Find the right tools and methods

This part will help to find the tools and methods suited for a project on the basis of the design cycle. Sustainability is an aspect that will be integrated into the design process just like any other aspect. The best way to integrate this differs per phase. For each phase of the cycle the goal and the relevant tools and methods are mentioned.

Phase 1: Explore and analyse assignment

To integrate sustainability into a design process the first important step is to set up relevant requirements and criteria on the subject. When doing this make sure to properly define the type of impact and which phase(s) of the life cycle of a product are taken into account. Make this measurable such that in the Analyse results phase it can be determined whether the goals have been met. Use the EcoDesign Strategy Wheel to find ideas for requirements and criteria.

Phase 2: Create & Collect solution

Here you will come up with sustainable solutions to arrive at your sustainability criteria. Use the EcoDesign Strategy Wheel and the designated 'Design For' tools as inspiration.

Phase 3: Conceptual design

In this phase a choose between concepts needs to be made. For this a quick estimate of how well the concepts scored on your criteria is needed. Use the EcoDesign Checklist or a less thorough version of the MET Matrix and the EcoDesign Strategy Wheel to get a rough but substatiated comparison of the concepts. Use the MET Matrix when taking into account only part of the life cycle of a product or only the material use, energy use or toxic emissions.

Phase 4: Embodiment

Depending on your criteria different 'Design For' tools could be useful. Minimising resource consumption, Design for Disassembly as well as the Product lifetime optimisation tool give practical advice to achieve each of their respective goals.

Phase 5: Prototype & Test

In this phase a quick check can be done on whether what you designed for in the previous phase was successful and how it can be further improved. Was the product indeed easy to disassemble? Are there parts that failed far too soon or were overdesigned? This quick check can be helpful before going to the next phase.

Phase 6: Analyse results

A far more precise analysis is performed in this phase compared to the Conceptual design and Prototype & Test phase. Check whether the requirements are achieved with the help of the 'assessment of' tools. The EcoDesign Checklist and the MET Matrix are very useful for this phase as well, only this time it should be executed far more precise. A more profound tool for executing this analysis is the Fast Track Life Cycle Assessment (LCA).

Phase 7: Iterate

In case you did not achieve your requirements, look at the used tools to find the most efficient and achievable way to improve your product. For example, when a target has been set for a particular CO_2 footprint, the LCA results can be used to find which aspect of your design has the most impact which will help you to do an efficient iteration.

Summaries of tools and methods

Below, a summary is provided of each 'assessment of' and 'design for' tool and method described in chapter "Tools and methods".

***MET Matrix -** 'Assessment of' tool*
The Materials and Energy use and Toxic emissions Matrix, commonly referred to as the MET Matrix, is a design tool that gives an overall insight into the environmental impact of a design during its life cycle stages. It should be used in combination with the EcoDesign Checklist and EcoDesign Strategy Wheel.

***EcoDesign Checklist -** 'Assessment of' tool*
The EcoDesign Checklist is used to check if a design meets the main environmental requirements and can be used in order to fill in the MET Matrix. It can also be used in combination with the EcoDesign Strategy Wheel.

***EcoDesign Strategy Wheel -** 'Assessment of' tool*
The EcoDesign Strategy Wheel is a design tool used in combination with the MET Matrix and EcoDesign Checklist. It can be used to review the measures taken to reduce the environmental impact of concept designs and see which are most beneficial.

***Fast Track Life Cycle Assessment -** 'Assessment of' tool*
With the Fast Track Life Cycle Assessment (LCA) the designer will go through the whole life cycle of a product: the production, the shipment, the use and the disposal of the product. Here the designer will check on all the possible environmental impact in every stage. After making an inventory of the full life cycle of the product, there are standard methods for assessing the impact of the inventory within each impact category. This can inform a redesign to reduce the environmental impacts.

***Design for Disassembly -** 'Design for' tool*
Design for Disassembly (DFD) is a design method that focuses on how a product can be designed for easy and economical separation of its parts and materials. DFD will enable the users of a product to replace, repair and recycle parts easily, saving money and environmental costs. This section will provide the designer with guidelines that should be followed in order to design the product for proper disassembly.

***Minimising resource consumption -** 'Design for' tool*
This section contains useful guidelines to minimize the resource consumption of a product. These guidelines are split into two optimisation strategies, namely minimisation of material consumption and minimisation of energy consumption. The guidelines form a pragmatic help for the designer, that will improve the environmental performance of the design.

***Product lifetime optimisation -** 'Design for' tool*
This section will provide the engineer with two design strategies that aim to optimise the useful lifetime of a product. The first strategy being to design for an extended lifetime. The second is to intensify the usage of the product. Pragmatic guidelines for the implementation of these strategies are included in this section.

Frame of reference

Frame of reference

The frame of reference chapter will equip users of this guide with the foundation necessary to understand how to design sustainably. The first section will briefly introduce users to different sustainable design strategies. The second section will give insight into the weighting and units commonly used to measure the impact of a good or service.

Sustainable design stategies

When attempting to improve a system or design it is important to be aware of the different approaches. There are three levels of potential impact on a system or design depending on the strategy applied:

- Optimising an existing system
  E.g. improving the efficiency of a car's engine
- Altering the existing system
  E.g. changing the car's engine from a petrol engine to a electric engine
- Designing a completely new system
  E.g. creating a new form of transport like the Hyperloop

At the different levels similar design goals can be set in order to improve the performace of the design with regard to sustainability. Whether creating a completely new system or improving an existing system, in both cases goals can be set to improve for example smooth disassembly of the product. In setting such goals and guidelines the follwoing tools and methods can be helpful; EcoDesign Strategy wheel, Design for disassembly, Minimising resource consumption and Product lifetime optimisation. The remaining tools and methods are more focussed on quantifying the impact of products.

Figure 1 clearly displays the different type of reductions that can be made by choosing a certain strategy. For the largest impact it is necessary to come with completely new innovations. It is important to keep this in mind when designing a product or even when choosing which company to work for.

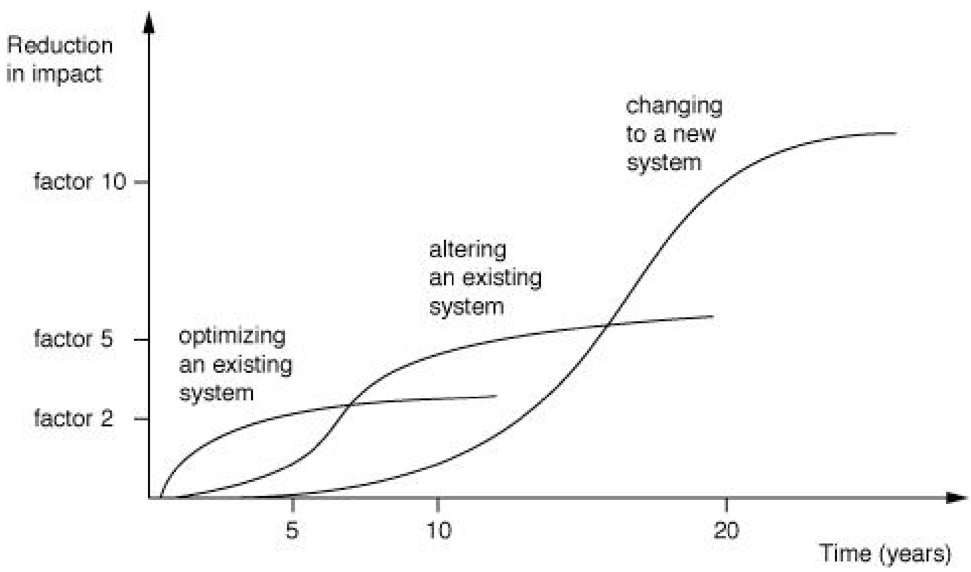


Figure 1 Reduction in impact vs. time [Kuijper et al., n.d.]

Measuring Impact

This section on measurements will provide the reader with insight into the units that are commonly used in the field of sustainability, the different types of impact categories that exist and the weighting that can be applied to shift the importance of a certain impact category. The information provided in this section is mostly taken from Humbert et al. [2012]. If the reader is interested in the different limitations and exceptions of the units described here, it is strongly recommended to take a closer look at that manual. The units mentioned in this guide can be used, they are however just examples rather than an exhaustive list.

An introduction to impact categories

The following paragraphs are an introduction to the most commonly used units that are applied when assessing the impact of a good or service. In order to assess the impact of the good or service an inventory of the relevant inputs and outputs of the product system should be created. This is often referred to as the product's Life Cycle Inventory (LCI). The data collected in this inventory depend on the scope and goal of the assessment. The different types of scopes commonly applied in a Life Cycle Assessment (LCA) are discussed in section "Goal and scope definition". The results from the LCI should be given the appropriate units so that the impact of the product can be compared to that of other products.

Processing LCI results can be tricky as it may be unclear which unit is appropriate for measuring and comparing a certain impact on the environment. In the following paragraphs a framework as suggested by Humbert et al. [2012] is explained. The framework suggests that the reader can describe the LCI results in units corresponding to three different levels impact categories namely: the midpoint, the damage and the normalised level. The first two levels are shown in Figure 2. The midpoint level contains the most specific impact categories. The impact categories in the midpoint level are subcategories of the impact categories contained in the damage level. In turn the impact categories in the damage level are subcategories of the normalised damage category. This allows an engineer to convert the results from the LCI into units that say something about

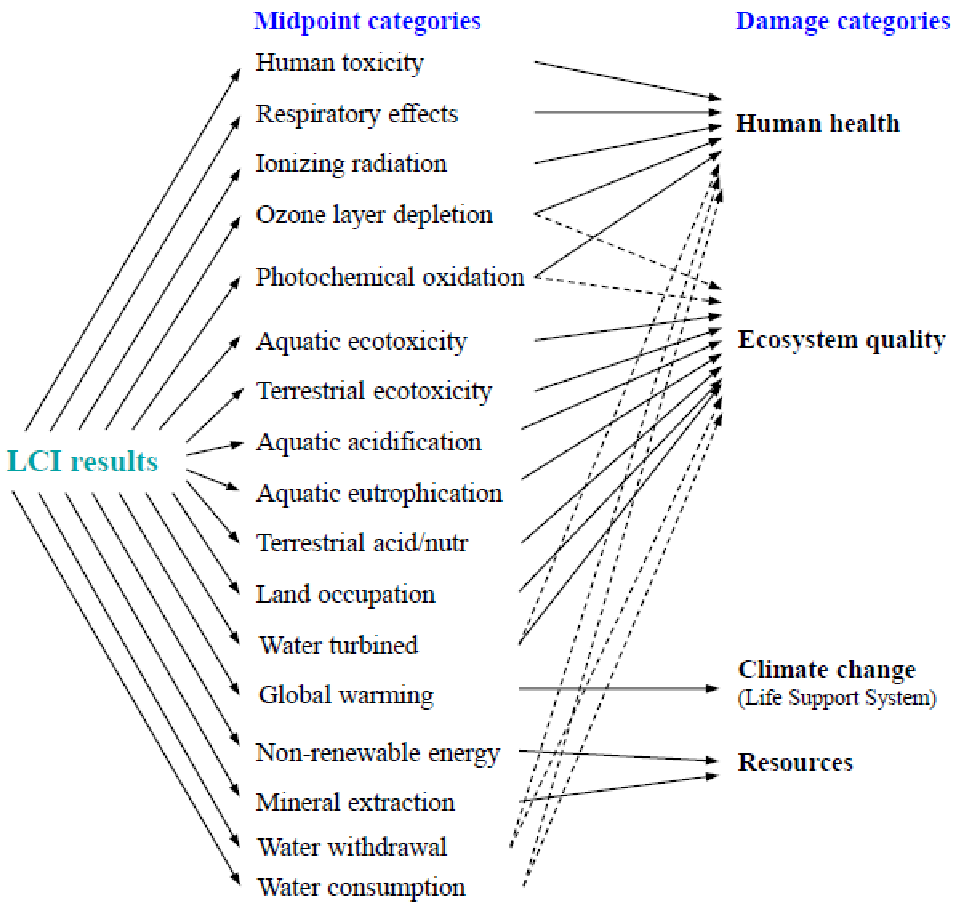


Figure 2 Midpoint and damage categories [Humbert et al., 2012]

the type of impact at different abstraction levels.
For example, an LCI may contain results regarding the amount of methane emitted by a cow. The engineer could convert these results into “CFC-11 into air-eq” (the unit that characterizes the impact category: ozone layer depletion) in order to compare this result with the impact of e.g. of a car. However, an engineer may also want to compare the impact that the emissions of a cow have on human health with the impact that ionizing radiation has on human health. This higher abstraction level brings us to the impact categories in the damage level. The units should be converted to DALY (the unit that characterizes the human health) for comparison in this impact category. If the engineer would want to compare the results at an even higher abstraction level the normalised damage unit can be applied.

Units
The following paragraphs will elaborate on the definitions of the units used to characterise the different impact categories.

At midpoint level
- “kg substance s-eq” (“kg equivalent of a reference substance s”) expresses the amount of a reference substance, s, that equals the impact of the considered pollutant within the midpoint category studies. E.g. the global warming potential of methane is 27.75 times higher than CO^2 thus the characterisation factor (CF) of 1 kg of methane is 27.75 kg CO^2_{-eq}.

At damage level
- “DALY” (“Disability-Adjusted Life Years”) characterises the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital). Default DALY values of 13 and 1.3 are adopted for most carcinogenic and non-carcinogenic effects, respectively [S.P., 2005]. For example, the sale of 1,000 sachets of oral rehydration salts (ORS) to prevent dehydration from mild and acute watery diarrhea among children under five in DRC averts 23 DALYs. In other words, 23 years of healthy life would have been lost in the absence of these 1000 sachets of ORS.
- “PDF·m^2·y” (“Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year”) is the unit to “measure” the impacts on ecosystems. The PDF·m^2·y represents the fraction of species disappeared on 1 m^2 of earth surface during one year. For example, a product having an ecosystem quality score of 0.2 PDF·m^2 ·y implies the loss of 20% of species on 1 m^2 of earth surface during one year.
- MJ (“Mega Joules”) is a measure of energy. It can for example be used to measure the amount of energy necessary extracted or needed to extract the resource.

At normalised damage level
- “points” are equal to “pers·y”. The absolute value of the points is not very relevant as the main purpose is to compare relative differences between products or components. The scale is chosen in such a way that the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. This value is calculated by dividing the total environmental load in Europe by the number of inhabitants and multiplying it with 1000 (scale factor) [Goedkoop and Spriensma].

Weighting
It is important to realise that when the life cycle analysis of a product or service is performed, a certain weighting is attached to the different impact categories. Often companies and governments give the climate change damage category a higher weighting because they find it of greater importance. It is interesting to consider whether this is a true representation of the impact of the product.

There are three common approaches used to determine the weighting of different impact categories. In the first approach all impacts are considered of equal value. The second approach is called the panel approach, where a group of representatives from a society are questioned to determine the weighting. The third approach is called the revealed preference approach, in which the weighting is made on the choices that are made in a society at that moment.

Table 1 on the next page, contains the units corresponding to the different impact categories. The units are subdivided into three different levels, namely the: midpoint, damage and normalised damage level.

Table 1 Impact categories and there corresponding units

Midpoint category	Midpoint reference substance	Damage category	Damage unit	Normalised damage unit
Human toxicity	kg Chloroethylene into air$_{-eq}$	Human health	DALY	Point
Respiratory effects	kg $PM_{2.5}$ into air$_{-eq}$			
Ionising radiation	Bq Carbon-14 into air$_{-eq}$			
Ozone layer depletion	kg CFC-11 into air$_{-eq}$			
Photochemical oxidation	kg Ethylene into air$_{-eq}$	Ecosystem quality	n/a	n/a
Aquatic ecotoxicity	kg Triethylene glycol into water$_{-eq}$	Ecosystem quality	PDF·m^2·y	Point
Terrestrial ecotoxicity	kg Triethylene glycol into soil$_{-eq}$			
Terrestrial acidification/nutrification	kg SO_2 into air$_{-eq}$			
Aquatic acidification	kg SO_2 into air$_{-eq}$			
Aquatic eutrophication	kg PO_4^{-3} into water$_{-eq}$			
Land occupation	m^2 Organic arable land$_{-eq}$*y			
Water turbined	Inventory in m^3			
Global warming	kg CO_2 into air$_{-eq}$	Climate change (life support system)	kg CO_2 into air$_{-eq}$	
Non-renewable energy	MJ or kg Crude oil$_{-eq}$ (860 kg/m^3)	Resources	MJ	
Mineral extraction	MJ or kg Iron$_{-eq}$ (in ore)			
Water withdrawal	Inventory in m^3	n/a	n/a	n/a
Water consumption	Inventory in m^3	Human health	DALY	Point
		Ecosystem quality	PDF·m^2·y	
		Resources	MJ	

Tools and methods

In this chapter, the different tools and methods that can be applied in order to design in a sustainable manner are described. The different tools and methods can be used separately. However, since they focus on different aspects of the design, using multiple will result in a more extensive analysis of the design.

It is recommended to take a closer look at the section “How to use this guide“ to help the reader choose the relevant tools and methods for their product. The secion gives a quick overview of the different tools and methods, which are for assessment or for designing and which are useful for each phase of the design process.

MET Matrix

Every product has a certain impact on the environment in terms of pollution, resources, energy use and waste. The Materials and Energy use, and Toxic emissions Matrix is an assessment tool used for analysing a design's impact on the environment in terms of these aspects. The tool has been conveniently abbreviated to the MET Matrix.

The MET Matrix has 3 columns: one for used Materials (input), one for used Energy (input), and one for emitted Toxins (output). These are the aspects which need to be reviewed during the 5 stages of the design's life cycle, which make up the matrix' 5 rows: The obtainment and consumption of materials and components, (factory) production, distribution, use or utilisation, end-of-life system/final disposal.

The MET Matrix is as 'assessment of' tool suited for the Conceptual design and Analyse result phase of the design process. In contrast to the other assessment tools, this tool lends itself well for analysis of only part of the life cycle of a product.

How to fill in the MET Matrix

As said before, the material use, energy use and toxic emissions need to be reviewed in each stadium of the design's life cycle. How to do that for each column will be explained in the section below:

- Material use

    This column should contain how many kilograms of non-renewable materials or materials that create emissions during production are used in the specific life cycle stage.

- Energy use

    This column should contain the energy consumption during the specific life cycle stage. This not only includes the electricity use of the design itself, but also includes the energy consumed by obtainment of raw materials, fabrication of the design, transportation, operation, maintenance, and the recovery of materials. A good insight in the energy that is used for the obtainment of raw materials and fabrication techniques, also known as embodied energy, can be found in CES EduPack.

- Toxic emissions

    This column should contain the toxic emissions to the environment (land, water and air), during the specific life cycle stage.

In order to accurately fill in the matrix, the EcoDesign Checklist can be of great help, as well as software packages like CES EduPack, SolidWorks Sustainability, and GaBi.

See also

An example of a MET Matrix filled in for a coffee machine can be found on the next page.

Further information on the MET Matrix can be found on:
http://wikid.io.tudelft.nl/WikID/index.php/MET_matrix

Figure 3 Example of a MET Matrix filled in for a coffee machine

	Use of MATERIALS (Inputs) M	Use of ENERGY (Inputs) E	TOXIC EMISSIONS (Outputs: emissions, effluent, waste) T
Obtainment & consumption of materials and components	- Copper (exhaustible material) (0,05 kg). - Steel (0,3 kg) - Aluminium (0,3 kg) - Polystyrene (PS) (1 kg) - PVC (0,1 kg) - Glass (0,4 kg) - Printed circuits (0,1 kg)	- High energy content in materials (Al, Cu) - Transport of ready assembled printed circuits from Asia (0.03 kWh)	- Fire retardants in printed circuit boards (↓) - Liquefiers for injection moulding (↓) - PS: Benzene emissions (↓) - PUR: Isocyanate (↓) - Emissions due to painting and gluing (↓)
Factory production	- Auxiliary materials (welding materials, degreasers and lubricants for the machines of the production system of the company, etc.) (↓)	- Energy in miscellaneous processes (Polystyrene moulding, aluminium extrusion, welding etc.) (↓)	- Metallic and plastic waste (offcuts and rejects) (↓) - Remainder of lubricants and degreasers for machines. (↓)
Distribution	- Product packaging. (polyethylene bag: 0.3 kg and cardboard: 0.1 kg) - Cardboard for repacking (↓) - Instruction manual (0,04 kg).	- Diesel fuel for transport (lorries) (0.3 kWh)	- Emissions from diesel fuel combustion (↓). - Remainder of packing: - Polyethylene bag (recyclable) (0.3 kg) - Cardboard (recyclable) (0.1 kg)
Use or utilisation	- ***OPERATION*** - Paper filters (7,3 kg) - Coffee used (65 kg)* - Cleaning materials (↓) - Water for cleaning (10.950 l)	- Energy consumption (375 kwh) a.- Heating: 281,25 kwh b.- Maintenance: 93,75 kwh **	- Waste from consumables (filter with coffee dregs, etc.) (72,3 kg) - Waste water from cleaning (10.950 l). - Emissions deriving from energy consumption (2305 kg CO_2).
	MAINTENANCE - Parts which are easily breakable (↓).	- Transport of maintenance providers (↓)	- Remainder of replaced parts (↓).
End of life system. Final disposal			***RECYCLING*** - Glass (0,4 kg) - Plastics (1,1kg) - Instruction manual (0,04 kg) ***DISPOSAL*** - Printed circuit board (0,1 kg) - Copper (0,05 kg) - Aluminium (0,3 kg) - Steel (0,3 kg)

[grey box] Priority impacts (detected with the aid of environmental consultant expert in Ecodesign).

* Consumption of coffee is allowed for at one 250 g packet per week throughout the 5 years of estimated lifetime. Despite the fact that the coffee is quantitatively one of the highest figures, it is the only one which cannot be minimised, so it has not been considered to be a priority.

** This breakdown may facilitate the generation of ideas for improvement on this environmental aspect.

EcoDesign Checklist

The EcoDesign Checklist is a checklist questioning the impact of a design on the environment, and can be used together with the MET Matrix and EcoDesign Strategy Wheel for assessment. The link at the bottom of the page povides an example of the EcoDesign Checklist.

The first part of the EcoDesign Checklist is a needs analysis which checks the ability of the design to fulfil its main and auxiliary functions. The second part of the checklist focuses on the environmental impacts of the design in each stage of its life cycle.

The checklist consists of two columns. The questions that need to be taken into account are in the left-hand column, while the answers and suggested improvements are in the right-hand column.

How to use the EcoDesign Checklist?

1. Define the design/part(s) of the design which will be evaluated.
2. Fill in the first part of the EcoDesign Checklist regarding the needs analysis.
3. Answer the questions regarding the environmental impacts of the design for each stage of its life-cycle.
4. Provide suggestions for improvement following the answers provided in the right-hand side of the EcoDesign Checklist. Make sure to check the EcoDesign Strategy Wheel for useful improvements.
5. Use the answers to fill in the MET Matrix.

See also

An example of an EcoDesign Checklist can be found here:
http://wikid.io.tudelft.nl/WikID/index.php/Example_of_an_EcoDesign_checklist

Further information on the EcoDesign Checklist can be found on:
http://wikid.io.tudelft.nl/WikID/index.php/EcoDesign_checklist

EcoDesign Strategy Wheel

The EcoDesign Strategy Wheel is commonly used in combination with the MET Matrix and EcoDesign Checklist in order to get a clear understanding of useful strategies for reducing the environmental impact of a design and which ones will be most beneficial. The tool can be used for design purposes as well as for assessment.

The EcoDesign Strategy Wheel is a spider web diagram with eight axes, one for each design strategy. The provided strategies are:

0. New concept development
1. Selection of low-impact materials
2. Reduction of material usage
3. Optimisation of production techniques
4. Optimisation of distribution systems
5. Reduction of impact during use
6. Optimisation of initial lifetime
7. Optimisation of end-of-life system

Using information from the MET Matrix and EcoDesign Checklist, specific improvement options to reduce the design's environmental impact should be given per design strategy. Each design strategy should then be evaluated and given a suitable score.

How to use the EcoDesign Strategy Wheel
Before using the EcoDesign Strategy Wheel it can be helpful to fill out the MET Matrix and EcoDesign Checklist.

1. Define the design/part(s) of the design which will be evaluated.
2. Give concrete improvement options per design strategy, specifically where the design has a great environmental impact. In this step using information from the MET Matrix and EcoDesign Checklist can be helpful to identify the areas of improvement.
3. Systematically score the design on each dimension of the Strategy Wheel. The score can be based on information obtained form the MET Matrix and EcoDesign Checklist.

See also
An example of an EcoDesign Strategy Wheel is shown on the next page.

Further information on the EcoDesign Strategy Wheel can be found on:
http://wikid.io.tudelft.nl/WikID/index.php/EcoDesign_strategy_wheel

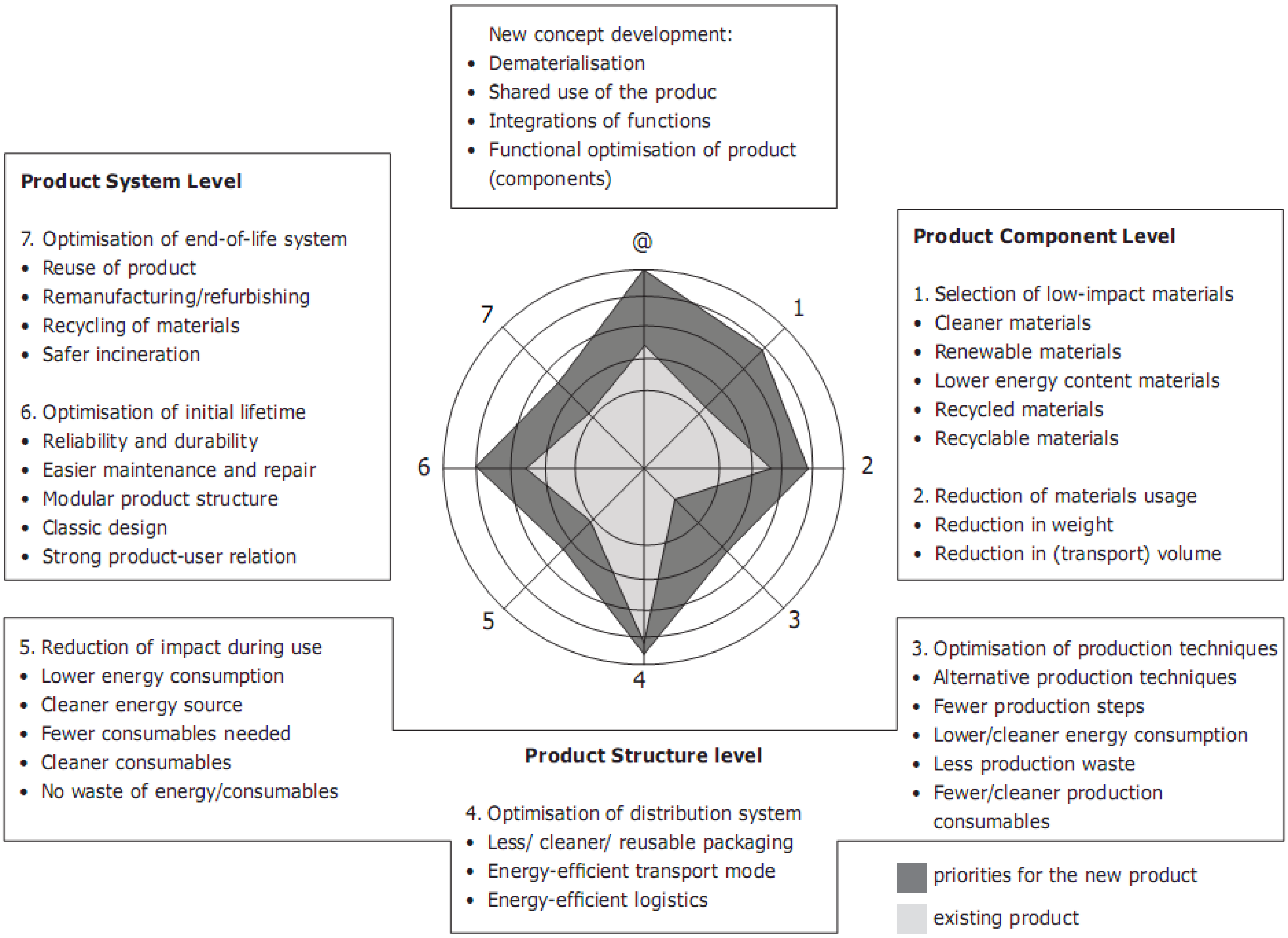


Figure 4 Example of an EcoDesign Strategy Wheel

Fast Track Life Cycle Assesment

Life Cycle Assessment is currently the most comprehensive assessment technique used to estimate the total environmental impact of the whole production cycle, starting with the raw materials all the way through to the end-of-life product. For the use of the LCA there are four stages that need to be considered, namely:

1. Goal and scope definition
2. Life Cycle Inventory
3. Life Cycle Impact Assessment
4. Interpretation of the results

Goal and scope definition

The Life Cycle Assessment begins with an explicit statement of the goal and scope of the study. Here the engineer sets out the context of the study and explains how the results will be communicated. The four steps are:

- The functional unit. What is the study unit? Think of kg, squared meter, etc. (look at the section “Measuring impact” or Appendix B for more examples).
- The system boundaries. Which processes need to be included in the analysis?
- The assumptions and limitations. What should be included and excluded in the study?
- The impact categories. Which impact categories will be included in the study? Think of toxicity, smog, global warming, etc. (see Appendix B for more examples).

In order to target the second question it is important to be aware of the different system boundaries that exist. The following points will provide the user with some commonly used boundary scopes:

- “Cradle to grave” - Usually denotes all the phases from raw materials through disposal.
- “Cradle to cradle”- Like cradle to grave except that it tracks where the product’s elements go after end-of-use, with special attention to recycling and reuse.
- “Cradle to gate” - Includes part of the product life cycle, typically either:
    - All upstream phases, not including the assessing company’s own processes; this is used to assess the “environment burden” of raw materials coming through the door; or
    - All phases through the assessing company’s manufacturing and assembly (the factory gate), bound for the customer, since this is the end of most manufacturer’s ability to direct influence impact.
- “Gate to gate” - A narrowly-scoped Life Cycle Assessment, focused on only one particular phase or set of phases of the product life cycle.

Life Cycle Inventory

The Life Cycle Inventory is used to analyse the entire environmental impact of the system. This is usually done by creating a flow chart of the entire life-span of the product. The flow chart should incorporate all the emissions (CO_2, N_x, etc.), raw material consumption (water, metals, etc) and fabrications (energy use) (see

Appendix B for more examples). The following life stages of the product should be taken into consideration:

- Raw material extraction
- Material processing
- Part manufacturing
- Assembly
- Product use
- End-of-life

Life Cycle Impact Assessment
After the inventory, the user will need to give the impacts a factor. This will be done in the Life Cycle Impact Assessment. This will be done with the following stages:

- Classification
- Characterisation
- Normalisation

Classification
To have a good overview of what all the impacts are and which impacts are a member of a given class, the classification stage is important. Here the user will put all the impacts, found in the inventory, in one of the following classes:

- Depletion of energy resources
- Depletion of raw materials
- Global warming
- Ozone layer depletion
- Acidification
- Smog
- Toxic substances
- Polluted waste

It is possible to place one environmental impact in multiple classes.

Characterisation
In this stage the user needs to assess each environmental impact to the corresponding impact category. This enables the comparison of the different impacts. There are different methods to the correct units. The best way to do this is with a database or computer program. Some examples of software packages that are commonly used are:

- CES EduPack
- GaBi
- ELCD
- NEEDS
- SolidWorks (Sustainable package)
- SimaPro
- TEAM
- Matlab (Math package)

The user should always aim at using more than one database or software program when performing a LCA. The results can than be compared, providing a more reliable outcome.

Normalisation
Here the user will normalise the results found in the characterisation stage. The different values should be divided by the total summation. These values can be plotted to give a visual overview of the different impacts. This will allow the results to be more easily analyzed and interpreted.

Interpretation of the results
In the last stage the user will analyze all the results obtained from the LCA. The results should point out areas for improvement of the environmental impact of the product.

Design for Disassembly

Design for Disassembly (DFD) is a design method that focuses on how a product can be designed for easy and economical separation of its parts and materials. DFD will enable the users of a product to replace and repair parts easily, saving money and environmental costs. This section will provide the user with guidelines that should be followed in order to design the product for disassembly.

DFD aims at extending the lifespan of the product. The easy disassembly of a product positively effects the maintenance, repair and upgrading of the product. It is easier to recycle, compost and combust the different components of a product. This prolongs the material lifespan. This results in added economical value to the product, which is a good incentive for using the guidelines in this section that will allow the user to perform DFD.

The main separation techniques currently applied are magnetic and induction separation, by hand and flotation. Often several of these methods have to be applied in order to recycle a product and its materials. The type of separation can be defined by combining to different degrees the following options:

- Disassembly alone
- Crushing the entire product and separating the materials

The comparison of crushing and DFD tends to favour crushing, especially for complex products. Disassembly however generally provides a better or equal quality and economic value of materials.

Guidelines to DFD

This section provides the reader with the guidelines that should be upheld in order to perform DFD. The guidelines are divided over four different areas of focus in order to give the method structure. All areas of focus are equally important for performing DFD.

Reduce and facilitate operations of disassembly and separation

This section will provide the reader with general guidelines to design an easily disassemblable product. The guidelines are subdivided into three sections, namely the overall architecture, shape of components and parts and the shape and accessibility of the product.

Overall architecture

- Prioritise the disassembly of toxic and dangerous components
- Prioritise the disassembly of components or materials with higher economic value
- Prioritise the disassembly of more easily damageable components
- Engage modular structures
- Divide the product into easily separable and manipulable sub-assemblies
- Minimise hierarchically dependent connections among components

Shape of components and parts

- Avoid difficult-to-handle components
- Avoid asymmetrical components

Shape and accessibility

- Avoid joining systems that require simultaneous interventions for opening
- Minimise the overall number of fasteners
- Minimise the overall number of different fastener types (that demand different tools)
- Avoid difficult-to-handle fasteners
- Design accessible and recognisable entrances and points for dismantling

Engage reversible joining systems

Reversible joining systems are key to designing a product for easy disassembly since they allow the different materials to be recovered from the product. The following guidelines provide the user with information as to which types of reversible joining systems are preferred and what to look out for when applying them.

- Employ a two-way snap-fit
- Employ joints that are opened with common tools (except when opening could be dangerous)
- Design joints made of materials that become reversible only in determined conditions
    i.e. shape memory polymer, this is a stimuli-responsive material with the ability to alter a programmed shape to its original shape upon triggering of an appropriate stimulus. A stimulus could be a given temperature or pressure [Thakur and Hu, 2017].
- Use screws with hexagonal heads
- Prefer removable nuts and clips to self-tapping screws

If the use of screws cannot be avoided follow the following guidelines:

- Use screws made of materials compatible with joint components, to avoid their separation before recycling
    When assembling plastic materials it is better to use thermoplastic screws made of polymers that are compatible with the components instead of metal screws.
- Use self-tapping screws for polymers to avoid metallic inserts

Permanent joint systems that can be easily opened

Using permanent joining systems should be avoided whenever possible because it hinders the disassembly of the product. If no other option is available for joining the parts together the user should follow these guidelines to make a permanent joint.

Types of permanent joining systems

- (Hot) rivets
- Pressuring systems
- Welding
- Solvent welding (of polymers)
- Adhesive bonding (i.e. glue)

Guidelines for easily disintegrated permanent joining systems

- Make sure the bond material is compatible with the materials
- Prefer ultrasonic and vibration welding with polymers
- Avoid gluing with adhesives
    * If gluing is necessary employ easily removable adhesives

Co-design special technologies and features for crushing separation

Crushing will not prolong the lifespan of the product but it can give an efficient result for separation and recycling of materials. Therefore crushing is often the most economical solution when recycling a product. The following guidelines should be upheld if after separation the materials are partly crushed:

- Use materials that are easily separable after being crushed
- Design thin areas to enable the break-off of incompatible inserts with pressurised demolition
- Co-design cutting or breaking paths with appropriate separation technologies for separating incompatible materials
- Employ joining elements that can be chemically or physically destroyed
- Make the breaking points easily accessible and recognisable
- Provide the products with information for the user about the characteristics of crushing separation [Vezzoli and Manzini, 2008]

Minimising resource consumption

Minimising resource consumption is a design tool which focuses on reducing material and energy consumption of a certain product. Reducing the amount of materials in the product not only limits the amount of materials extracted, but it also means fewer processing, transportation and disposal costs. Therefore, minimising material use impacts the entire life cycle of a product [Vezzoli and Manzini, 2008].

In the interests of clear understanding and an efficient supporting structure for designers, the guidelines are divided into two according to the nature of the resource:

- Minimising materials consumption
- Minimising energy consumption

Minimising materials consumption
Minimising materials consumption can be achieved by applying a variety of guidelines:

- Minimising material content
- Minimising scraps and discards
- Minimising materials consumption during usage

As described by Vezzoli and Manzini [2008] there are a couple of guidelines for material content minimisation:

- Dematerialise the product or some of its components, which is the process of removing some of the (redundant) materials in the design. A good example of dematerialisation is “Ikea Air”, which is inflatable furniture that reduces the material cost by approximately 85%
- Avoid over-sized dimensions. This is one of the most important aspects for a mechanical engineering student, who may use his/her mechanics of materials knowledge to make the design as lightweight as possible. Thus reducing the amount of material used. The goal should be to design a product using as little material as possible without compromising the strength and rigidity of the product. Increasing the structural stiffness by designing shapes with a high second moment of inertia, like ribbed or cylindrical structures, may contribute to using fewer materials.
- Digitise the product or some of its components. A good example is the software enabling us to pay with cards or even mobile phones instead of paper and coins.

Furthermore, it is not only important to look at the amount of material in the final product, but to think about the manufacturing processes as well. It is important to select processes that reduce scraps and discarded materials during production. One should be aware of the amount of material lost during production.

As mentioned by Vezzoli and Manzini [2008] there are a few guidelines to minimise materials consumption during usage of the product:

- Design for the efficient consumption of operational materials. For example a toilet that only flushes 3 L of water instead of 6 L of water due to a more efficient design.
- Design for the more efficient supply of raw materials. A good example is an underground irrigation system that reduces the water consumption between 65% and 90% by delivering the water directly to the roots.
- Design systems for the consumption of passive materials, like using rainwater to flush the toilet.
- Design for the cascading of recycling systems, by using the output of one system as input for another system.
- Set the product’s default state at minimum materials consumption, such as setting a printer to double-sided printing as default.

Minimising energy consumption
Minimising the energy consumption during the entire life cycle of a product is an important aspect of sustainable design. This paragraph discusses multiple ways to minimise the energy consumption on the basis of these guidelines:

- Minimising energy consumption during pre-production and production
- Selecting systems with an energy-efficient operation stage

Minimising energy consumption starts during the design process. Mechanical engineering students can have a great impact in this stage of the life cycle of a product. While designing a product one can select materials with low energy intensity. According to Vezzoli and Manzini [2008] "aluminium production consumes a great deal of energy, especially when compared with other materials or recycled aluminium; the latter allows a reduction of approximately 90%."

A computer programme that can assist in selecting a material is CES EduPack, as it provides many details about the material properties, including sustainability related properties such as the embodied energy of a material. Plotting different material properties on different axes in a graph provides a clear overview of suitable materials.

There are several guidelines in Vezzoli and Manzini [2008] for selecting systems with an energy-efficient operation stage, namely:

- Design attractive products for collective use. The special lanes for busses to encourage the use of public transport are an example of design for collective use.
- Design for energy-efficient operational stages.
- Design systems for the consumption of passive energy sources. A fridge that is built into a the wall of a house, using the (cold) outside temperature to cool, drastically reducing the amount of power consumed.
- Engage highly efficient energy conversion systems.
- Design/engage highly efficient engines and energy power transmission.
- Design/engage highly efficient energy power transmission (Example 5.33)
- Scale down the weight of transportable goods
- Design energy recovery systems. Think about a car storing energy when braking using a flywheel.

Product lifetime optimisation

In order to design for an optimal lifetime of a product the useful lifetime of a product must first be defined. Vezzoli and Manzini [2008] define the useful lifetime of a product as: “Useful lifetime measures how long a product and its components would last under normal working conditions, maintaining its conduct and performance at accepted or even predetermined standard levels.”

There are two strategies to optimise a product’s lifetime. First of all, one could extend the lifetime of the product. It is important to design long-lasting products seeing as the disposal of a product has a negatively impacts environment and replacement comes with the environmental and economical burden of pre-production, production and distribution. The second strategy is to intensify the usage of the product. Where the time of non-usage is minimised, which reduces the actual number of products while still meeting the demands.

Designing for appropriate lifespan

Designing components that last longer than the useful lifetime of their products usually creates unnecessary waste. Therefore, the components should have a similar lifetime as the useful lifespan of the product itself.

Designing for reliability

As described in Vezzoli and Manzini [2008] product reliability is one of the most important quality criteria. Unreliable products create waste and have high economic and environmental impacts as they will have to be repaired or substituted. Reducing the overall number of components, simplifying the design and eliminating weak links in the design are some guidelines for a reliable design.

Facilitating Upgrading and Adaptability

Technology evolves, this can make parts of a product outmoded. Often whole products are disposed because a single part of it has become technologically obsolete. Exchanging parts that have become obsolete is paramount to overcome this problem. Engineers should aim at enabling both software and hardware upgrading. A modular design can facilitate easy hardware upgrading.

Facilitating Maintenance and Repair

If a product cannot be maintained or repaired, it will be disposed. Therefore, a few guidelines for facilitating maintenance and repairs have been created by Vezzoli and Manzini [2008]:

- Design products that need less maintenance/repairs.
- Simplify access to and disassembly of components to be maintained/repaired. See also the section “Design for Disassembly”. The air engine BR 700 from BMW and Rolls Royce is a good example of a modular structure with easy access to maintainable components.
- Avoid narrow slits and holes to facilitate access for cleaning.
- Pre-arrange and facilitate the substitution of short-lived components.
- Equip the product with easily usable tools for maintenance/repairs.
- Design components according to standards to facilitate substitution of damaged parts.

Facilitating Re-use

According to Vezzoli and Manzini [2008] re-use is the second use of a product or its components after it has been disposed of. Re-use also benefits from well maintainence and repair, thus these sections should be kept in mind when designing for re-use.

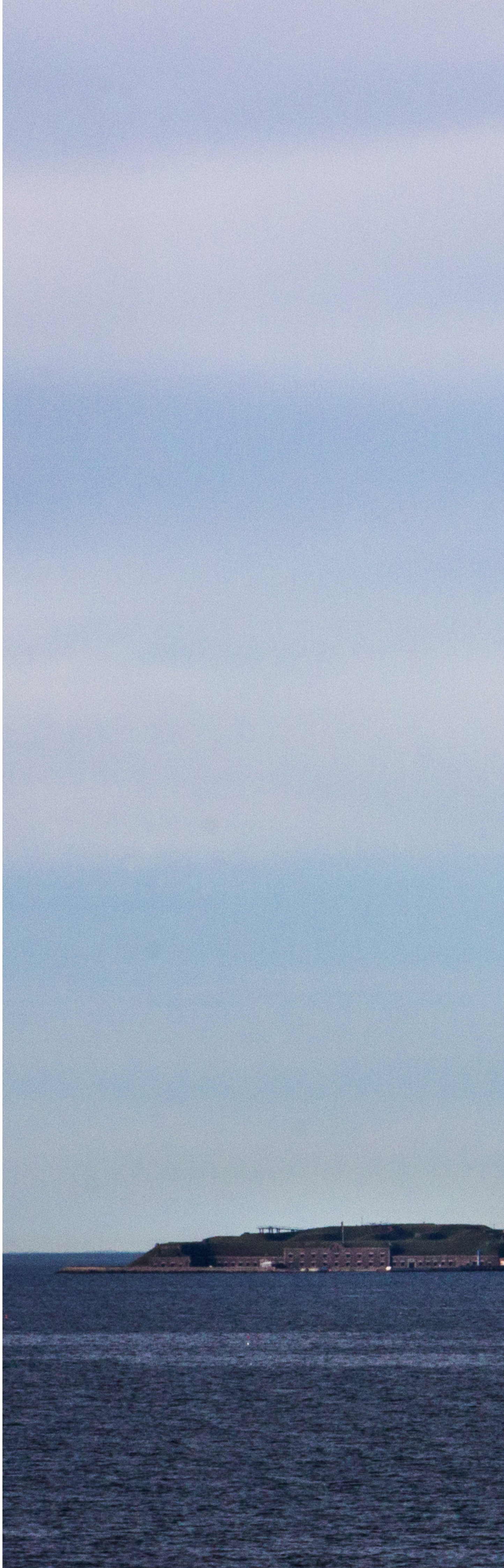
Again, there are several guidelines to facilitate re-use by Vezzoli and Manzini [2008]:

- Increase the resistance of easily damaged and expendable components. If the screen of a phone is broken, the chances of it being reused are reduced. Making the screen more impact resistant could facilitate re-use. Furthermore, it is important to facilitate access to and removal of retrievable components, such as the screen of a phone.
- Design modular and replaceable components. Modular design not only facilitates hardware upgrading, but also the re-use of hardware. Vezzoli and Manzini [2008] gives the following example: after their disposal photocopiers of Rank Xerox are disassembled, its components are used in new photocopiers after examination.
- Design reusable auxiliary parts, such as a reusable filter in a coffee machine or refillable cartridges in a printer.
- Design for secondary use. A well-known example is the jar that holds the hazelnut spread ‘Nutella’ that may later be used as a glass.

Intensifying Use

Vezzoli and Manzini [2008] created multiple guidelines for intensifying use:

- Design products and services for shared use. Examples are the ‘OV fiets’ or ‘Mobike’, which facilitates the the rent of a bike at multiple locations and anyone with a subscription can rent the bikes.
- Design products with integrated functions.
- Design products or components on demand. An example is an Italian publishing company that offers printing-on-demand. A book is only printed, after customers have requested/bought a copy online.



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Appendices

Appendix A: Abbreviations

CF	Characterisation factor
DALY	Disability-Adjusted Life Year
DFD	Design for Disassembly
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MET	Materials Energy and Toxic emissions
MJ	Mega Joule
ODS	Ozone-Depleting Substances
PDF	Potentially Disappeared Fraction
PM	Particulate matter

Appendix B:

Midpoint & damage categories

Appendix B contains more elaborate descriptions of the different midpoint and damage categories. Some of the considerations made for the selection of the unit are also given. For a more detailed discussion on the use of the units can be found in the "Impact 2002+: User guide" [Humbert et al., 2012].

Midpoint categories
This section defines and describes the different midpoint categories. The appropriate units for each category can be found in table 1.

Human toxicity
Human toxicity represents all effects on human health, except for respiratory effects caused by inorganics, ionising radiation effects, ozone layer depletion effects and photochemical oxidation effects. Those are considered in separate impact categories. This is mainly because their evaluation is based on different approaches.

Respiratory effects
This impact category refers to respiratory effects which are caused by inorganic substances. The CFs are given for emissions into air only (as it is not very likely that these pollutants will be emitted into soil or water). Damage CFs are expressed in DALY/kg and are taken directly from Eco-indicator 99 by Goedkoop and Spriensma.

Particulate matter (PM) can be classified based on their particle size. "$PM_{2.5}$" covers all particles < 2.5 µm, "PM_{10}" covers all particles < 10 µm and "PM_{tot}" covers all particles < 100 µm.

The midpoint CFs are expressed in kg $PM_{2.5}$ into air−eq/kg and obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (PM2.5 into air).

Caution should be taken to avoid double counting. This is especially valid for PM_{10} and $PM_{2.5}$ (the latter is already counted in PM10) and for NO_x and NO_2 (the latter is already counted in NOx). Therefore, only one of the three CFs ($PM_{2.5}$, PM_{10} or PM_{tot}) should be applied to the inventory.

Ionising radiation
Ionising radiation is defined as radiation that carries enough energy to liberate electrons from atoms or molecules, thereby ionising them [DeprecatedFixerBot, 2018]. Ionising radiation has a damaging impact on human health and can be carcinogenic. For the impact category ionising radiation the CFs are given for emissions into air and water. No CFs are currently available for emissions into soil. Damage CFs are expressed in DALY/Bq and taken directly from Eco-indicator 99 by Goedkoop and Spriensma. Midpoint CFs are expressed in Bq Carbon-14 into air−eq /Bq and obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (Carbon-14 into air).

Ozone layer depletion
Ozone depletion describes two related phenomena observed since the late 1970s: a steady decline of about four percent in the total amount of ozone in Earth's stratosphere (the ozone layer), and a much larger springtime decrease in stratospheric ozone around Earth's polar regions. The latter phenomenon is referred to as the ozone hole. There are also springtime polar troposphere ozone depletion events in addition to these stratospheric events.

The main cause of ozone depletion and the ozone hole is man-made chemicals, especially man-made halocarbon refrigerants, solvents, propellants, and foam-blowing agents (chlorofluorocarbon (CFCs), HCFCs, halons), referred to as ozone-depleting substances (ODS). These compounds are transported into the stratosphere by the winds after being emitted at the surface. Once in the stratosphere, they release halogen atoms through photodissociation, which catalyse the breakdown of ozone (O_3) into oxygen (O_2). Both types of ozone depletion were observed to increase as emissions of halocarbons increased [Cluebot N, 2018].

The CFs of ozone layer depletion are given for emissions into air only, as it is not very likely that the considered pollutants will be emitted into soil or water. The midpoint CFs are expressed in kg CFC-11 into air−eq per kg and obtained from the US Environmental Protection Agency Ozone Depletion Potential List (EPA). Damage CFs are expressed in DALY/kg and for the midpoint reference substance (CFC-11 = Trichlorofluoromethane) directly taken from Eco-indicator 99 (Goedkoop and Spriensma 2000). The damage CFs for other substances are obtained by multiplying the midpoints (in kg CFC-11 into air−eq per kg) with the CFC-11 damage CF [Humbert et al., 2012].

Photochemical oxidation

Photochemical oxidation is secondary air pollution, also known as summer smog. It is the formed in the troposphere caused mainly by the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals such as ozone. Photochemical oxidation causes breathing problems, eye irritation, damage to some materials (eg: plastic, rubber) and crops [LCANZ]. The photochemical ozone creation potential value of a particular hydrocarbon is a relative measure of how much the ozone concentration measured at a single location varies if emission of the hydrocarbon in question is altered by the same amount as that of a reference hydrocarbon, usually ethylene [GHKBIS].

Aquatic ecotoxicity

The CFs of aquatic ecotoxicity are given for emissions into air, water and soil and quantify the ecotoxicity effects on (surface) fresh water (referring to streams and lakes). No CFs are available for emissions into groundwater, stratosphere and oceans.

Terrestrial ecotoxicity

Terrestrial ecotoxicity CFs are calculated in a similar way as aquatic ecotoxicity CFs for emissions into air, water and soil. CFs for heavy metals only applies for metals emitted in dissolved form (ions). It has been estimated that the substances have ecotoxic effects only by exposure through the aqueous phase in soil.

Aquatic acidification

The CFs for aquatic acidification are given for emissions into air, water and soil. Damage CFs are expressed in PDF·m^2·y/kg and calculated by multiplying the midpoint CFs by 8.82E-3 PDF·m^2·y/kg SO_2 into air$_{-eq}$.

Aquatic eutrophication

The CFs for aquatic eutrophication are given for emissions into air, water and soil. Damage CFs are expressed in PDF·m^2·y/kg and calculated by multiplying the midpoint CFs by 11.4 PDF·m^2·y/kg $PO_4{}^{-3}{}_{-eq}$ into water.

Terrestrial acidification and nutrification

The CFs are given for emissions into air only. No CFs are currently available for emissions into soil and water. Damage CFs are expressed in PDF·m^2·y/kg and taken directly from Eco-indicator 99 by Goedkoop and Spriensma.

Land occupation

Land occupation damage CFs are expressed in PDF·m^2·y/m^2·y and are taken directly from Eco-indicator 99 by Goedkoop and Spriensma. As specified in Eco-indicator 99, the damage factors are based on empirical observations of the number of plant species per area type. In such observations all effects of the area type are included. This means that next to occupation effects, the effects of emissions (pesticides and fertilisers) are also included. To avoid double counting in these categories ((eco) toxicity of pesticides and acidification and eutrophication potential of fertilisers), only emissions that “leave” the field (through water, erosion and harvest) and emissions that are “above normal use” should be taken into account in the LCI.

Water turbined

The inventory of water used only by turbines (in hydropower dams) for energy (i.e., electricity) generation is expressed in m^3 of water. It is the sum of the total quantity of water turbined to generate the electricity necessary during the life cycle processes. The potential impacts of water turbined, e.g., on ecosystems quality, biodiversity or human health, vary depending on the location (whether the region is short of water or not) and the type of dam (run-of-river, non-alpine dams or alpine dams). The midpoints CFs are based on volumes of m^3 water turbined.

Global warming

Global warming CFs are given for emissions into air only. At the damage level the impact from global warming is presented in a separate damage category that is expressed in kg $CO_{2\text{-eq}}$ into air / kg, identical to the midpoint category. The midpoint CFs for global warming are expressed in kg $CO_{2\text{-eq}}$ into air / kg and taken directly from the list published by IPCC.

Non-renewable energy

CFs for non-renewable energy consumption, in terms of the total primary energy extracted, are calculated using upper heating values. Damage CFs are expressed in MJ total primary non-renewable energy / unit extracted (unit is kg or m^3) and taken from ecoinvent et al. [2003]. The midpoint CFs are expressed MJ as well.

Mineral extraction

Damage CFs for mineral extraction are expressed in MJ surplus energy / kg extracted and taken directly from Eco-indicator 99 by Goedkoop and Spriensma. The midpoint CFs are expressed in MJ as well. The midpoint CFs can be expressed in kg $Iron_{\text{-eq}}$ $(\text{in ore})_{\text{-eq}}$/kg extracted, obtained by dividing the damage CF of the considered substance by the damage CF of the reference substance (iron, in ore), however, this is not recommended for use.

Water withdrawal

Water withdrawal includes the water use expressed in m3 of water needed, whether it is evaporated, consumed or released again downstream, without water turbined (i.e., water flowing through hydropower dams). It considers drinking water, irrigation water and water for and in industrialised processes (including cooling water), fresh water, sea water. The actual impacts of water withdrawal, e.g., on human health, ecosystems quality or resources, vary depending on the location (whether the region is short of water or not, sometimes referred to as "water stressed"). The midpoint CFs are based on volume of water withdrawal expressed in m^3.

Water consumption

The midpoint CFs of water consumption are simply based on the volume of water consumed expressed in m^3.

Damage categories

Human health

The "human health" damage category is the sum of the midpoint categories "human toxicity", "respiratory effects", "ionising radiation", "ozone layer depletion" and "photochemical oxidation". Human health impact is expressed in "DALYs".

Ecosystem quality

The "ecosystem quality" damage category is the sum of the midpoint categories "aquatic ecotoxicity", "terrestrial ecotoxicity", "terrestrial acid/nutr", "land occupation", "aquatic acidification", "aquatic eutrophication" and "water turbined". Ecosystem quality impact is expressed in "$PDF \cdot m^2 \cdot y$"

Climate change

The damage category "climate change" is the same category as the midpoint category "global warming". Even if it is considered as a damage category, climate change impact is still expressed in "kg $CO_{2\text{-eq}}$".

Resources

The damage category "resources" is the sum of the midpoint categories "non-renewable energy consumption" and "mineral extraction". This damage category is expressed in "MJ".

Colophon

Sustainable mechanical engineering guide 2019

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