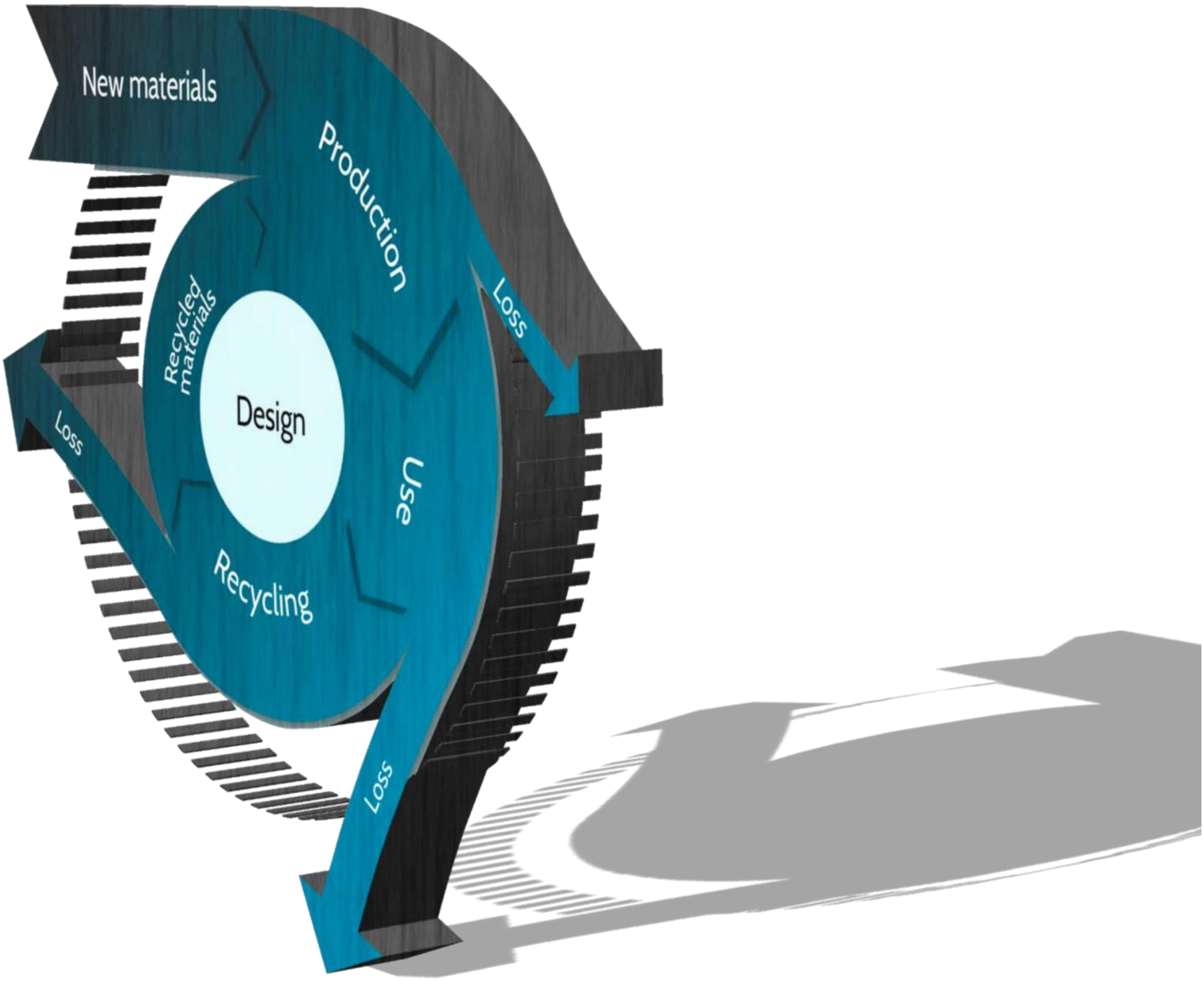
Idea catalogue for design optimisations in the product life cycle

-Assembly methods and design for the environment



Rethink Resources

SDU LIFE CYCLE ENGINEERING

FOREWORD

The idea catalogue is made as a part of the project Rethink Resources. Rethink Resources is an innovation centre made to help Danish production companies' competitiveness in a market characterised by increasing resource scarcity.

In 2013 the parliamentary environment committee funded the establishment of a partnership that can strengthen the green transition in Danish industry by promoting environmental technology, focusing on resourceefficient solutions. Rethink Resource was then formed as a partnership between Teknologisk Institut, Syddansk Universitet, Development Centre UMT and CLEAN.

The resource scarcity issue is challenging more production companies' earnings potential. Rising prices of raw materials and energy challenge the conventional linear business model with a use and throwaway culture. New circular business models are under development, which considers factors such as innovative product design, development of service-based business models instead of customer owned products, and new waste separation technologies.

One of the biggest challenges in this context is that most products today is a part of the global supply chain, which can be difficult to understand and even harder to influence. To ensure the effectiveness of circular business models, that minimise the loss of resources, it is necessary to provide financial gain through the entire value chain.

The activities include among others:

- Assessment of products with a focus on the resource consumption, optimisation of product design including assembly methods, and potential business models
- Establishing of usable generic tools
- Communication through showcases and exhibitions
- Workshops, seminars and conferences

CONTENT

INTRODUCTION

Danish companies are struggling to maintain a profitable business in Denmark. The high labour cost in Denmark makes more companies look abroad for a cheaper production. In 2010 it was thus estimated that up to 14,000 jobs a year was outsourced to lower-wage countries. Previously, it was mainly the big companies that moved abroad, but the trend shifted so more small and medium-sized companies also decided to move the production abroad. For the company, the immediate effects of moving abroad were higher profits, more sales and higher salaries for the remaining workers in the company.

The primary reason for the Danish companies to repatriate the production to Denmark is the better quality of the products and the greater flexibility in the production. In addition to Figure 1, also the ability to automate part or the entire production made Danish companies repatriate their production. The automated assembly may become even more important in the future.

What prompted the company to repatriate the production to Denmark?

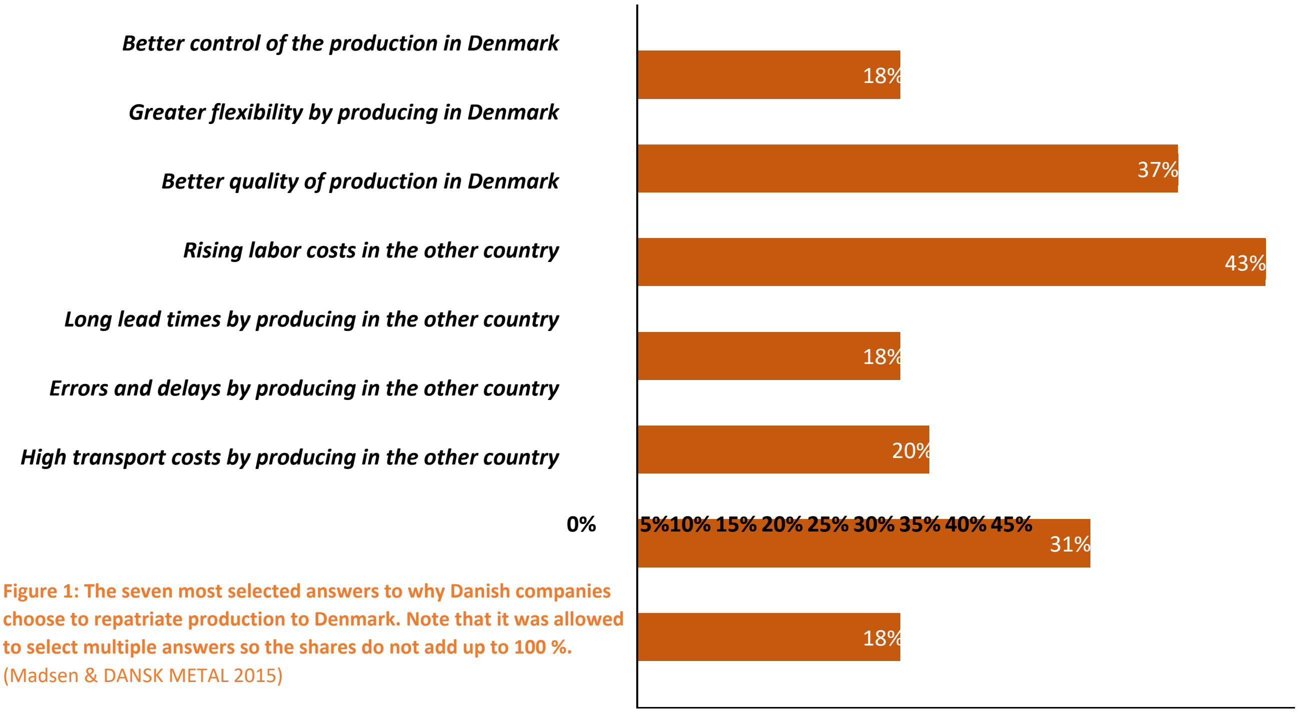


Figure 1: The seven most selected answers to why Danish companies choose to repatriate production to Denmark. Note that it was allowed to select multiple answers so the shares do not add up to 100 %. (Madsen & DANSK METAL 2015)

Besides the mentioned advantages for the company, there may be some risks by shifting production abroad. The company is likely to lose some of the control of the production abroad simply due to the distance, which also may result in a lower quality of the products. Another downside of outsourcing is that the delivery time can increase significantly, and the subcontractor often has other and bigger companies to service. These issues have also contributed to more and more companies are moving their production back to Denmark again. A survey among companies in the reunion -Dansk Metal- showed that one of four companies who previously moved all or part of their production abroad repatriated the production to Denmark. In Figure 1 it is indicated what prompted the company to repatriate the production to Denmark.

A way to lower the production cost, whiteout moving abroad and thereby keep the benefits of producing products locally, could be `design for assembly´. Besides an improved production, design for assembly also allows new business models with a higher recovery of resources and thereby improved environmental performance. Also, it might become possible for some companies to obtain a circular business model by optimising the design so products or part of the products can re-enter the production cycle again.

ABOUT THE CATALOGUE

This report is structured as an idea catalogue. The catalogue aims to provide companies with ideas to improve both the assembly of products and the environmental performance of products. First, is the MECOmethodology presented, which is a methodology to assess products environmental performance, but adjusted to include some considerations about the assembly techniques. The following sections each present a guideline how to improve the product according to the desired design strategy. Each of the design strategies fits a different stage in the product life-cycle. Section 2 is a general design guideline for dematerialisation. Section 35 handles different assembly techniques and section 6 handles design for modularity as a possible tool to combine different design strategies It should be noted that all design guidelines are rough guidelines and are intended as an idea catalogue with ideas that potentially can improve the assembly and the environmental performance of products and therefore not a step-by-step guide..

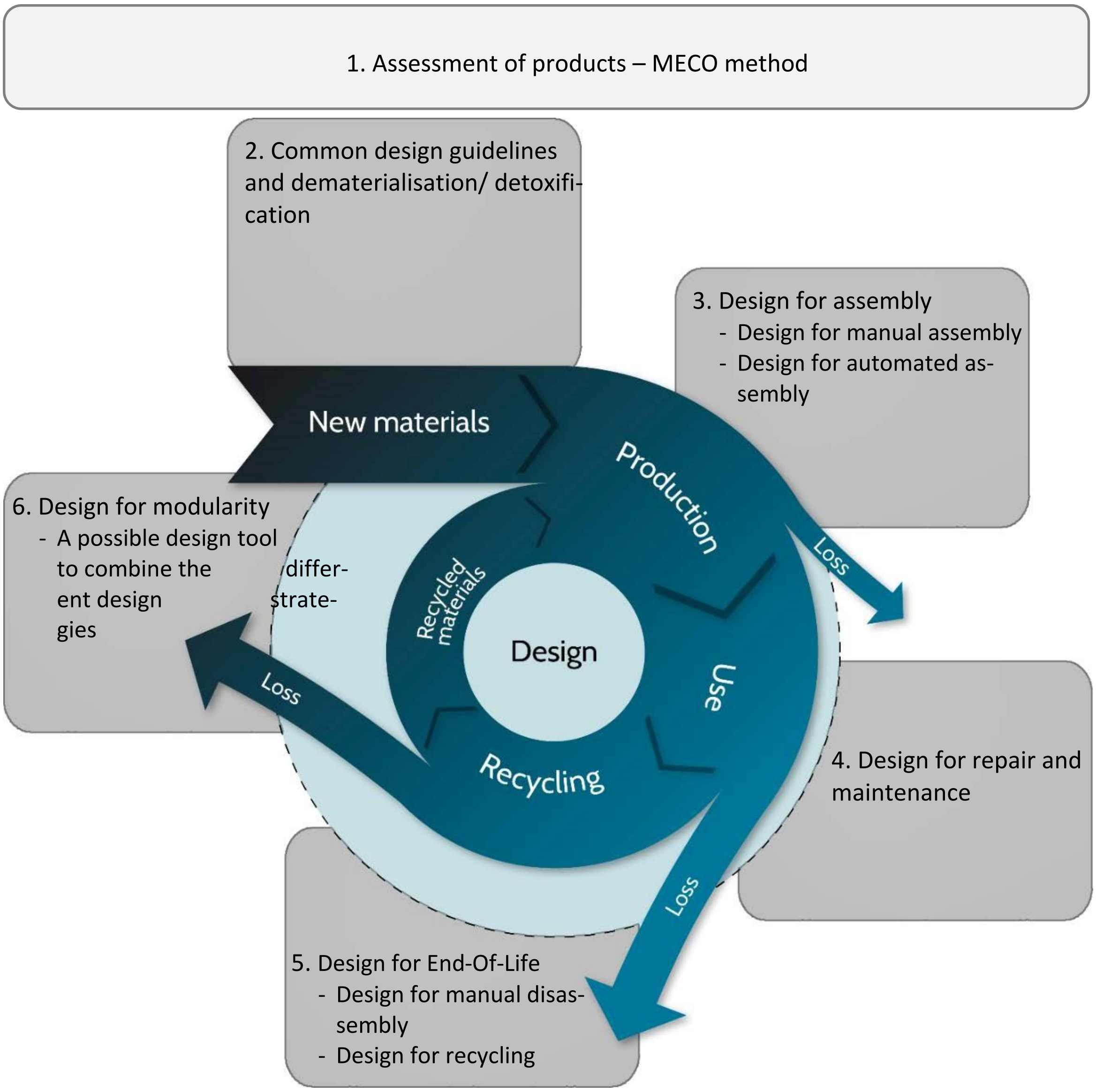


Figure 2: A visual presentation of the structure of the idea catalogue. Each section represents a different approach to improving the product design. It should though be noted that the different guidelines have many commonalities.

1. ENVIRONMENTAL ASSESSMENT OF PRODUCTS – MECO METHOD

This section briefly explains one of the most basic methods to assess a product's environmental performance and pinpoint potential environmental concerns in the lifecycle of a product. One of the tools to evaluate a product and the product lifecycle is a life cycle assessment, but such an assessment can be both timeconsuming and complicated. A solution could be to perform a simplified life cycle assessment such as the MECO-methodology. The MECO-methodology is an easily accessible method that reflects the life cycle approach. The MECO-methodology enables people in small and medium-sized companies, with knowledge of the environmental conditions, to perform a quick assessment of their products (Pommer et al. 2003).

The MECO-method includes the whole life cycle from extraction of raw materials to the product is disposed of and discarded. The work is conducted as a matrix that provides an easily accessible overview of the environmental impacts of the product and enables the company to pinpoint possible focus areas to improve. The offset of the MECO model is the **M**aterials, **E**nergy, **C**hemicals, and **O**ther (MECO) in the lifecycle of the product. The MECO matrix is possible to conduct in various detail levels and depending on the detail level different outcomes can be accomplished. The "input" to the matrix is the weight of each material in the product. The "output" is then the energy consumption expressed as MJ and CO_2 and the content of scarce resources expressed as mPR[1].

In Table 1 an example of the MECO-matrix for a bathroom scale is presented.

The classic overview of the MECO matrix provides the company with a clear indication of where in the lifecycle the product has the highest environmental burdens regarding energy and resource consumption. This example is a little unusual since the bathroom scale has the highest impacts in the material phase, both regarding energy and resource consumption. Besides pinpointing the phase with the highest impacts, it is not possible to state which individual material and subassembly that have the highest impacts.

A workaround to this problem is to divide the MECOmatrix into materials and main components/subassemblies so the individual parts are presented in the chart, and are logically grouped into main components. This workaround should be relatively easy to conduct since the overall MECO-matrix already includes the needed information. The aim is to highlight different aspects of the product only by rearranging already performed work. The main components are determined according to the location and function of the part. If an exploded view of the product is available, it can ease the work of dividing the product into main components. Alternatively, a manual disassembly could also be beneficial both according to the MECO matrix and the division into main components. In figure 3 below an exploded view of a bathroom scale is shown.

Raw materials phase *Production phase* *Use phase* *Disposal phase* *Transport phase*

[1] The content of scarce resources is determined using Person Reserves - the amount of known available reserves calculated relative to the Earth's population.

Raw materials Quantities	*ABS: 0.3 kg Glass: 2.04 kg Cardboard: 0.4 kg Aluminium: 0.06kg Steel: 0.01 kg "PCB": 0,018 kg "LCD": 0,04 kg etc.*	*Release agent Lubricant*	*Batteries: 0,7 kg Detergents*		
Resource consumption	*Crude oil: 0.005 mPR Natural gas: 0.008 mPR In: 4 mPR Au: 0.75 mPR Fe: 0.011 mPR Mn: 0.023 mPR etc.*		*Fe: 0.1 mPR Mn: 0.2 mPR Zn: 0.09 mPR*	*Crude oil:- 0.0025 mPR Natural gas: -0.004 mPR Au:- 0.3 mPR Fe: -0.01 mPR Mn: -0.022 mPR etc.*	
Energy Primary	*100 MJ*	*25 MJ*	*30 MJ*	*-75 MJ*	*4 MJ*
mPR (crude oil)	*0.096 mPR*	*0.024 mPR*	*0.03mPR*	*-0.048 mPR*	*0.0039 mPR*
Chemicals	*Fluorides used when manufacturing aluminium. Heavy metals used when making copper. Vinyl chloride monomers used for making PVC.*	*Crude oil distillates (undesirable?) Hydrogen peroxide (C, R34)*	*Acetic acid (C, R34)*		
Other	*Extraction of metals, working environment issues*	*Die casting of PS, emanations*	*Decalcification, odours from acetic acid*	*Not known*	*No comments*

Table 1: Example of a MECO-matrix of a bathroom scale. Note that the numbers only reflect possible values for a bathroom scale, and are therefore not actual values. Furthermore, it should be noted that PCB (printed circuit board) and LCD (display) here is placed under raw material phase, alternatively the materials in the subassemblies could be presented directly in the matrix.

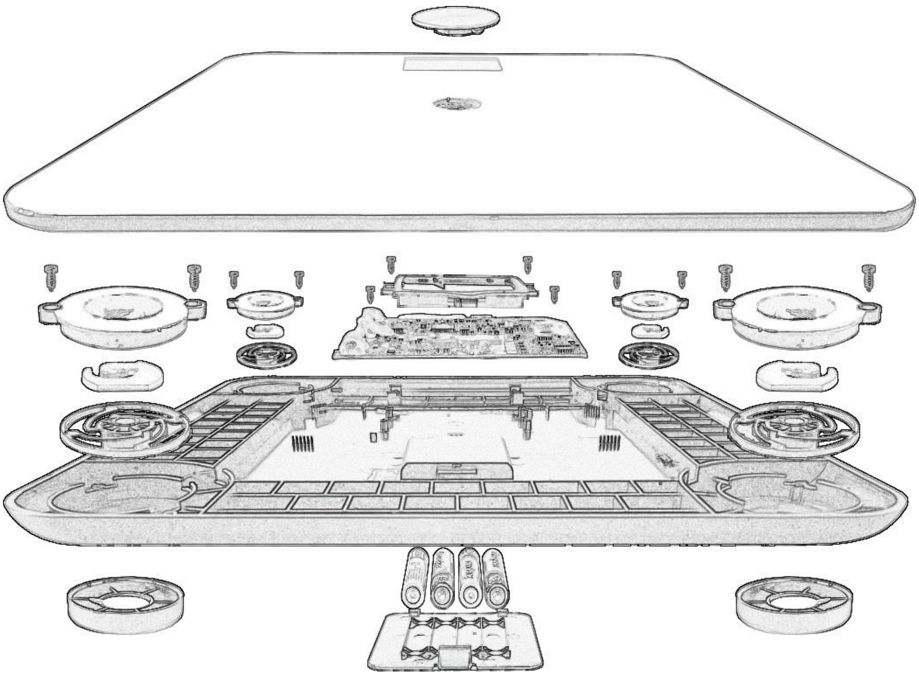


Figure 3: Exploded view of a bathroom scale. The aim of the exploded view is logical to group the components into subassemblies/main components. The main components in this example could be cover, feet/weighing mechanism, display, printed circuit board, batteries, wires, and packaging. Note that the packaging and wires not are included in the drawing for simplicity.

The bathroom scale in this example can be divided into seven overall main components, which is the cover, feet/weighing mechanism, display, printed circuit board, batteries, wires, and packaging. After the division into main components, it is possible to rewrite and group the MECO-matrix so it fits with the newly grouped main components.

Furthermore, it should be noted how the product is assembled so that possible drawbacks can be highlighted. The assembly method of the product can both have an impact on the assembly time, and on how the product performs at services and End-Of-Life. The aim is to create a product that is easy to assemble,

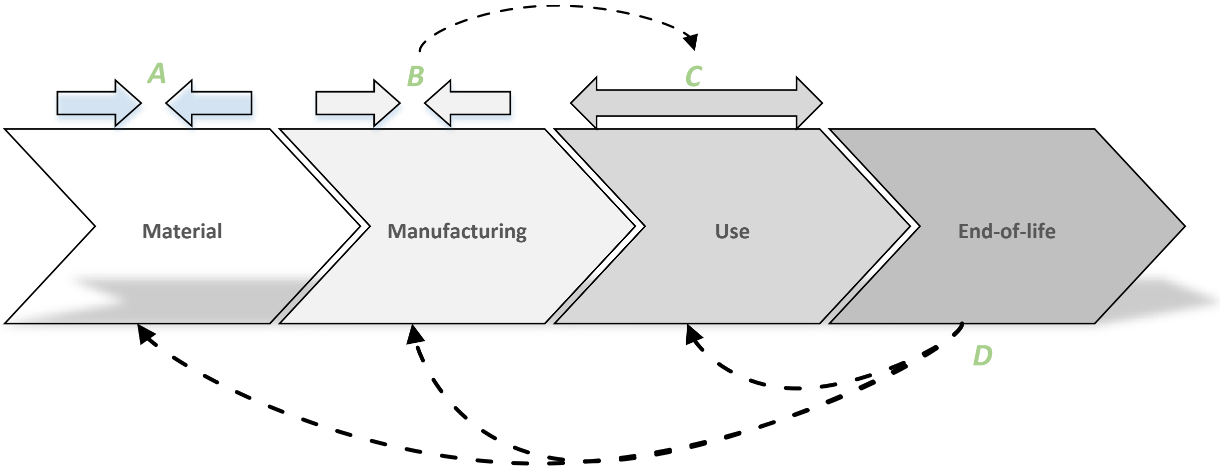


Figure 4: Presentation of the different strategies included in this catalogue

service and disassemble or has a proper separation in the waste handling system.

Depending on the results of the rearranged MECOmatrix, it is possible to obtain different strategies to improve the product both environmentally and regarding production. The different strategies included in this catalogue are presented in Figure 2, and in the below Figure 4.

Figure 4 tries to explain the different pathways for the product throughout its estimated lifetime and where the different strategies can have an effect.

The first effort to reduce to environmental impact arises in the material stage (A). The effort should focus on reducing the impact of the materials, often by reducing the amount of material, or by replacing the material with another with less impact.

Afterwards, in the manufacturing stage (B) the aim is to reduce the assembly time and production cost, either by manual assembly or automated assembly. Besides reduced assembly time and lower cost, the assembly method can also have a great effect on the product's useful lifetime and End-Of-Life performance.

In the use phase (C), which often is the phase with the highest impact, some products can benefit of a prolonged lifetime. If a product is suited for a long lifetime, it is important that spare parts are easily available. When the product then at some point no longer is needed, and the product is discarded there are multiple pathways possible for the product (D).

The shortest pathways in Figure 4 are both the most economical and environmental attractive solutions since the product resell value is higher than the scrap value, and the product displaces the production of a new similar product, which means that energy is saved, and the related CO_2 emission is avoided. Even though the product as a whole not is suited for reuse, it is not necessarily the truth for the entire product. Some parts of the product might have a longer lifetime and can re-enter the manufacturing stage after a thorough inspection. If the product has reached its technical lifetime and no parts are suited for reuse, then is it probably shredded and the different materials are recovered with varying effectiveness. To improve the overall environmental performance of the product, it can be beneficial to reflect on how the product is discarded and treated End-Of-Life, and design the product so it has a proper separation in the most likely waste treatment system.

2. COMMON DESIGN GUIDELINES AND DEMATERIALISA-TION/DETOXIFICATION

The common design guideline describes the basic approach by either reducing or substituting a material with a material with less environmental impact. It may sound like assembly methods, and design for the environment are two separate topics, but I reality they are in many ways interconnected. Some of the classical approaches to design for environment is (Fiksel 2009):

Design for dematerialisation

- Which e.g. consider reduction of virgin materials, increasing use of renewable materials, remanufacturing/refurbishment of components, reduced size and mass of product and leased product service.

Design for detoxification

- Which e.g. consider reduction of hazardous substances, emissions and waste. Increasing responsible waste treatment and avoiding waste.

Design for revalorization

- Which e.g. consider product recovery, product disassembly and product recovery.

Design for capital protection and renewal

- This approach aims to improve workplace health and security and reduce the environmental impact on the climate. Also, protection the company brand.

Especially within design for revalorization, the assembly method is of great importance when the product is disassembled End-Of-Life. Also, if the product is intended to be refurbished at some point, it is beneficial if the design of the product supports the refurbishment. Therefore, are design for environment and assembly methods highly related, and many synergies can be unveiled when one combines these approaches in a coherent strategy. The strategies concerning assembly methods are not described here but covered in the following section. The below-listed guideline mainly focusses on design for dematerialisation and detoxification.

The general design guideline is (Circular Economy Toolkit n.d.; Fiksel 2009):

- Reduce energy consumption. From an environmental procurement to lower end-use power consumption. Using less energy in the production phase, transportation phase and use phase of the product is of great importance.

- Reduce customer's material consumption in the use phase of the product.

- Using alternative materials with the same characteristics, but with a lower environmental impact. This lower environmental impact can be both regarding energy consumption and the resulting CO_2 emissions or by replacing a material with another material with same properties but with a lower consumption of scarce resources.

- Using alternative materials that have the same characteristics but is lighter. Lighter materials can especially be important for products that are "moving" since the energy consumption than can be reduced.

- Reducing the amount of material in the product. Depending on the type of product it is possible to create different profiles that give the material the necessary strength, but with a reduced material consumption

- Using materials without toxic substances.

- Use more recycled material in the product, since the energy to produce recycled material is lower than that of virgin material.

- Use bioplastics since bioplastics are based on renewable resources.

The environmental benefits of applying the two last suggestions, and especially the last one, are more questionable. The reason that it might be questionable to use recycled materials is that the supply of recycled material often is limited and fixed. This limitation will cause other potential buyers of recycled materials to buy and use virgin material instead. Conversely, one can argue that an increased interest and demand from companies will lead to more materials being recycled. In general, it is better to design the product so most of the materials End-Of-Life can be recycled.

The benefit of bioplastics is that the materials are based on a renewable resource. However, there may be some complications, which means that the use of bioplastic can have a higher environmental impact than ordinary plastic. Also, there are some ethical issues, like using agricultural materials for products instead of food. These aspects will not be further explained here, but it is advisable to examine the advantages and disadvantages of the use of especially bioplastic. Bioplastic and the environmental aspects are further described in the Danish Environmental Protection Agency's website (Miljøstyrelsen 2014)

2.2 Economic considerations

Within design for environment, there are some obvious benefits connected to less use of material and energy. The reduced use of materials and energy often translate into savings and higher profit. If the material reduction is caused by a change in design or change in the material the cost of this may overcome the potential savings. In general, the value of a sustainable business model can be very hard to quantify, and the value of thinking green has been improving over the years.

In the 1960s the mindset of the companies was compliance with the law, but this mindset has changed a lot over the past decades. Already in the 1970s, the companies started to think about systematically environmental risk management to avoid accidents that may affect the exposed nature and people for a long time and avoiding lawsuits. In the 1980s the connection between cleaner production and operational efficiency become more recognised by the companies. The goal was to prevent pollution by generating less waste, recycling waste, avoiding toxic or hazardous substances, process simplification and source reduction. Then from the 1990s to today the extended producer responsibility developed and concepts like product stewardship were created. Also, raising awareness of the connection between sustainability and shareholders led to increasing focus on the full value change (Fiksel 2009).

All these changes have an impact on the value creation of the company. A sustainable business with high operational efficiency are producing less waste, using less energy and have decreasing risks. Therefore, the tangible financial value of the company is improved, but also the intangible assets can be improved. The intangible assets that can be improved is the company reputation, brand and innovation. Also, when a brand of a company is improved it is more likely that it is able to attract the best co-workers. Finally, the value for the stakeholders can be improved.

2.3 Environmental considerations

Many of the environmental considerations are interconnected with the above-discussed consideration of value and economy. Since the profit of the company can increase when implementing design for environment a more effective production can also improve the environmental profile of the company. The profit and value can though to some extend easily be monitored. According to the environment, many different impacts can occur in the lifecycle of the product. It is therefore of great importance to keep track of which impacts that are most relevant for the company and a given product. In this idea catalogue, the main focus is on CO_2 emission and the consumption of scarce resources. Some other local and global impacts are listed in the below table.

Category	***Impact***	***Substances contributing to the impact***
Global	Greenhouse effect	Carbon dioxide and other greenhouse gases.
	Ozone depletion	CFCs and other, similar substances which degrade the ozone layer.
Regional	Acidification	Acidic compounds, mainly of nitrogen and sulphur, which cause acid rain.
	Nutrient salt loads	Emissions of nitrogen and phosphorus contributing to algae growth and oxygen depletion.
	Photochemical ozone formation	A mixture of organic solvents and nitrogen compounds which cause groundlevel ozone.
Local	Human toxicity	Emission of toxic substances which may affect human beings in the short term.
	Eco-toxicity	Emission of toxic substances into the aquatic environment or into the soil which may affect animals, plants, and other organisms in the short term.
	Persistent toxicity	Emission of toxic substances which are non- degradable or very slow to degrade. These substances affect human beings, animals, and plants in the long term.
	Waste	
	Bulk waste	Usually at landfills.
	Slag and ashes	Usually at special waste disposal sites.
	Hazardous waste	Requires special treatment.
	Radioactive waste	Requires special treatment.

Table 2: List of some of the local and global impacts that can be included in a lifecycle assessment. (Pommer et al. 2003)

To keep track of the different impacts, it is beneficial to perform a life cycle assessment. Depending on the outcome of the assessment different initiatives can be made. The suggestions in the general design guideline concerning dematerialisation and detoxification have especially an effect on the energy consumption, the related CO_2-emission and the use of scarce resources. If the downsizing is due to a different choice of material, the content of scarce resources per kilo of material should be investigated and also the needed energy to produce the material. So even though the material is lighter, it can still contain more scarce resources which need more energy for extraction than the original material.

3. DESIGN FOR ASSEMBLY

Design for assembly is a well-known approach to reducing the manufacturing cost of products.

The design for assembly guideline aims to reduce the assembly time by an optimised design of the individual parts and considerations about the placement of the different connectors. Besides a reduced assembly time, a side benefit of applying design for assembly could potentially be an improved environmental performance EndOf-Life. Before adopting a design for assembly approach, the existing production should be properly assessed to reveal possible bottlenecks. There are several different methodologies for evaluating and improving the design for assembly. The three most commonly used methods are summarised below (Mital et al. 2014):

The Boothroyd-Dewhurst DFA Method

- A method to evaluate and refine existing design, by assessing the assembly sequence and the assembly time of each part. The assembly time consists of both a handling time and an insertion time for the different components. The next step is then to find the "theoretically needed parts" by reducing the total parts count by eliminating or combining some of the parts. This reduction of parts is then performed as an iterative process until the optimal design is obtained.

The Hitachi Assembly Evaluation Method

- A method originally used to develop an automatic assembly system for subassemblies and does not distinguish between manual and automated assembly. The aim is to assess the ease of assembling by two indicators. The first indicator is the difficulty of the assembly operation. Depending on the operations a penalty score is assigned. The optimal operation is a simple downward movement with a penalty score of zero while an operation like soldering has a penalty score of 20. All parts are then evaluated to produce an evaluation score for the whole assembly. The second step is then to evaluate the improvements according to the cost of the assembly. Savings can be obtained by reducing the number of parts, or simplifying the operations.

Lucas DFA Method

- A method divided into three stages. The first stage is a functional analysis to assess which parts are essential and which are non-essential. A good initial target is if the design consists of more than 60 % essentials parts. Otherwise, the nonessential parts should be reduced as much as possible. The second stage is a handling/feeding analysis which takes into accounts possible handling concerns such as shape, weight, orientation, etc. of the parts. The target is to calculate a handling ratio based on a handling index and the number of essential parts. The third and last stage are a fitting analysis where an index is given to each of the parts depending on their requirements for fitting such as resistance to insertion and restricted vision during the assembly. The target is to calculate a fitting ratio based on the fitting index and the number of essential parts.

Common for the mentioned methodologies is that they all share the emphasis on product simplifications and reduction in the total parts count for the assembly. When the total parts count is reduced it also often causes a complication of the remaining parts. So while the assembly cost is reduced, the cost of manufacturing might increase, due to more complicated parts. Some different design guidelines are available, which also considers the manufacturing stage called DFMA (Design for Manufacture and Assembly). Furthermore many of the methodologies are further refined and are available as computer programs.

The below design for assembly guideline does not look into the different methodologies but instead provides some general ideas for a more effective production. The guideline consists of two sections. The first section describes the guideline for manual assembly and the second section describes the guideline for automated assembly.

3.1.1 Design for manual assembly

The most common way to assemble products is manual assembly, but the high wages countries struggle to keep a profitable production. A tool to overcome this chal-

lenge is `design for manual assembly´. The `design for manual assembly´ consist of two natural stages where the first stage is the handling of the parts and the second stage is the fastening. The handling is simply when the objects are moved and oriented so the objects can be properly fastened in the second stage. There are multiple suggestions to improve the design in each stage, and things to consider whether could be implemented in the company.

For the handling stage, numerous geometrical features can have an impact on the assembly (Boothroyd 2005):

- It is Beneficial if the part has an end-to-end symmetry, so the part obtains symmetry around its insertion axis, the part is then easier to fit since it is harder to misplace. Therefore, if the parts are completely symmetrical, it is very hard to misplace. It is often not possible for all parts to be symmetrical, but for some this could be a solution.
- If the part not is suited to be symmetric, it should instead be made clearly asymmetric to help the orientation of the part, so it is harder to misplace. This feature will reduce to time to place the parts, and reduce misplacement.
- If the parts are stored in bulk, there is a risk of the parts jamming, stacking or tangling and it should, therefore, be considered how to redesign the parts to prevent this. This redesign could be done by adding a feature that simply makes it impossible for the parts to jam, stack and tangle.
- The size of the parts can become either too big or too small for fast handling. Parts that are slippery, have sharp edges, are hazardous or have any negative effect on the workers' health should also be avoided.

Since the guidelines are very common, it could be a good idea to investigate bottlenecks in the production, and the solutions could very well be improving the design of the parts handled within this section.

In the fastening stage

- When parts are inserted, the risk of jamming should be minimised. This could be done by adding a feature that simply makes it harder for the part to jam. Jamming could also be prevented by designing the parts, so they contain a fixation feature, so parts simply fall into place. It should also be considered to lower the friction of insertion, so the maximum allowed clearance is preferred. If only a small clearance is allowed, there is a risk of air resistance complicates the insertion process. A solution could be a small hole or corridor that allows air relief during the insertion.
- Use of standardised parts across different models and product lines. The standardised parts should be designed with ease of handle in mind. Standardised parts are further discussed in the part of modular design.
- Use fixation tools that can help the parts to be fixated when assembled, and avoid the need for holding down parts doing the assembly. It is therefore preferably to consider when parts need two-hand handling and how to minimise the time with two-hand handling.
- If parts are released or "dropped" into position, the part should be located into the right position when released.
- Consider the types of fastening. Threaded fastening is more time consuming that snap fits. If screws are needed, then use the same types of screws to avoid time loss due to change of tool.
- When screws are used it is beneficial to consider how to make an assembly with as few repositions steps as possible. So screws are positioned from the same side.

Additionally, it is very beneficial if the total number of different parts is reduced in the product since fewer parts then need handling and fastening. Also if two parts need connection by wire, the two parts should be located as close as possible and preferably interconnected in the same assembly if possible. When parts are connected either by wire or screw, make sure there is proper space to fasten the object or use snap fits. Finally, also make sure that the design minimises the need for adjustments during the assembly. When parts are reduced, the mix of different materials is also likely to be reduced. This reduction in different materials could be beneficial for the environment since the risk of cross termination End-Of-Life in the shredding system then is reduced.
Also, snap connections have these possible benefits.

3.1.2 Design for automated assembly

An alternative to manual assembly is `design for automated assembly´, which could be a solution to have a profitable assembly in high wage countries. The automated assembly is, though a technology in growth which implies that more assignments can be carried out by robots in the future than today.

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The design for automated assembly has many commonalities with `design for manual assembly´, since tangling, jamming, etc. preferably also should be avoided no matter if it is a robot or human being performing the assembly. Therefore, is many of the below-described guidelines already described in the above design for manual assembly, and written again to pinpoint which considerations also should be taken into account in `design for automated assembly´. The design for automated assembly consists in general of two different technologies which are high-speed automatic assembly and robot assembly. As the names suggest, the two technologies are quite different from each other and have both benefits and drawbacks.

The high-speed assembly often consists of different machines only able to perform one assignment, and therefore often specific to the product produced. Therefore, the technology is not suited for changes in the design, since these kinds of machines are not able to adapt to the changes without a prior and often expensive change of the construction of the machines. This form of automation is also often referred to as hard automation.

The design guideline for high-speed assembly is:

- Reduce the number of parts to a minimum
- A suitable stable base part upon the product can be built on is preferable. Furthermore, is it an advantage if the product can be built in a layer fashion, so the product can be built from above, without the risk of moving the already placed parts.
- Provide chambers, tapers or alike to guide the parts for correct placement.
- Avoid if possible screws and other time-consuming operations and instead facilitate the use of snap fits.
- Use a high percentage of standard parts.
- Avoid the risk of similar parts tangling when placed in bulk in the feeder.
- Symmetrical or clearly unsymmetrical parts can be oriented easily. If the parts are difficult to orient an extra orientation machine may be necessary, which will increase the cost a lot.
- A design of parts, with a low centre of gravity, can facilitate the feeding of the parts.

The robotic assembly is performed by one or more robot arms, at a varying number of workstations and is controlled by a PLC (Programmable Logic Controller) or a computer. This type of assembly is more flexible than the high-speed assembly and is often referred to as soft automation.

The design guidelines for robotic assembly are:

- Reduce the number of parts, and includes features such as chambers, or similar to make parts selfaligning.
- Avoid the need for holding down during the assembly, and especially for a single robot arm workstation. Therefore, use self-locating properties if the part not is secured after insertion.
- Design the different parts with respect for the gripper, so as few different grippers are needed.
- Design the product so it can be assembled in a layer fashion (Vertical assembly directly from above) upon a suited and stable base. If the product can be built in a layer fashion, the requirement for the robot arm is reduced.
- Avoid the need for reorientation of the product during the assembly.
- Design the different parts so they can be easily handled from bulk without tangling, stacking,
- etc. Also, avoid parts that are fragile or too delicate to be handled by a robot.
- Consider how the parts are fed to the robot. By using an automatic feeder make sure that the parts are easy to orient, and are fed in the right direction

so the parts can be easily gripped and assembled with the lowest requirements of the robot arm.

Reducing the total parts count in an assembly is properly the most important design guideline for both high-speed automatic assembly and robotic assembly. A reduction in the total part count can imply a reduction in needed machines or robots and thereby reduce the overall investment, and increase the overall profit.

3.2 Economic considerations

The economy of the three different assembly approaches is visually compared in the below figure.

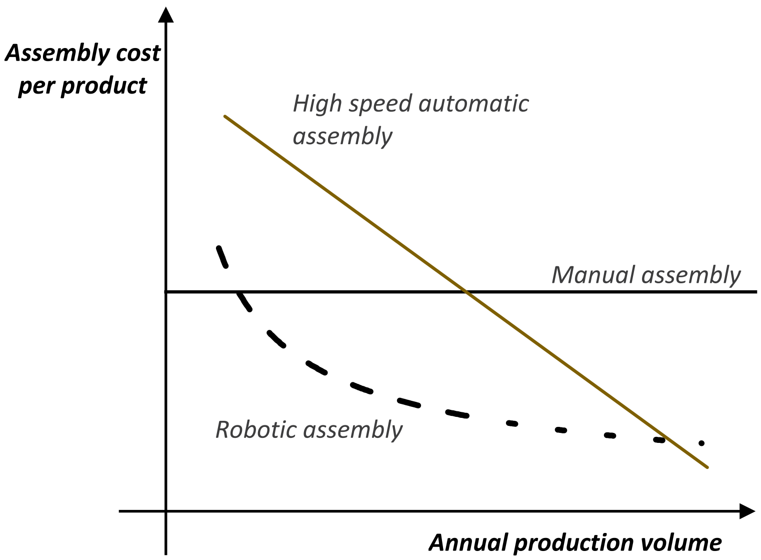

Figure 5: Visual comparison of the assembly cost of robotic assembly, high-speed assembly and manual assembly compared to the annual production volume (Mital et al. 2014)**.**

The manual assembly requires the lowest capital investment, but the cost per product is constant regardless the annual production volume. The production is also very flexible, and changes to the product are easily implemented. Although the mentioned benefits, there is often an upper limit to the profitable production volume since the manual assembly at some point then will compete with automated assembly. The wages which are country specific are of great importance and would influence the constant cost per product in a positive or negative manner. The high-speed automatic has the highest initial cost, but the cost per product decreases with increasing volume of production. Furthermore, this type of assembly is often only suited for one type of product and lacks generally flexibility towards changes in the production. The high-speed automatic assembly is the most profitable of the three mentioned alternatives at a very high annual production volume. The robotic assembly is by all matters somewhere between the manual assembly and the high-speed automatic assembly. The initial cost is higher than for manual assembly but lower than the high-speed assembly. Also, the flexibility of the system lies in between the two other alternatives. At high annual production volumes, the robotic assembly becomes costlier than the high speed automated assembly.

In the above Figure 5 are manual assembly, robotic assembly and high-speed automatic assembly compared according to annual production volume and assembly cost per product. Besides the different assembly techniques, it is also important to consider the degree of automation. It is therefore not a question of manual assembly or automated assembly, but rather or question of which processes are most beneficial to automate, and which should be kept manual. The optimal degree of automation is very much dependent on the type of product, and annual production volume. When the degree of automation increases, there is a trade-off between decreasing wages and by increasing capital costs, maintenance costs and energy costs (Ceroni 2009). The behaviour of the assembly costs at different automation levels are visually presented in the below Figure 6:

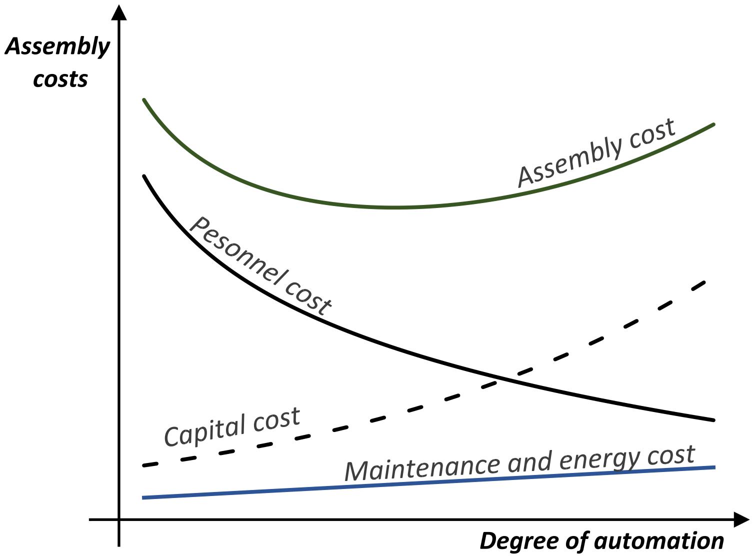

Figure 6: Visual comparison of the assembly cost and the degree of automation (Ceroni 2009)**.**

The optimal degree of automation is then when the assembly costs have reached a minimum. The choice and degree of automation should be carefully evaluated before any investments, including considerations if the product is suited for automation or the design of the product would require too extensive changes, which might also affect the quality of the product.

3.3 Environmental considerations

Design for assembly techniques mainly focuses on the cost, where an improved design eventually should result in lower assembly costs. The aim is therefore not directly related to any environmental concerns, but an increased focus on the assembly method could also benefit the environment. If a product is easy to assemble it may very well also be easy to disassemble, since e.g. maximum clearance, and a reduced count part properly would increase the end of life performance. With a maximum clearance of the individual parts, it is easier to remove valuable parts, and the reduced parts count implies a reduced mix of materials, which might benefit the environmental performance in a shredder, by improved liberation.

It is, however, questionable whether or not design for assembly has a positive environmental effect, but it could very well facilitate, or improve the possibilities for a more circular approach. If the product is both easy to assemble, and disassemble the potential for a beneficial circular business model is improved. A circular business model has the potential to substantial improve the environmental performance of products.

4. DESIGN FOR REPAIR AND MAINTENANCE

The lifetime is of great importance for the products overall environmental performance, but also as an indicator of the quality of the products.

It is often preferable for the consumer to purchase longlasting quality products that have a proper function for many years, maintaining its fashionable appearance. The paradox is that companies would benefit more by a shorter lifetime, and varying trends. Both the shorter lifetime and the varying trends are drivers for a more rapid change of products and the lifetime of products can, therefore, have many constraints. Depending on the type of product a proper lifetime is important. Both durable and nondurable products face different drawbacks, and it is, therefore, beneficial to determine a suited lifetime for the product.

4.1 Design for repair and maintenance

Design for repair and design for maintenance is design strategies to minimise the downtime of products benefitting both the producers and the customers. It is especially during the warranty period the producers can benefit from a quick service, since it is possible to reduce the labour cost of the repair, and in the long term, the customer may be more loyal to producers with good and efficient service. Also after the expiration of the warranty the producers could possible benefit of selling replacement parts and in general be acknowledged by the customers as a producer of long lasting products which are easy to repair. The environmental performance of the product is also improved when the product has a proper lifetime.

Also within design for repair, there are different available methodologies depending on the product. Many methodologies are created based on the need for maintaining costly equipment such as aircraft or other machines where downtime is very costly. Overall there are two types of maintenance which is corrective and preventive maintenance and as the names imply the corrective maintenance is forced when a product or a system fails. The preventive maintenance is then a strategy to prevent failure or at least the probability of failure. The methodologies are best described as prediction models for maintenance, and the majority of the available models is based on preventive maintenance. Two examples of models are described below (Mital et al. 2014):

The SAE (The Society of Automotive Engineers) Maintainability Standard

- The SAE maintainability standard is formulated as a standard to obtain early in the design stage of a product or a system. The aim is to create or assign a score for lubrication and maintenance items. The operation receives then a score based on each of the following indicators: location, access, operation, miscellaneous considerations and a frequency multiplier. For example, if the maintenance can be done semi-annually on ground level by a visual check with easy access with no need for special tools or special operations the overall score is low, which is equal to a highly maintainable product.

The Federal Electric Method

- The federal electric method consists of different steps and applies time as an indicator for the maintainability of products and systems. There are four major steps in this method which is, identification of the main components, determination of failure rate for the identified components, the time required for maintenance of each component, and calculation of the expected time for maintenance based on information from the first three steps. To calculate the time for maintenance a standard repair time chart is used, with more than 300 repair task. These tasks are based on different actions regarding the maintenance which is, location, isolation disassembly, interchange, reassembly, alignment and checkout. This method aims to provide an estimation of the time needed for maintenance, and a short maintenance time is obviously desirable.

Both of the mentioned methodologies have both benefits and drawbacks. The SAE maintainability lacks the time consideration of maintenance and needs more flexibility towards more complicated maintainability tasks. The federal electric method is based on empirical studies, and there is, therefore, risk margins of error in the calculated repair time. Even though the mentioned uncertainties, both methodologies are useful tools to grade the maintainability of products that can be used for benchmarking design improvements.

In generally many methodologies are developed in connection with heavy duty equipment, military equipment and alike, but design for repair is also applicable to commercial products. The different methodologies may though need some “calibration” to fit commercial products.

When adopting the approach for design for repair there are some general rules that support ease of repair (Mital et al. 2014):

- That parts can be easily removed without damaging other parts in the process
- Minimise the need for specialised tools to repair the product

- Make visible part identification for easy clarifications of part origin and suited replacements
- Different form factors might be helpful in the reassembly process, and also guiding pins can help the process of proper location
- For heavy parts handles or other features for ease of handling should be considered
- Avoid sharp edges of parts that can cause injury during the disassembly
- Provide clear access to components and parts. Especially if the product contains a line of replaceable units
- Provide clear access to the connectors and also provide cables with codes throughout the whole cable for easy identification

Furthermore, there is also several rules of thumb for design regarding maintainability:

- Accessibility for parts or subassemblies that require routine inspections, so those parts or subassemblies are placed so they easily can be accessed, and replaced if needed. Proper connections that facilitate a quick replacement is preferably for electric, mechanical, etc. type of connections.
- Modularity in the design facilitates in general easy replacement, with no further adjustments when the modules are inserted again. The design for modularity is further discussed in section 6.
- Simplicity and standardisation are both important towards an easily maintainable product. A simple product, with few parts, and no need for tools for disassembly is easy to repair. If tools are needed, standard tools are preferred. Also, stand materials, connectors, fasteners, etc. are advantageous since standard parts often both are cheaper and allows for easier replacement.
- Foolproofing for parts or subassemblies that seem to be similar should have different design features that prevent misplacing.
- Testability, which allows the product to be tested without any disassembly is important towards a design for maintainability.

Furthermore, if "home" maintenance and repair is encouraged by the producer, replacement parts and manuals should be easily available for the consumer.

When products are easy to maintain, it often also implies that the products are easy to disassemble.

4.2 Economic considerations

The importance of the lifetime and the reliability of a product is very much dependent on the application. High military grade equipment and alike all favours a high reliability while consumer goods often are accepted with a lower reliability. The average consumer is more focused on the purchase price than the reliability of the product. Furthermore, are design trends, and product variety two factors affecting and shortening the lifetime of products. The varying trends and frequent update of e.g. phones all thrive consumers to buy new equipment often on the expenses on well-functioning products, so it can be reasonable to question the needed lifetime of products, and especially some fashion products. Planned obsolescence can backfire since the consumers can be unconvinced that purchasing a new product is worth the money.

If the product has too low reliability, the expenses of warranty cost will increase which will induce higher total cost for the producers. Contrary the expenses for manufacturing a too reliable design will also increase the total cost, together with the expenses of the design changes. There is then an optimum degree of reliability where the total costs are minimised. The cost of reliability is visually presented in below Figure 7:

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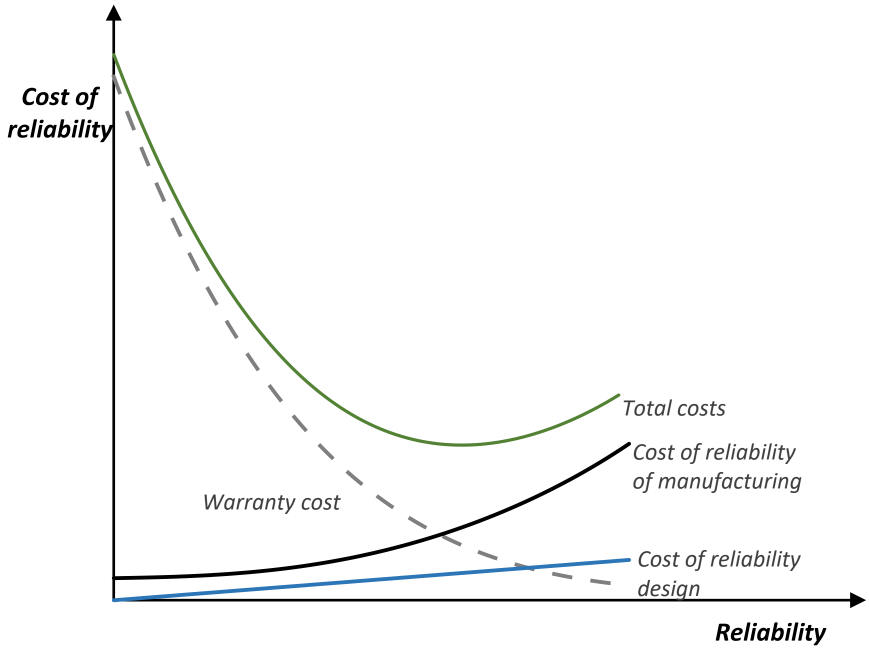

Figure 7: Visual presentation of the cost of reliability and the degree of reliability (Fei et al. 2008).

Both a too reliable design and too unreliable design are economically unattractive for the company. Design for reparability can decrease the warranty costs and thereby decrease the total costs. After expired warranty, the producers are supposed to me economical independent of further breakdowns of products. A too short lifespan after the warranty can affect the publicity of a company and affect future sales negatively, and the company can even face a class-action suit like Samsung faced for a faulty capacitor in their LCD screens (Anon n.d.).

When designing a product for repair and maintenance new business opportunities arises. When a product is designed to be quickly repaired or maintained the cost for the customer can be reduced and lead to more customer interested in repair and maintenance of the product. Also, sales of spare parts and increased customer loyalty can be important drivers to facilitate design for maintenance and repair.

4.3 Environmental considerations

The benefits of a product with a long lifetime is that the energy demand to produce a new product is displaced to a later point in time which means that the environmental burden is diluted over more years so the products environmental performance is improved when the yearly contribution is accounted over the full lifetime of the product. Below in Figure 8 is a simplified example of the of a product where the embodied energy, energy for manufacturing, energy in the use phase, the required energy for disposition and the End-Of-Life potential (The 'credit' associated with the recovery and reuse of material/components when the product is discarded) is distributed over five, and ten years.

The yearly contribution is halved when the lifetime is doubled except for the use phase. The use phase has the same yearly energy consumption all years during the lifetime. Therefore, a long lifetime of products is in some cases not always preferable. For some product categories, the power consumption is the crucial part of the overall environmental performance which often is the case for most powered consumer goods.

At a certain point, some products are simply outdated due to a high-energy consumption, while a new similar product has such reduced energy consumption that it would be more environmental friendly to replace the product with a new and more effective model.

Below in Figure 9 is a simplified example of the accumulated energy consumption for a product. The accumulated energy consumption consists of the embodied energy, energy for manufacturing, energy in the use phase, the required energy for disposition and the End-Of-Life potential, and is based on the same data as Figure 8.

Furthermore, is it assumed that the annual energy consumption is lowered by 6 % per year for a new similar product.

Figure 9 shows then a comparison of the environmental performance when the product is changed after two years, after seven years, and is displaced after 15 years. The example is entirely fiction.

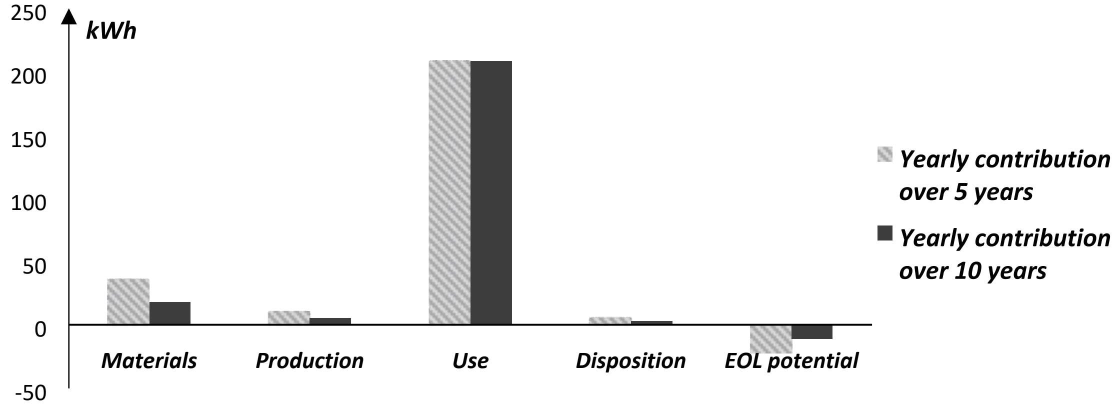

Figure 8: Visual presentation of the yearly energy consumption of a fictive product.

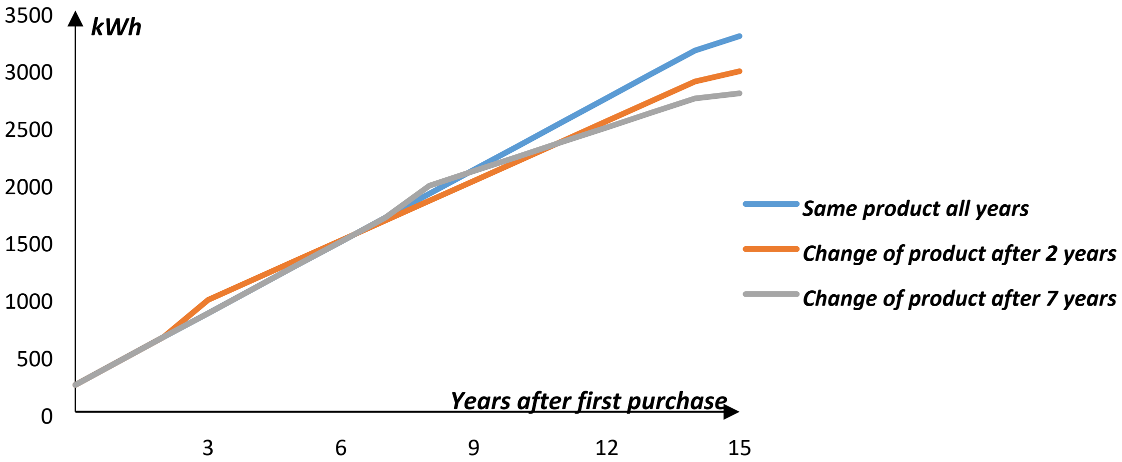

Figure 9: Lifetime energy consumption of a fictive product when the yearly energy improvements of new models are 6 %

Depending on when the product is changed, and how much the efficiency of the product has improved it can be a good idea to change a product to a more efficient model. In the above example in Figure 8 the least energy consuming approach over a period of 15 years is to change the product after seven years, followed by the change of product after two years. In this specific example, the product is less suited for a long lifetime, but the yearly energy improvement is also assumed to be rather high, compared to the needed energy to produce the product itself. At some point, the possible energy improvements are reduced due to technical limitations, and the yearly annual energy improvement is lowered or neutralised. Therefore, at this point or when the yearly improvement is becoming relatively small, it is relevant to extend the lifetime of products.

The below Figure 10 is based on the same data as Figure 9; the only differences are that the energy consumption in the use phase is lower, and the annual energy efficiency improvement now is 2 % for a new and similar product.

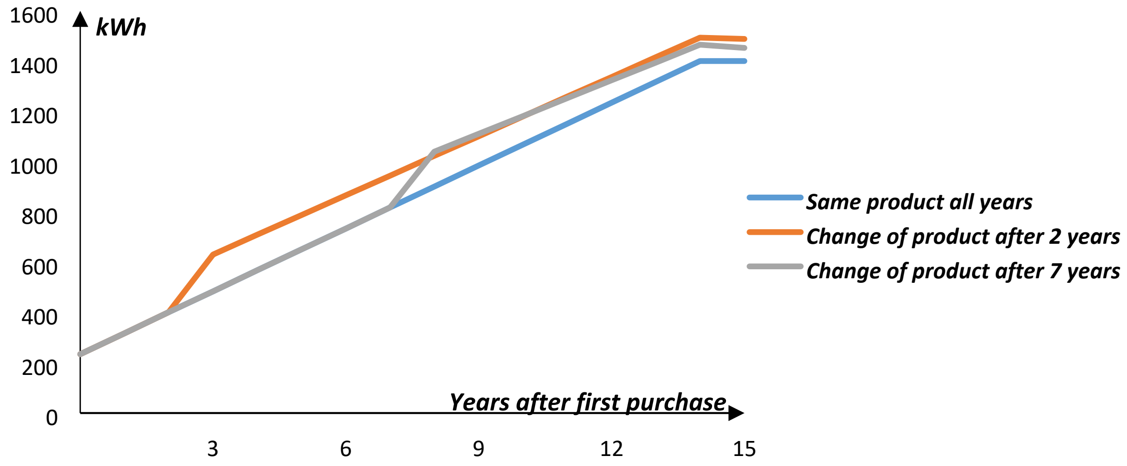

Figure 10: Lifetime energy consumption of a fictive product when the yearly energy improvements of new models are 2 %

Overall Figure 10 shows the same tendency as Figure 9, but the energy consumption for producing a new product is relatively higher, and the benefits of replacing the product are displaced. The least energy consuming approach is now to keep the same product all years followed by the change of product after seven years.

The above two figures could also have been presented in CO_2-emission or lifetime costs for the consumer. The energy consumption and the CO_2-emission are directly related to each other, so increased energy consumption implies an increased CO_2-emission. In the use phase, the lifetime costs are also highly related to the energy consumption, and it can therefore also sometimes be economically beneficial for the consumer to replace a product at some point. In the future, the correlation between energy and CO_2 will decouple due to more renewable energy, and potentially also the smart grid. These two factors would potentially also decouple the correlation between energy and the lifetime costs, so it could very well be more important when energy is used than the amount of energy used.

5. DESIGN FOR END-OF-LIFE

Many companies and suppliers do not take responsibility for their products End-Of-Life, since it can be a costly task, so many products end up in a common collecting scheme or at drop-off centres. Some producers and importers are subject to the extended producer responsibility, but the needed payment is very small compared to the retail value. For a 64 kg fridge, the producer or the importer only has to pay around 2 DKK, and the retail value can vary between a couple of thousands Danish kroner to more than ten thousand Danish kroner. The fee is relatively small since the discarded products have a certain value which the producers are missing out on, and on top on that pays a small fee. Though there are also expenses for the producers if they offer a take-back solution for their products, and especially the transportation can be a concern. If a take-back solution is not preferably, the company can still improve the products environmental performance by design for recovery. Design for recovery does not add any value for the company but can improve the publicity and corporate responsibility.

5.1.1 Design for disassembly

Design for disassembly could potentially be a tool for the companies to facilitate a profitable take-back solution of products. Already now more manufacturers such as HP, Grundfos, Apple, EPSON, H&M and much more are offering to take their old products back. In today's Denmark, the Eco-design directive is only concerning the energy consumption of products, where the Nordic Ecolabel scheme also considers other aspects such as flame retardants in plastics. For some products, the Nordic Ecolabel scheme also includes some environmental requirements for the design of the product, and a computer, for example, must comply with the requirements concerning disassembly and upgradeability unless specified otherwise. Requirements concerning disassembly may become more common in the future and the producers obtaining design for disassembly and recycling may have shown due diligence, and therefore might have an advantage on the market later.

Within design for disassembly, there are several different possible pathways which are described in Figure 4, and the aim can vary greatly. The discarded product can be repaired, obtain different levels of remanufacturing, of be recycled at a material level. Therefore, there is also multiple methodologies towards design for disassembly, with different indicators. Below are some different methodologies presented:

Total time of disassembly (Gungor & Gupta 1997)

- A methodology made to pinpoint the best disassembly process among several alternatives according to the total time of disassembly. This methodology suggests a mathematical formula to calculate the total time of disassembly based on the disassembly sequence, disassembly time of each component, disassembly direction and joint types. The alternative with the shortest time of disassembly is then the preferred one.

Rule-based recursive selective disassembly sequence planning for green design (Smith & Chen 2011)

- Instead of focusing on disassembly of the total product this methodology focuses on selective disassembly of e.g. valuable parts. The methodology is a based on a disassembly sequence planning and is based upon four matrices and five disassembly rules. The four matrices are used as a basis to describes the geometric relation between parts. The four different matrices consist of information on the direction of fasteners, components and the interconnection between fasteners and components, motion constraints for fasteners and motion constraints for components. These matrices are then the foundation for the disassembly planning process, which is defined by five rules depending on the placement and interconnection of the different parts and fasteners.

Common for both methodologies is the importance of the type of fastener, placement and the clearance for an operation. Both methodologies can be applied for both a complete an incomplete disassembly and there can be some benefits of a selective disassembly and grouping of valuable parts in a product. These directions are also implied in the guideline for design for disassembly, which is presented below (Chiodo 2005):

- Minimise the number and type of fasteners, so the need for tool change is minimised during disassembly so the disassembly time is minimised
- The fasteners should be easy to access and remove, so the maximal allowed clearance is obtained
- Easy to locate disassembly points
- If snap fits are used, they should be obviously located and possible to open with standard tools
- It is beneficial if fastener and material are either identical or compatible to recycle together
- The use of adhesive should be minimised or compatible to recycle together with the material
- Minimise the length of cables to reduce the risk of copper contamination, or connection points could be designed so they break
- Simple product design is preferable

Some of these suggestions also comply for design for recycling since some parts might have no or low interest. These parts can then be sold as scrap, and the value will increase with the purity. Therefore, fractal snap fits around a valuable part could be a solution to minimise the needed time to separate specific parts of interest. Parts that nevertheless are sold as scrap and e.g. remelted are not subject to loss of value if the parts break doing the disassembly, which can be exploited in the design structure.

Another option for easy disassembly is active disassembly which utilises the improvements in material science, which allow materials to change form when heated and thereby allow an easy disassembly e.g. if all screws in a product lose their threads when heated. This also implies that no materials are broken during the disassembly, and some technologies allow parts to change form when heated and then to shaped into its original form when cooled. Depending on the application these smart materials can react on different impacts such as temperature, moist, light, current, and other energy carries.

5.1.2 Design for recycling

Design for recycling is quite complicated since products often are discarded together with a high variety of other products so there is a risk of contamination in the different output fractions from the waste handling companies. Besides the risk of contaminants from other products, the products itself might contain parts that are poorly recycled together. It is, therefore, important to design a product so it End-Of-Life is proper liberated and especially parts that not are able to be recycled together.

One of the main barriers to design for recycling is the value creation. The value creation will mainly happen at the waste handling company since they benefit from the better design and consequent pure waste streams that are more valuable. One of the best ways for the producers to benefit from a design for recycling strategy is by advertising that the product has a proper design, and the company cares about the environment and available resources.

For design for recycling, it is important to consider (Reuter & Schaik 2013):

- To reduce the use of materials, and especially the use of materials that will cause loss or contamination in the recycling process. It should be considered how the materials would behave in the sorting and processing End-Of-Life

- To identify materials in assemblies those are combined in an inappropriate way so resources are lost during recycling. An example could be the connection between metal screws and plastic, where one of them is lost if the materials are not fully

  liberated before recycling. Besides the obvious troubles with plastic and metal mix, not all types of metals can be recycled together, which also is the case for plastic. In Figure 11 the metal wheel is shown. The metal wheel explains which resources are recovered depending on which kind of smelter treating the metal.

- In Table 3 a rough guideline for which types of plastic that can be recycled together is shown. If it is beneficial to divide a product into subassemblies so each subassembly can obtain the most appropriate End-Of-Life treatment with the highest possible recovery rate.

- Proper labelling both on plastic, but also general futures such as marking of tapping points of generators

- How the to obtain maximum liberation End-Of-Life. Minimise the use non-reversible adhesives, and avoid the use of bolt/rivets of dissimilar materials.

Like all the other guidelines, the design for recycling is a rough guideline. However, specially design for recycling is complicated since the product is recycled with a range of other products, and the produced waste streams a further treated depending on the specific composition of the stream.

Further, it should be noted that all products have a unique material composition and thereby a unique fingerprint, so it should be considered to produce simple simulations of how the product performs End-Of-Life.

Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy) Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy) Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

Mainly to Benign Low Value Products Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

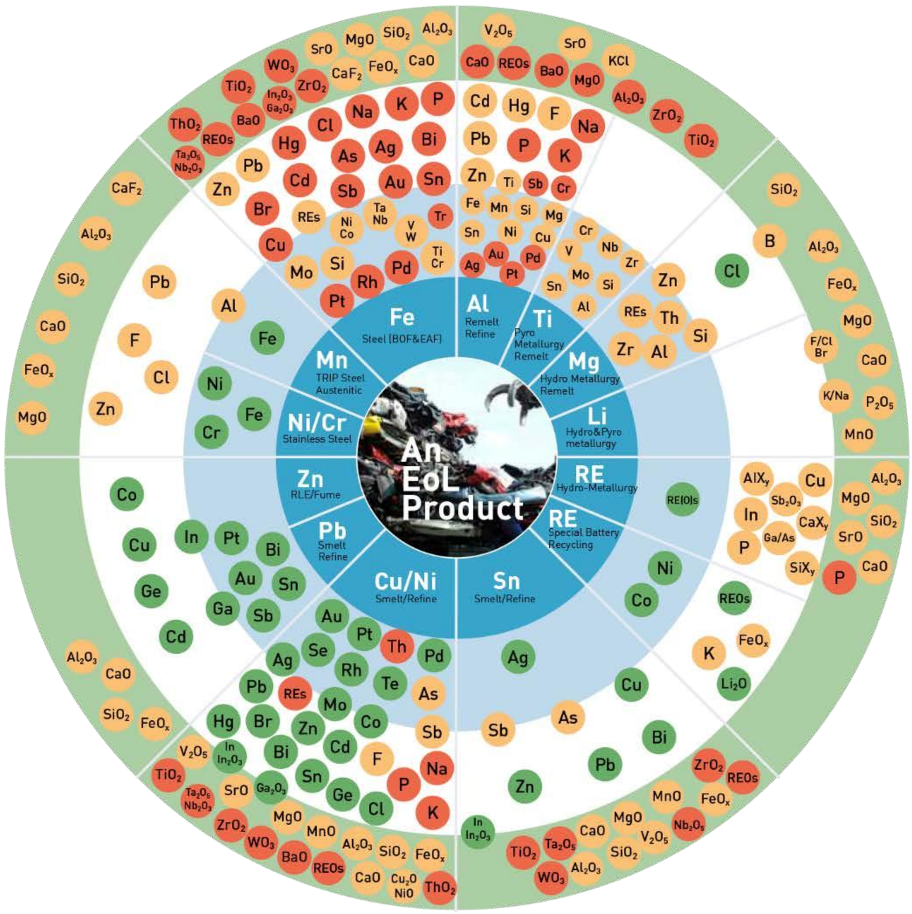

Figure 11: Metal wheel. The metal wheel shows which resources that can be recovered at the different types of smelters (Reuter et al. 2013) **More information on the metal wheel can be found on the homepage of UNEP.**

Additive

Excess component

Important Plastics	PE	PVC	PS	PC	PP	PA	POM	SAN	ABS	PBTP	PETP	PMMA
PE	1	4	4	4	1	4	4	4	4	4	4	4
PVC	4	1	4	4	4	4	4	1	2	4	4	1
PS	4	4	1	4	4	4	4	4	4	4	4	4
PC	4	3	4	1	4	4	4	1	1	1	1	1
PP	3	4	4	4	1	4	4	4	4	4	4	4
PA	4	4	3	4	4	1	4	4	4	3	3	4
POM	4	4	4	4	4	4	1	4	4	3	4	4
SAN	4	1	4	1	4	4	4	1	1	4	4	1
ABS	4	2	4	1	4	4	3	4	1	3	3	1
PBTP	4	4	4	1	4	3	4	4	3	1	4	4
PETP	4	4	3	1	4	3	4	4	3	4	1	4
PMMA	4	1	3	1	4	4	3	1	1	4	4	1

Table 3: Recycling compatibility of different types of plastic. 1= Compatible, 2 = Compatible with limitations, 3 = Compatible only in small amounts, 4 = Not compatible (Chiodo 2005)

5 .2 Economic considerations

There is a great variety of different methodologies and standards available depending on the aim and the completeness of the disassembly. Overall the completeness of the disassembly can be categorised in complete disassembly and incomplete disassembly. There are multiple reasons that an incomplete disassembly can be more attractive than a complete disassembly for the company.

A complete disassembly is rarely performed due to some constraints such as the complexity, uncertainties and high labour costs, so it is often not a profitable business.

The incomplete disassembly is targeting the valuable parts or modules that can be reused, remanufactured or alike. When some parts or modules are removed from the product, the remaining part can potentially obtain a higher scrap value due to fewer contaminants in the stream.

In the below figure is the optimal disassembly strategy visually presented:

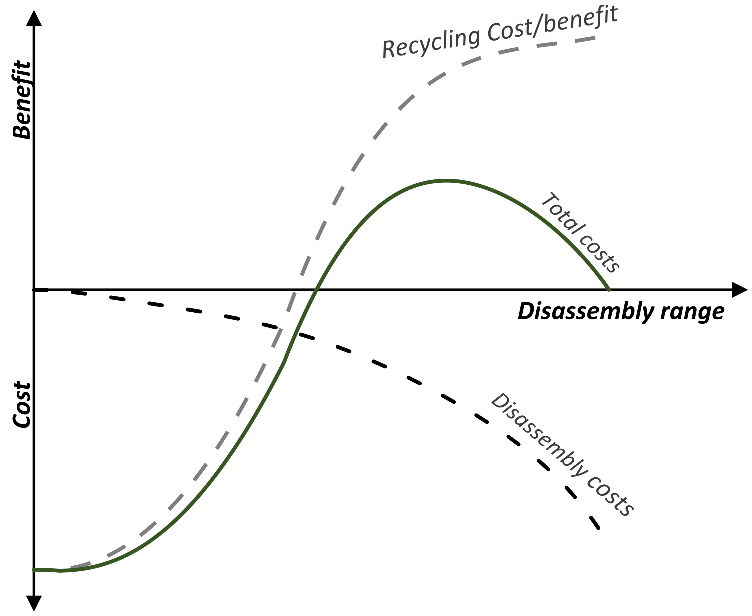

Figure 12: A visual presentation of the cost-benefit ratio and the disassembly range (Mital et al. 2014).

The cost of disassembly increases with the disassembly range, so an incomplete disassembly is cheap, and a full disassembly is expensive. The income potential increases with the disassembly range, so an incomplete disassembly has low value and a complete disassembly has a high value, but the potential increase flattens towards the full disassembly since the increase more or less are related to higher scrap value. The optimal strategy is when the maximum profit can be obtained. The optimal strategy is very much depending on the product type, and some products might never reach a profitable business model. As mentioned earlier proper design can reduce the disassembly cost and thereby increase the profit.

5.3 Environmental considerations

When the value of waste fractions increases in value, it is due to fewer contaminants. With fewer containments, the recycling process becomes more effective. Some resources cannot be recycled together which will cause some losses when a product not Is properly liberated and may also cause that the new recycled material has worse properties. When a material is recycled, proper liberation is important also according to the needed energy to sort the materials. Even though recycling requires energy, it is possible to save more energy since the recycled material suppresses the need to mine virgin resources. The needed primary energy to produce 1 kg of wrought iron is 24.5 MJ and in comparison, the needed energy to produce 1 kg of recycled wrought iron is 7 MJ. Therefore, there is a potential energy saving of 17.5 MJ/kg wrought iron recycled and a corresponding amount of CO_2. As stated earlier the recycled amount of material is limited, and it is therefore of high importance that products fit the End-Of-Life treatment so the materials can obtain a high recovery rate.

A better liberation of products End-Of-Life also secures that most of the resources within the different materials are recycled. Sometimes some of these resources are mixed in other materials where they are not wanted but only tolerated to a certain degree. This accumulation of resources in materials where they are of no use can be limited with a proper design strategy for the product.

6. DESIGN FOR MODULARITY

Design for modularity can potentially be a way to obtain a sustainable product, which also is a possible keystone for combining the different strategies. All of the above mentioned design strategies can be a part of a modular design. The term modular can vary a lot across the different companies and modular design can have a different meaning depending on the company. Even though the term might vary the fundamentals of modular design are common. Create modules that can interchange, and provide well-defined interfaces. Furthermore, this design strategy also facilitates modular product architecture and/or modular manufacturing processes. Therefore, more types of modularity exist and three of them is described below:

Modularity in products

- A modular product consists of different blocks and sub-systems. The product is able to fulfil various functions depending on the different blocks. These blocs are the interchangeable with other blocks. For modular product it is important there is a common product architecture where the different blocks can be fitted. This combination allows a variety of products to be created upon the same base. The most well-known example of a modular product is a computer. The computer has a motherboard upon different modules can be changed such as the graphic card, hard drive, ram and so on. These changes can be done with little or no changes to the other modules.

Modularity in design problems

- Modularity in design problems can also be divided into "blocks" containing simpler sub-problems. These smaller sub-problems are then often easier to solve, but the solution to one sub-problem can often affect another sub-problem. These interconnections between different sub-problems are ideally reduced with modularity in design problems. Since the aim is to decompose the overall problem into independent subproblems, so the solution to a subproblem only may lead to minor modification in other subproblems

Modularity in production systems

- Modularity in production systems is the modularity in the manufacturing process. Over the past decades, a variety of different machinery has appeared in the production line also within modular machinery caused by the lack of standards. To create a proper modular production line, it is important to classify the machines into functional groups that can respond to different production requirements. In general, one can divide a modular production into four types of production modules. The four production modules are primitive production elements, motion units, modular fixtures and configurable control units.

The modularity of products and production systems are interconnected. Previously when the dominant automation was hard automation, it was costly to change the production line. The new robot arms allow better flexibility which properly are beneficial in the modular production line. So trough the improvements of automated assembly the benefits of modular design can be increased. Also, by the modular design, the product obtains a common product platform which means that less different parts need handling. To some extent modular design can fit with all the above-described design guidelines. Modular design allows for easy repair, maintenance and disassembly through the different blocks that can be interchanged with new blocks and at End-Of-Life the blocks can be separated.

When designing a modular product, it is important to create each of the blocks with respect to the desired functionality. How the different blocks should be designed can vary after which type of modular design that is implemented in the product. There are several ways to modulate a product, and two of these are described below:

The function structure heuristic methods

- Is based on sub-function blocks that are created by the decomposition of the function of the product. The interaction between the different blocks is then represented as material, energy and information flows. A different variation of this approach has appeared were consideration of assembly time and recyclability also is included. This model is not always suited for very complex products since human judgement is involved in the process.

Design structure matrix based methods

- Is the most commonly used method to facilitate a modular design. The method has an emphasis on the relationship between the different blocks. The relationship is established by the use of a matrix and clustering algorithms, and the blocks are thereby formed. The interaction between the different blocks can be numerous and can for example also include environmental concerns. Since this method are based on matrices, the human judgement is eliminated, and this method also applies well to computer programs.

Before applying a modular design to a product, it is important to investigate the market. The product might look a little different than the customer is expecting or the functionality is not on par with competing products. For an established company there is a risk of alienating existing customers, and this should be avoided by proper testing and screening of the market.

5 .2 Economic considerations

By applying modular design in products the company can potentially create high cost-savings but also apply some risks. The modular design has numerous of advantages, and many of these have their offset in the common product platform. When modular design is applied within a company, the manufacturing process can be simplified and consolidated. The aim of the modular design is among other to reduce the overall count part that the company procure. This decrease in variation of parts can result in the retirement of assembly lines since less unique parts needs handling. Furthermore, when more assembly lines handle the same module design a shared process can be implemented, and the production becomes more flexible and agile.

The decrease of different parts is also an advantage within the procurement. When fewer parts are needed the inventory management and stock keeping becomes simpler. Also, the range of suppliers can be reduced, and strategic relationships can be made. This translates into a better pricing of parts and overall better trade conditions. Besides the improvement, in production and procurement, the marketing and sales can also be improved. Even though the number of unique parts has decreased, it is possible to create a higher customization to a product at a lower price. The product is created to be changed which also is beneficial in at service and repair of the product and the better service also increase the customer loyalty a satisfaction. The modular design can also decrease the time to market since the production is more effective since some of the design are reusable.

The modular design can somehow “harvest” all the mentioned benefits of the different design guidelines in this idea catalogue. If more optimisation can be made throughout the entire life, it is possible to achieve a higher profit. The modular design is the keystone to ensemble the benefits from production, procurement, maintenance, repair, and End-Of-Life treatment. When profits are created by servicing the product, it also complies with the ideas of circular economy. The circular economy is described in Figure 13.

The disadvantages of modular design are very much connected to the benefits. The implementation of a new design often results in high initial investments and it can be a challenge to change the existing production. The procurement is also to some extent challenged when the suppliers are altered. New suppliers might not comply with the same standards and might cause delays in the beginning. Furthermore, the search for cost savings can reduce to focus on customer needs and lead to lower sales.

5.3 Environmental consideration

Depending on how the modules are created a variety of different environmental benefits can be accomplished and all the described benefits – of the other design guidelines – can also be mentioned here. Especially the consideration about lifetime and End-Of-Life can be improved by a modular design. When the lifetime of products is extended, and the materials are recycled with high efficiency the energy for extracting new resources are reduced. Then both CO_2 is avoided, and scarce resources are preserved.

When products have a prolonged lifetime they are kept in the “loop” which fits very well with the ideas of circular economy. The product can be kept functioning for many years while vital parts are updated. Discarded parts can then either be refurbished or recycled which is also the case of the remainder of the product when it is discarded. In this way, it is possible to create loops and

27 keep the product and material in circulation. The circular economy is

visually presented below:

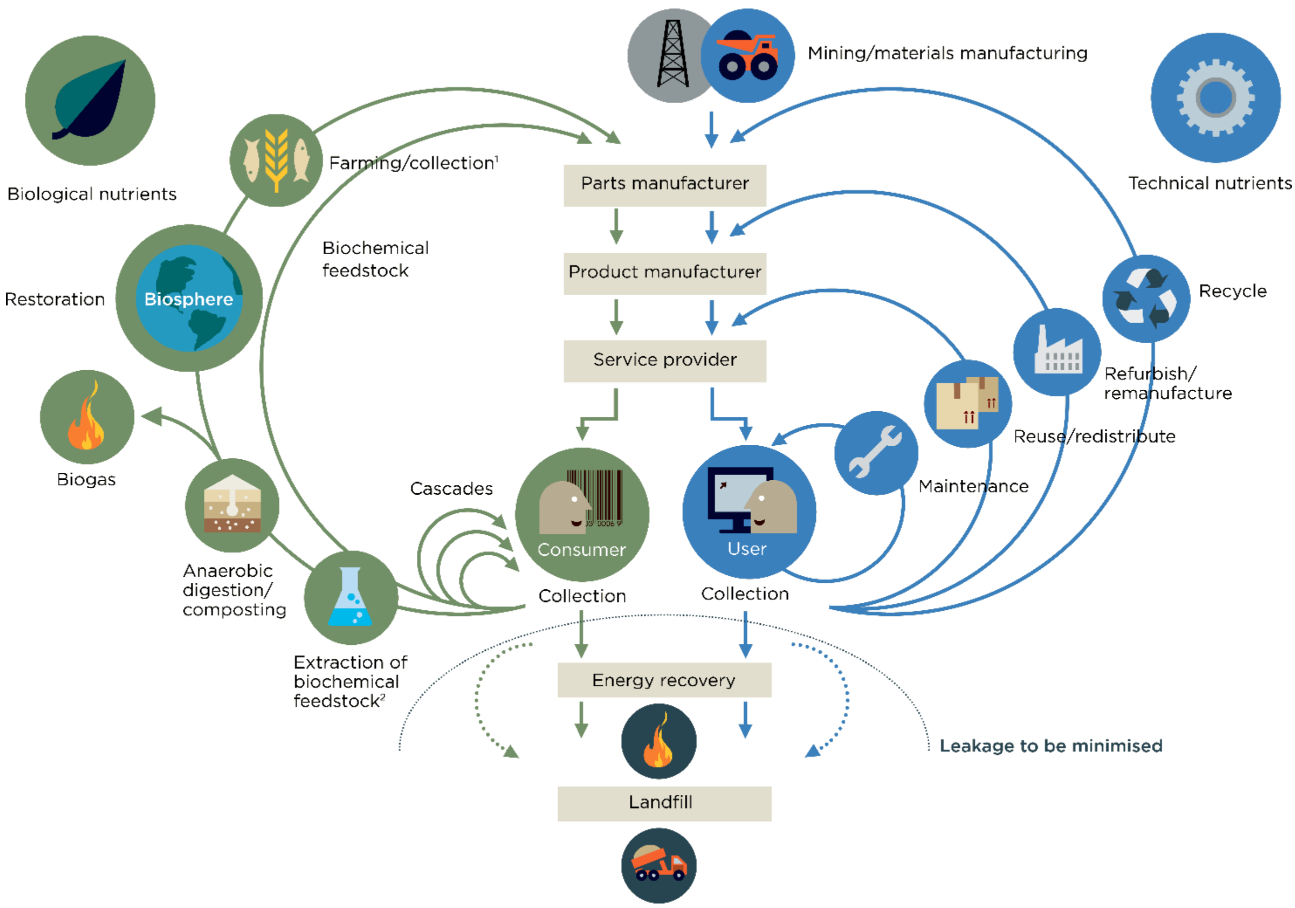

Figure 13: Visual presentation of circular economy (Ellen MacArthur Foundation 2013).

The circular economy has both biological nutrients and technical nutrients. The technical nutrients are all the classical made materials created from resources such as iron while biological nutrients are made of renewable resources. In this context, the focus is on technical nutrients which often a scarce. The modular design and circular economy can in this context keep the products and materials in the smaller loops for a longer time. Even at End-Of-Life, the modular design can prove to be more effective. The combination of circular economy and modular design can be an effective way to reduce the CO_2 emission from mining new resources and keeping the scare resources in circulation.

FINAL REMARKS

The assembly methods of products have a high impact on how the products perform according to the economic and the environmental performance. A proper design can both improve the profit of the company and reduce the environmental impact.

The assembly methods are generally a concern in the manufacturing stage, but the society is moving towards are more sustainable future where producers are more responsible for their products throughout the entire life of the product. This transition is in these years expressed as the growing interest of the circular economy, but the circular economy is challenging the established companies with a linear business model. This design guideline provides examples of how to change the assembly method according to ease of assembling, design for repair and maintenance, design for End-Of-Life, and design for modularity. The design for modularity has the potential to "harvest" the benefits of all the assembly methods mentioned above and work very well in a circular business model.

By changing the assembly method, the focus is often on cost saving. In a linear business model, these cost saving can be achieved especially in the manufacturing stage. The circular economy seeks to sell a service instead of products. If service of a product should be profitable, it is important to rethink the design and assembly method so the maintenance and repair of products can be profitable instead of an expense. Also, when products are discarded they still contain a lot of value. This value might be expressed as a resell value or scrap value that are out of reach if not the product is designed properly.

The environmental benefits of the circular economy are numerous. When products are kept in the loop for longer time energy is saved, and CO_2 emissions are avoided. It is though important to track the environmental performance of a new design. It is hard to quantify whether or not a new design is more environmental friendly is it is not properly assessed. For this assessment, it is suggested to perform a lifecycle assessment or a simple lifecycle assessment as described in this catalogue. The design guideline for dematerialisation and detoxification, repair and maintenance, design for End-Of-Life and design for modularity all have the potential to improve the environmental profile.

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