CHALMERS

# Guidelines and Design Strategies for Improved Product Recyclability

## - How to Increase the Recyclability of Consumer Electronics and Domestic Appliances through Product Design

*Master of Science Thesis in Industrial Ecology*

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*Division of Physical Resource Theory*
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2012
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## Table of Contents

## Acknowledgements

This report is the result of a Master thesis carried out as part of the Master's Programme in Industrial Ecology at Chalmers University of Technology in Gothenburg, Sweden. The goal of this thesis was to create an easy and user-friendly set of guidelines to support product engineers in designing better recyclable electronic products.

The project was carried out at the department of Sustainability at Philips Consumer Lifestyle in Amsterdam, the Netherlands.

A very special thank is given to my supervisor Eelco Smit; Senior Manager in Sustainability and Recycling expert at Philips; for his help, support and advice throughout the entire project. Thanks also to my supervisor Ulrika Lundqvist; division of Physical Resource Theory at Chalmers University of Technology in Gothenburg, Sweden; for helpful suggestions and discussions. Finally, thanks to my wonderful fiancé Frank for always being there and my family who have supported me in every way possible.

Rotterdam, October 2012

Natalie Hultgren

## Abstract

This master thesis has been carried out at Philips Electronics, a company producing electronic products in the sectors Lighting, Healthcare and Consumer Lifestyle. As a global company producing electronics, there is increased attention given to the problem of electronic waste (e-waste). Electronic products are often not designed with its end of life considered, and often contain hazardous substances and materials or material combinations that are difficult to separate. The purpose of this thesis has been to create guidelines and design strategies on recyclability to support engineers at Philips Consumer Lifestyle in designing products that are easier to recycle. This project is a step in Philips focus on sustainability and closing the materials loop, with the aim to contribute to solving the e-waste problem.

The methods used in this thesis included literature study, interviews, a survey and testing of products, resulting in a list of guidelines and design strategies on recyclability. The user-friendliness of the guidelines was given particular attention since a previous project on recyclability resulted in a very complex and time-consuming tool, which ended up not being used. Therefore the focus was set on making a tool or set of guidelines as user-friendly and concise as possible. Expertise in recycling should also not be required, which has been considered when formulating the content. An extensive list with advice on recyclability in product design was narrowed down by input from recycling companies and product testing to identify the most important points of advice. Ideas for implementation were discussed with engineers and architects.

The resulting tool is a set of 14 design strategies divided over four guidelines. The guidelines are stated below and each one contains a number of design strategies with specific advice in product design for recyclability.

- Guideline 1: Do not use hazardous substances
- Guideline 2: Enable easy access and removal of hazardous or polluting components
- Guideline 3: Use recyclable materials
- Guideline 4: Use material combinations and connections that allow liberation

The implementation at Philips is advised to be done stepwise, with awareness through presentations and workshops as the first two steps, followed by discussion in product teams and a final integration in the product development process.

Advice on recyclability can help engineers design products that are easier to recycle. This can in turn contribute to saving resources, energy and emissions as well as mitigate effects on human health and the environment. A recyclable product design does not by itself solve the problem with e-waste, but needs to be combined with efforts in collection systems, organization and improvements in the recycling process.

*Keywords: design strategy, e-waste, guideline, product design, recyclability*

# Terminology

*Guideline*

A guideline in this context is a set of design strategies for recyclability; for example "Use recyclable materials" or "Use material connections that allow liberation". In the guideline "Use recyclable materials" a design strategy is for example "Use common plastics" or "Do not use thermosets".

*Strategy*

A strategy is here referred to as a design strategy and defined as a practical approach on how to comply with a guideline. Examples of such practical strategies are "Do not use connections that enclose a material permanently" or "Do not use any PVC (Polyvinylchloride) in the product".

*Recyclability*

The term recyclability is here defined as the "recycling potential" of the product. It takes into account chemical content, which materials are used, how materials are combined and how components are connected. It includes materials that can be diverted from the waste stream and returned to use as a part or raw material for the manufacture of a new product. This should be possible to perform through a process that is widely available at present. It is in this case not measured as the percentage of recyclable materials used in a product, which sometimes occurs in other contexts.

*CRT glass*

A CRT (Cathode Ray Tube) is a vacuum tube holding an electron source or emitter and a fluorescent screen used to view images. For safety reasons, the front is usually made of thick lead glass. CRTs have largely been replaced with new display technologies such as LCD, plasma display, and OLED, which have lower production and distribution costs. CRT glass is difficult to recycle, due to its content of lead and phosphors. The US Environmental Protection Agency (EPA) includes discarded CRTs in its category of "hazardous household waste".

*LCDs*

An LCD (Liquid Crystal Display) is a type of display that uses the light modulating properties of liquid crystals (LCs). LCDs are used in many different applications such as computer monitors, televisions, instrument panels and various consumer electronics such as video players, gaming devices, clocks, watches, calculators, and telephones The LCDs have replaced cathode ray tube (CRT) displays in many applications.

*Engineering plastics*

The term engineering plastics refers to a group of plastic materials that possesses superior mechanical and thermal properties, compared to the more commonly used commodity plastics. Commodity plastics are for example Polystyrene (PS), Polyvinyl chloride (PVC), Polypropylene (PP) and Polyethylene (PE). Engineering plastics usually refers to thermoplastic materials (polymers that become mouldable at a certain temperature, and returns to a solid state when cooled) rather than thermosetting materials (polymers that harden irreversibly). Examples of engineering plastics are Acrylonitrile butadiene styrene (ABS), Polycarbonates (PC) and Polyamides (PA).

*Screening*

Mechanical screening consists of taking coarse ore material and separating it into multiple grades depending on particle size. It is performed in many industries, for example mining and mineral processing, agriculture, plastics and recycling.

*Magnetic separation*

Magnetic separation is a process in which magnetically prone materials are extracted from a mixed materials stream using a magnetic force. It is commonly used in mining technology and as a step in the recycling process.

*Eddy current separation*

In Eddy current separation, a powerful magnetic field is used to separate metals from non-metals in a material stream. Eddy current separation is mainly used for non-ferrous parts like copper and aluminium. A thin layer of mixed materials are transported on a conveyor belt, where the eddy current is applied. Eddy current separators can consist of either a rotating drum with permanent magnets, or make use of an electromagnet. At the end of the conveyor belt is an eddy current rotor, causing metals to be thrown off the belt, and non-metals to simply fall off the belt due to gravity.

*Density or gravity separation*

Gravity separation is an industrial method of separating two components. Gravity separation is used in many different industries, due to their cost effectiveness and in some cases excellent reduction. Gravity separation is attractive since it generally has low capital and operating costs, uses few chemicals that might cause environmental concerns and the recent development of new equipment improves the range of separations possible.

# 1 Introduction

## 1.1 Background

E-waste (electronics waste) has become an increasing environmental concern worldwide. It is the sector that grows fastest within the municipal waste stream and the content can be significantly hazardous (Naturvårdsverket, 2011). An increasing amount of initiatives are started to deal with the e-waste problem and its consequences on the environment and impacts on human health and safety. One example is the StEP (Solving the E-waste Problem) initiative which is a joint step of several UN organizations to unite industry, governments and NGO's to facilitate sustainable e-waste handling (StEP website, 2012). Another example is the GreenElec EU-project, which is aimed to accomplish a more efficient use of resources by designing and manufacturing electronics that enable more effective recycling. A central issue related to this thesis consists of planning for efficient recovery of materials by taking into account the end-of-life already in the electronics design (GreenElec, 2012).

As a result of the constant strains on the environment, companies are expected to contribute to managing the ecological issues caused by their products. To minimize the load on the environment while keeping our high living standards demands the progress of innovative technologies. With the goal to further utilize materials and components, recycling is an example of such a technology (Kriwet et al, 1995).

Extended Producer Responsibility (EPR) is a developing policy principle aiming to reduce environmental impact from the entire life cycle of a product or product system. It is based on the producer-pays principle, and a means for encouraging design and production of electrical and electronics equipment accounting for repair, upgrading, reuse, disassembly and recycling of products. In the early 1990's, a number of countries started to incorporate the concept of EPR, particularly in the form of take-back regulations (Tojo, 2008). One of the product groups where application of EPR principle has been implemented is electrical and electronic equipment (EEE). Following this, the Waste Electrical and Electronic Equipment (WEEE) Directive, (EU Directive 2002/96/EC) was published in 2003(EC, 2003). Producers are requested to finance the collection, treatment, recovery, and environmentally sound disposal of WEEE. The WEEE Directive aims for reduced waste quantities as well as the reuse and recycling of electronic waste. The aim is also to improve environmental performance of all the actors concerned during the products' life cycle and to reduce the amount of e-waste going to landfill (Naturvårdsverket, 2009).

In spite of increased awareness of e-waste issues, many electronic products are still designed with non-recyclable materials or constructed in ways that make them difficult to take apart. Tools on Life Cycle Assessment (LCA) are often used and can provide a very good overview on a product's impact on the environment, also divided over the different phases of a product, such as the raw material extraction, the use phase, etc. It can be used to gain valuable information about products and their key areas of improvement. However, an LCA does not provide any practical advice on how to improve a product's performance. It delivers a quantified result on environmental performance but without the advice on how a product can be improved. Philips is using LCA-tools such as SimaPro and EcoScan to measure the environmental performance of their products. However, the results of these LCAs do not vary a lot within the product categories. For example, an iron or a fryer continuously receives high environmental impact in the use phase, due to its heating elements. Therefore it is known that the most improvement for this product category can be reached in focussing on energy reduction. LCAs are therefore not providing enough new information to justify doing an LCA on every product, unless a new technology is designed (Smit, 2012).

There are many concepts with general guidelines on how to improve the environmental performance of products such as Design for Environment and Sustainability (DfES), Design for Disassembly (DfD) and Design for Recycling (DfR) (Graedel & Allenby, 2007). However, there is no tool that provides a set of detailed design strategies for engineers with practical advice focussing on recycling and closing the materials loop for consumer electronics (Smit, 2012). The existing guidelines in DfR can be described as an unstructured collection of many specific rules. Kriwet et al stated (1993) that the aim of researching the topic of DfR therefore should be to provide the designer with a set of guidelines that are simple, easy to apply and easy to evaluate. Preferred is also to form groups of advice and divide them in relation to design aspects.

The need for this research is illustrated by the fact that there is currently no tool in use that focuses on how to increase the "recyclability" – or recycling potential – of a product. What is missing is an easy, user-friendly tool on recyclability for engineers to use in the early design phase, where the opportunities to make changes is still present (Smit, 2012). Such a tool could support engineers in making better recyclable products, by integrating elements of materials selection, material combinations, product constructions, connections and chemical content influencing the recyclability. Important is that it can give engineers practical advice on improving the recyclability of products, to avoid causing problems in the recycling process.

### 1.1.1 Company description

Royal Philips Electronics is a global company with 122 000 employees worldwide and their headquarters located in Amsterdam. Philips states their mission as "improving people's lives through meaningful and sustainable innovation" and strives to be a global leader in the health and well-being sector (Philips, 2012a). Royal Philips Electronics consists of three sectors; Philips Lighting, Philips Healthcare and Philips Consumer Lifestyle. This thesis is focused on the products of Philips Consumer Lifestyle.

### 1.1.2 Sustainability at Philips

Philips states that they see environmental improvement as an opportunity for innovation, and is continuously working to minimize the impacts of products, processes and services (Philips EcoVision, 2012). Since 1994, Philips has implemented solid action programs with quantifiable targets to drive improvement. These programs focus on improving the environmental performance of Philips products as well as the company's everyday operations. A series of programs have been executed starting with the Philips Environmental Opportunity Program in 1994. In 1998 the first EcoVision program followed, which continued through 2001. In 2002, EcoVision II was launched and ran until 2005 followed by EcoVision III 2006-2009. EcoVision 4 started off in 2009 and was succeeded in 2010 by EcoVision 5 which also incorporated the social side of sustainability with a target for the amount of lives Philips aims to touch. EcoVision 5 focuses on global issues and trends, and broadens Philips' approach to sustainability beyond the environment to clearly reflect the company's Health and Well-being strategy.

As a part of their current sustainability program; EcoVision5; Philips has identified three sustainability key performance indicators (KPIs). These KPIs are 'energy efficiency', 'care' and 'materials' and Philips Consumer Lifestyle is specifically taking the lead in 'materials' (Philips, 2011). Philips wants to improve their environmental performance regarding materials and improve closing the materials loop by increasing the recyclability of their products. Their goal for 2015 is to double collection, recycling amounts and recycled materials in products, compared to 2009. Philips has also set a number of goals and 'end-points' that they work towards, which are (Eelco Smit, 2012);

- Our products and packaging will not let any energy and materials go to waste
- Our products and packaging will be fully fit for continuous recovery and reutilization
- Our products and packaging will be free of any substances that will harm people and the environment
- Our products will exceed the lifetime expectations of our customers
- Our products do not harm the global society in any way.

### 1.1.3 Project background

To increase the recyclability of their products, Philips wants to develop guidelines for engineers with a focus on how to make a product easier to recycle. These guidelines should be incorporated into a tool that can easily be used by designers in their daily work and provide an indication of how recyclable a product is.

As a step in this direction, a tool for improving the recycling potential of products was made in a previous Master's thesis on a Design For eXcellence (DFX) method (Peters, 2012). It resulted in an Excel-tool for product engineers to quantify the recyclability of a product. It was based on qualitative weighing factors and named the Product Recyclability Indicator tool (PRI-tool).

The PRI-tool was found useful in testing but there were several questions on the content of the tool and the assumptions behind the quantified score that a product was rewarded. For example, if a product complied with legislation such as RoHS and REACH, the product received half the score possible to obtain. There was also an overlap between several strategies. Philips own list of regulated substances; named the Philips Regulated Substances List (RSL); was also not considered. For the weighing factors applied, three recycling companies were asked for input, regarding which 'consequences' in the recycling process were most important to prevent. They all rated 'toxic waste' as most important, however, the main part of Philips electronic products do not result in a toxic waste stream. This input showed as the base for the weighing factors applied in the tool, which also made Philips question its accuracy (Eelco Smit, Senior Manager Sustainability). The design strategies with practical advice were also not tested or evaluated by recycling companies.

The fact that more than half of the design strategies in the PRI-tool (24 out of 42) contributed to only 15% of the total score possible to achieve, also did not contribute to the user-friendliness. There was no application of the Pareto principle, also referred to as "the 80/20 law" or "the law of the vital few and trivial many" (Juran, 1950). The Pareto principle states that roughly 80% of the effects come from 20% of the causes, emphasizing that by identifying the key causes it is often possible to be able to achieve about 80% of the effect. The application of this principle or another method to shorten the tool and focus on the strategies giving the most impact could likely have resulted in a shorter and more concise list of guidelines.

To summarize; the guideline on chemicals was rewarding points for basic mandatory legislation, with overlap in the content on chemical legislation by not considering substances already regulated by Philips RSL. Regarding the other guidelines; several of them were repeated and not clearly formulated, weighting factors were not objectively assigned, and the list of design strategies very long, making the tool both time-consuming and complex. These issues together resulted in the initiation of this project.

## 1.2 Purpose

This thesis is written with an intention to contribute to solving the enormous e-waste problem that is being acknowledged around the world. The purpose of this thesis is to support engineers in designing better recyclable electronic products, to make e-waste easier to recycle. This includes making them easier to disassemble, easier to process in the recycling process, selecting materials that are recyclable and to avoid certain chemicals and hazardous substances. It should focus on creating awareness among engineers and to emphasize how the design of a product influences its recyclability. The engineer should understand that a product that is designed now will come back as waste in a number of years, and then needs to be possible to recycle. The advice given should be clear, practical and specific enough for engineers to understand and apply in product design, without possessing expert knowledge in recycling.

### 1.2.1 Philips tool requirements

Discussions with Philips Sustainability department (Smit & van Veen, 2012) resulted in the shared view that the desired tool or guidelines on recyclability should focus on improving for the future. It should also include Philips company specific regulations, such as their focus on phasing out certain substances (Philips, 2012d). They should not; like the PRI-tool; award points for avoiding materials and substances that are already restricted by legislation. The aim of the tool is not to give a fully scientific and quantified result, since it has been agreed that a qualitative user-friendly tool that actually can be implemented is preferred above a scientific and time-consuming tool that is unlikely to be used. It is more important that the tool results in a number of comprehensive guidelines that increase the awareness among engineers, providing simple and practical strategies on design for recyclability.

To keep the tool as user-friendly as possible, the most important guidelines will be chosen and the less important ones will be left out. This will be done by conducting a survey where recyclers can provide input on what is most important. The tool should provide guidance towards where Philips wants to be in the coming years, and not necessarily towards the most ideal situation far ahead of where technologies and legislation are today. To take a stepwise approach towards better recyclable products is desired, to make implementation of the guidelines technically possible to achieve. This also means that guidelines require updating on a regular basis.

To summarize, the guidelines will not include basic legislation. The guidelines will also not include substances or materials that are already included in Philips Restricted Substances List (RSL). It will not include packaging policies (Directive 94/62/EC), since they fall under another category of legislation (EC, 1994). As mentioned above, it will focus on improving for the future. This means that it aims towards higher environmental performance (such as towards demands for the Green products, which is Philips line of environmentally better performing products) and towards preparing for future legislation. The concept of the tool is illustrated in Figure 1.

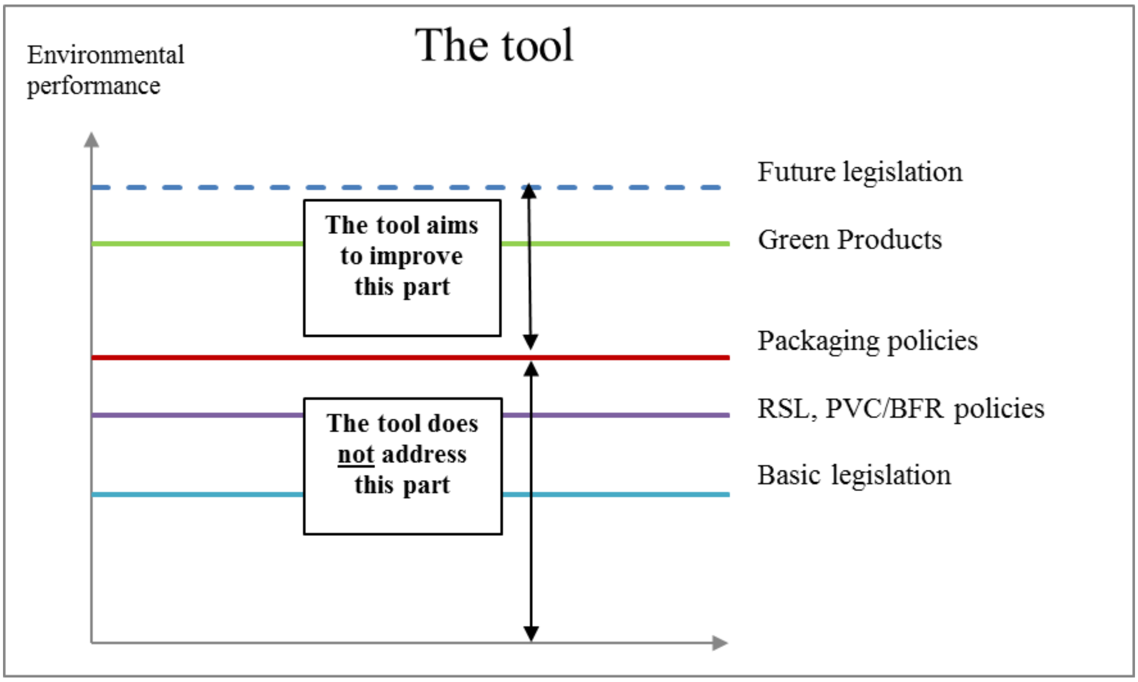


**Figure 1. Philips tool requirements (Smit & van Veen, 2012).**

A further purpose is to improve the content of electronic products by minimizing the use of hazardous substances, which is particularly important in case the product does not end up in controlled recycling (shredding). This is to mitigate the health risks involved in uncontrolled recycling in third world countries.

The main objectives of this thesis are

- To come up with a set of guidelines and practical design strategies for recyclability
- To select the most important guidelines and design strategies from this set based on expert input from recycling companies, with the aim to make the recycling of an electronic product as easy as possible based on state of the art recycling technologies
- To create a user-friendly tool for engineers with advice on how to increase a product's recyclability
- To give suggestions for practical implementation of a tool on recyclability at Philips

A tool in the context of this thesis does not necessarily need to involve a quantified outcome, but should be something that can be used as guidance to work according to.

## 1.3 Scope

The scope of this Master thesis has included several aspects, starting with the analysis of the PRI-tool since this thesis is continuing the research of that project. The PRI-tool was analysed in detail to conclude the need for further research and understand its limitations, and why it is not used at Philips today. A special focus was set on chemical legislation, since concerns regarding this part were expressed by Philips. To understand the topic of recycling, a literature review on related topics and previous work in this field was conducted.

### 1.3.1 Delimitations

The recycling markets that this thesis focuses on are the markets with mechanical treatment such as shredding, other markets (with potentially different) recycling technologies are not taken into account. However, the case that products end up being recycled on the streets in third world countries (uncontrolled recycling) have been considered from a health and safety point of view. The focus in this project is on design for recycling of small household electronics. For a list of examples of such products, see Appendix A. Other types of electronics are not taken into account.

A group of materials that were left out are rare earth metals. This decision was made based on the limited time of the project and that the issue of rare earth metals can be seen as more of a trade matter (Scheijgrond, 2012). This means that it is mainly a question about how willing countries are to trade and share their resources; it is thereby more a matter of trading than about the actual abundance of resources. The resources are present on earth, at least to a certain extent, but the questions are where they are present and if those countries wish to trade those resources with other countries.

This project focuses on the general content and design of guidelines for engineers; and software design or programming of a 'tool-interface' is not part of this project.

# 2 Method

To give an overview of the structure of this research, this section describes the method used in this thesis. The method starts with a literature review including an analysis of the PRI-tool. It then moves further to interviews with experts and the distribution of a survey of guidelines for experts and recycling companies. To obtain feedback from engineers, interviews are conducted followed by tool design and a final session with product testing together with engineers and interview with product architects. The method used in this thesis is illustrated in Figure 2.

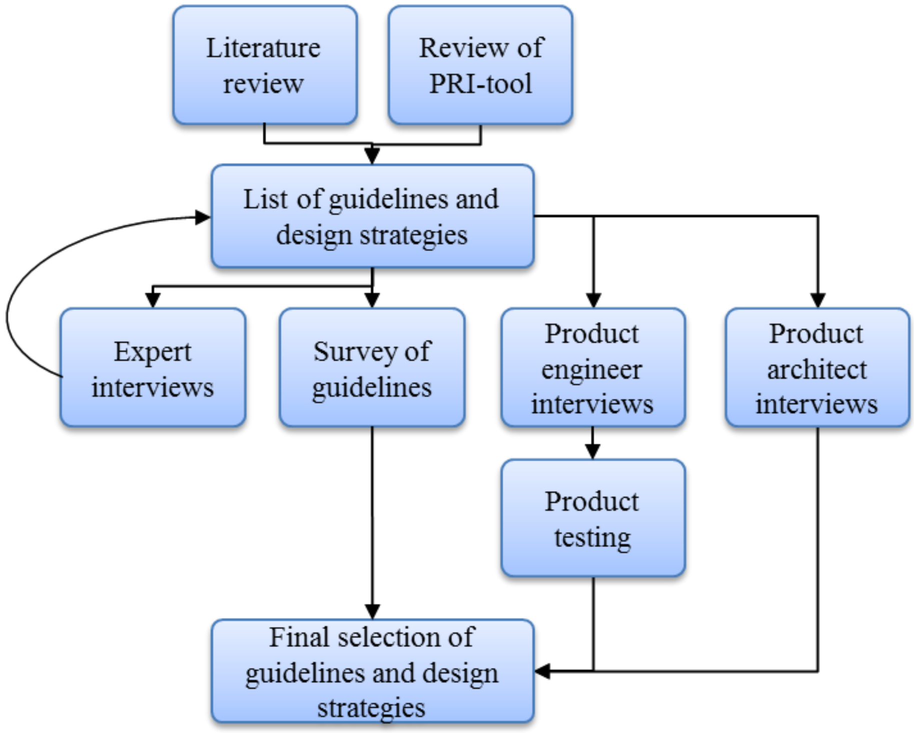


Figure 2. Flowchart of the method used in this thesis.

## 2.1 Literature review

As a starting point for creating a tool on recyclability, it is essential to provide an overview of the topic of recycling as well as topics closely related to e-waste. The method in this thesis therefore starts with a literature study on related topics, where previous work in the form of master theses, PhDs and other initiatives in the field are studied. A number of questions were developed as a starting point for what background information is relevant for this section. These questions are stated below and a literature review based on these questions is presented in the Literature review section.

- What policies exist for producers regarding environmental responsibility?
- What current legislation exists around electronics and substances used in products?
- Does Philips have any company specific regulations on top of basic legislation?
- How does electronics recycling work today and what are expected future developments?
- What materials and substances in electronics are problematic from a health, safety and environmental perspective?
- What are the benefits of recycling e-waste?
- Are there material combinations that should be avoided?
- How is the concept of Design for Recycling defined and how is it related to sustainability?
- What has been done in the field of recyclability and environmental tools at Philips?

- What tools for environmental performance are used at Philips today?
- What other initiatives are taken on a national or European level?
- How does the product development process work and where in this process could advice on recyclability be integrated?

## 2.2 Analysis of the PRI-tool

The analysis of the PRI-tool started with an interview with the previous student at Philips who created that tool. The purpose of this was to understand the concept of that tool, how it was programmed and what the choices of weighing factors and scores were based on.

With the chemical legislation found in the literature review, the guidelines and design strategies in the PRI-tool were then critically evaluated. The chemical content from the PRI-tool was compared to legislation such as REACH and RoHS and Philips Regulated Substances List (RSL), to find out which substances were already covered. The remaining advice on recyclability from the PRI-tool were then analysed and the advice considered relevant based on Philips tool requirements were added to the list of design strategies.

## 2.3 Interviews with experts

Following the literature study and the analysis of the PRI-tool, interviews with experts were carried out. The aim was to gain feedback on the recyclability guidelines that was found in the literature review and in the PRI-tool. The interviews were conducted with the purpose to check if experts agree with the guidelines found and if they have any suggestions for additions. The purpose was also to check if the content covers all aspects of product recyclability.

Interviews with 14 experts in the fields of e-waste and materials recycling, chemicals, sustainability and health and safety were conducted. The experts consisted of academic experts as well as business managers. The academic experts consisted of professors and researchers in the areas of materials, chemicals and recycling, and the business managers consisted of sustainability managers and directors. A list of experts interviewed can be found in Appendix B.

A study visit to a recycling company was also conducted to observe and understand the influence of product design on the dismantling of an electronic product. The purpose of this visit was to see how the first step in the recycling process is conducted to help visualizing the impact of how a product is designed in how easy or difficult it is to dismantle. See Appendix C for a detailed description of the study visit.

## 2.4 Survey

Based on the input achieved in the literature study and during interviews, a list of guidelines and design strategies for recyclability was put together. This list was used in the following step where a survey on the guidelines and design strategies for recyclability was conducted, to find out which advice is most important to increase the recyclability of electronic products. The purpose of the survey was to identify what advice is considered most important by recycling companies and experts based on the recycling process. The purpose of the survey was also to contribute to the user-friendliness of a tool on recyclability by narrowing down the collected list of design strategies. Some of these strategies have very likely more impact than others, and to avoid creating a tool that is too complex and time consuming, it is desired to keep it as clear and concise as possible.

### 2.4.1 Construction of survey

A survey was constructed with the content formulated as strategies or statements divided over four guidelines. The scale chosen for this Thesis was a Likert scale. Likert scales are commonly used to measure attitude, while providing a range of responses to a certain question or statement (Cohen et al, 2007). Five categories of response is the most common number of categories used. The respondent was in this survey requested to grade each strategy between 1 and 5 to indicate the level of importance.

To enable sorting out the most important ones and ensure that not all statements were given the same grade, a response limit was applied. This can be seen as a way to rank the statements in combination with applying the Likert scale. A restriction was therefore added to the survey in the form on an even distribution. The survey consisted of 39 strategies, which (rounded up to 40) meant an even distribution of 8 of each score. Each grade 1-5 could be given 8 times each, with the purpose of respondents only assigning high values to the statements that really are important. This is supported by the fact that the number of statements (strategies in this case) needs to be narrowed down, since it is not desired from a usability perspective to have a tool with 39 strategies to go through. Particularly since some of them are likely to have a bigger impact than others in product design. The desired end result is between 10-20 strategies, which is why this restriction was applied in agreement with Philips (Smit, 2012).

### 2.4.2 Distribution of survey

The survey was distributed by email to 12 recycling companies and experts in the field of electronics recycling. The survey received 10 responses, consisting of six recycling companies and four experts. The recycling companies participating in the survey were:

- **Stena Technoworld**, Gothenburg, Sweden. Sverker Sjölin, Taina Flink and Martin Alehem.
- **Sims Recycling Solutions**, Eindhoven, the Netherlands. Nick van Dijk.
- **Remondis Recycling**, Luenen, Germany. Sebastian Schormann.
- **Coolrec (Van Gansewinkel Group)**, Eindhoven, the Netherlands. Roel Verbrugge.
- **HKS Scrap Metals**, Amersfoort, the Netherlands. Alfred Jager.
- **Reclaimed Appliances UK**, Lincolnshire, United Kingdom. Robert Truscott.

The experts participating in the survey were:

- **Jaco Huisman**, Scientific Advisor at United Nations University Bonn- StEP, Director at OsevenfortytwO and Associate Professor at Delft University of Technology.
- **Feng Wang**, PhD student, Delft University of Technology; researcher at UNU Institute for Sustainability and Peace (UNU-ISP).
- **Ruud Balkenende**, Principal Research Scientist, Photonic Materials and Devices, Philips Research Eindhoven.
- **Ab Stevels,** Professor in Applied EcoDesign at Delft University of Technology, Delft. Worked with Eco-Design at Philips for many years.

The results from the survey were then analysed by calculating the average score that each strategy received. It was decided together with the sustainability department that a design strategy needs to have received an average score of 3 or higher in the survey to be selected as important. The ones close to this score, between 2,5 and 3 will be evaluated by product testing to ensure that no important ones are neglected.

## 2.5 Product testing

The same list of design strategies that was used in the survey was then tested on six of Philips products. The purpose with product testing was to see how Philips products perform on recyclability today, and also to determine if more design strategies than the ones with an average score of 3 should be included.

The list of guidelines was tested together with engineers from the departments of Coffee, Kitchen Appliances, Shavers and Garment Care at Philips in Drachten. The products tested are listed in Appendix G and consisted of two coffee machines, a kettle for boiling water, a shaver and two irons. The testing involved going through the list of design strategies to indicate whether each product currently can comply with them.

The result from the testing sessions was then used to make a final decision on if more design strategies than the ones with an average score of 3 should be included in a tool for recyclability. If more than half of the tested products (more than three out of six) could not comply with the design strategies that received a score between 2,5 and 3 today, those were included in the list as advice to improve for the future.

## 2.6 Interviews with engineers

Product engineers were then interviewed, regarding the content of the guidelines as well as possible ways to integrate them into their daily work. The purpose is also to receive feedback and comments on content and usability and ensure that the knowledge and work routines of the target group are understood.

The list of guidelines was then evaluated together with a group of engineers in a discussion session to understand what information they have access to regarding materials and chemicals. This is very important to be able to provide them with a comprehensive tool that is easy to use and understand. Four engineers in the Coffee and Floor Care (vacuum cleaners) departments participated in the session and two engineers were interviewed by phone. Questions discussed during these sessions were whether they currently use any environmental tools, what information they have access to and the different responsibilities within each department. User-friendliness was also discussed and how to possibly integrate the guidelines into their daily work.

## 2.7 Interviews with product architects

During the interviews conducted with engineers, as well as during discussion with Philips Sustainability Team, it was discovered that it was necessary to involve also the product architects in the development of a tool for recyclability. This was particularly necessary to understand where in the product development process such a tool could be used, and the product architects have the overall responsibility for the whole product structure and content which can help impact the recyclability of the product. Interviews with product architects thus served as the main method to reach the objective of how to practically implement the guidelines and design strategies. In these sessions, ways to incorporate the tool at Philips was discussed, as well as if and how a score on recyclability performance could be given for products.

# 3 Literature review

Based on the questions stated in the Method section, a literature study is presented below to provide necessary background information to be able to properly understand and analyse the subject. Previous work in the field of recyclability was reviewed. Topics such as extended producer responsibility, legislation, electronics recycling, health and safety, material combinations and their relevance to this thesis were described. Previous work at Philips was also reviewed as well as company specific regulations, other tools and initiatives and the product development process at Philips.

## 3.1 Extended Producer Responsibility (EPR)

Extended Producer Responsibility (EPR) has been defined by Lindhqvist (1992) as

"an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal of the product".

EPR aims to promote the integration of environmental costs associated with products throughout their life cycles into the market price of the products. The concept of EPR was first officially introduced in Sweden in 1990 by Thomas Lindhqvist in a report to the Swedish Ministry of the Environment. Producers are held responsible for the costs of end-of -life management of their products, and encouraged to design environmentally friendly products by means of financial incentives.

EPR is based on a number of recycling and waste management systems together with certain policies to encourage Cleaner Production. EPR suggests a shift in responsibilities, from consumers and waste management authorities to the producer of the products. The origin of this idea was raised by several persons involved with waste and recycling for a long time, together sharing the view that the previous method was not leading to environmental improvements (Lindhqvist, 2000).

Individual Producer Responsibility (IPR) is a further development of EPR that basically implies that each individual producer is responsible for the take back of their own brand's products. IPR is based on EPR but have taken it one step further by implying that the costs should be different for different companies, based on how well their products can be recycled. The costs for recycling products are according to EPR shared among companies, while if IPR was to be implemented, the products of each producer would have to be recycled separately. If a company makes products that are easy to recycle, they would be awarded with lower recycling costs.

Generally, it is more expensive to recycle poorly designed products, and in EPR the cost of this hits all producers collectively through increased shared costs. IPR is expected to be very difficult to practically implement, due to the high costs of separate collection and recycling. To recycle products separated by brand is more costly, needs more employees and is difficult to organize. IPR could help encourage producers to optimize their design for low cost recycling but such a program is at the moment incredibly complex to manage (IPR WEEE, 2012).

The concepts of both EPR and IPR shows the changing responsibilities for products and the fact that producers nowadays need to consider what they put on the market.

## 3.2 Review of existing legislation for electronic products

To give guidelines and design strategies on substances in products, current legislation needs to be described. This section highlights existing legislation for electronic products regarding electronic waste, chemicals and hazardous substances.

### 3.2.1 The Waste Electrical and Electronic Equipment (WEEE)

The Waste Electrical and Electronic Equipment (WEEE) Directive (EU Directive 2002/96/EC) is a European legislation that was adopted in 2003. It involves targets for collection, recycling and recovery for electrical products aimed to improve the situation with huge amounts of hazardous e-waste (EC, 2003). The main aim of this directive is to prevent waste electrical and electronic equipment (WEEE). Furthermore, it seeks to support the reuse, recycling and recovery of such wastes to minimize waste disposal (European Commission, 2002). The Directive is also focused on improving the environmental performance of all the actors involved in the lifecycle of electric and electronic products. Operators involved in the treatment of WEEE are of particular concern but producers, distributors and consumers are also included. It is based on that the "producer pays", and they are requested to finance collection, treatment and recovery of WEEE. The aim is to improve the performance of EEE products and reduce the amounts of e-waste going to landfill (Naturvårdsverket, 2011).

The WEEE Directive also sets targets for collection, recovery and recycling of electronics for the member countries of the European Union. The collection targets are currently at 4 kg per person but will increase as of 2016 to 45 tonnes of WEEE to be collected for every 100 tonnes put onto the market in the three coming years. In 2019 the targets will increase further to a rate of 65 tonnes of every 100 tonnes put on the market. Exact numbers of targets for different categories of WEEE can be found in Article 11, Directive 2012/19/EU (EC, 2012).

### 3.2.2 REACH

REACH is an EU legislation that came into force on 1 June 2007 and stands for the Registration, Evaluation, Authorisation and Restriction of Chemicals. It is aimed to improve the protection of the environment and human health from chemical risks (ECHA, 2012a). REACH applies to chemical substances in industrial processes as well as chemicals encountered in our daily life. Chemicals can be found in a wide range of products such as paints, detergents, clothes and electrical appliances. REACH therefore involves most companies in the EU, and to comply with regulation a company need to identify and manage the risks related to substances they produce and put on the market. REACH includes an extensive list of substances that are regulated or restricted for use, and companies are required to register their compliance and use of these substances. Companies have to show to ECHA that the substance can be safely handled and clearly indicate the risks involved to the users. The responsibility is put on the companies, and if the risks cannot be managed authorities can restrict its use in various ways. The long-term goal is to substitute dangerous substances with less hazardous ones (ECHA, 2012a).

#### *3.2.2.1 SVHCs*

Substances of Very High Concern (SVHCs) are listed by the European Chemicals Agency (ECHA) and can be identified as substances that may have serious and often irreversible effects on human health and the environment. The list of SVHCs is also sometimes referred to as the 'Candidate list'; since it contains substances that are candidates to become regulated in REACH. They are thereby candidates to end up being included among substances covered in the REACH legislation. ECHA aims at ensuring that the risks resulting from the use of SVHCs are controlled and that the substances are replaced where possible (ECHAb, 2012). The first step in controlling these risks is to identify substances that may have serious effects on human health or the environment. A substance can be proposed as an SVHC by an EU member state or by the European Commission. If the substance is acknowledged as a SVCH, it is added to the list of SVHCs by the ECHA.

When a substance is added to the SVHC list, legal obligations are created for companies that are manufacturing, importing or using such substances. The idea with publicly suggesting a substance as an SVHC before submitting a proposal is to give information in advance to industry and other stakeholders (ECHAc, 2012).

#### *3.2.2.2 CARACAL*

CARACAL (Competent Authorities for REACH and Classification, Labelling and Packaging) is an expert group which advises the European Commission and ECHA on questions related to REACH and CLP (Classification, Labelling and Packaging). The 'CARACAL list' is a list of substances that in time are expected to meet the criteria of Substances of Very High Concern (SVHCs) as defined above. Substances on this list are not yet restricted, but the list provides a good indication of possible substances for future restriction (SinList, 2012). The difference between the CARACAL list and the SVHCs is that substances on the CARACAL list are candidates for addition to the list of SVCHs, while SVHCs in turn are candidates for ending up being regulated in REACH.

### 3.2.3 RoHS

The RoHS Directive (Restriction of Hazardous Substances) in electrical and electronic equipment was adopted by the EU in February 2003. The use of six hazardous materials is restricted in the manufacture of different types of electrical and electronic equipment (EC 2002). The restricted substances consist of four heavy metals and two flame-retardants; Lead (Pb), Mercury (Hg), Cadmium (Cd), Hexavalent chromium (Cr6+), Polybrominated biphenyls (PBB) and Polybrominated diphenyl ether (PBDE). The RoHS Directive is closely related to the WEEE Directive on Waste Electrical and Electronic Equipment. It aims to implement cleaner production and thereby controlling the environmental impact of Electrical and Electronic Equipment (EEE). RoHS makes sure that mercury, lead, cadmium, hexavalent chromium and brominated flame retardants PBB and PBDEs are not present in new EEE (Naturvårdsverket, 2011).

## 3.3 Company specific regulations, Philips RSL

Philips Regulated Substances List (RSL) contains a list of substances including those:

- Banned by law or by Philips
- Whose use requires monitoring due to regulatory demands
- Whose use Philips due to the precautionary principle wants to monitor or restrict

All suppliers at Philips are required to comply with the RSL. To ensure the RSL includes the same substances as BOMcheck the RSL is regularly updated. BOMcheck stands for "Bill Of Materials" check and is an industry platform developed to standardize the way companies collect chemical composition information from suppliers. Despite the fact that there is no regulation on certain substances yet, the RSL contains a number of substances that Philips wants to phase out based on precautionary principles (Philips RSL, 2012). The precautionary principle was adopted by the UN Conference on Environment and Development in Rio de Janeiro in 1992, and states that

"in order to protect the environment, a precautionary approach should be widely applied, meaning that where there are threats of serious or irreversible damage to the environment and/or health, lack of full scientific certainty should not be used as a reason for postponing cost-effective preventive measures" (Philips, 2012b).

To simplify, Philips philosophy is that “prevention is better than cure” which that is the reason for including substances in their own regulation (RSL) that is not yet restricted.

## 3.4 Electronics recycling

The most common form of electronics recycling in Europe is shredding, often in combination with a first dismantling step. To recycle products in organized facilities as commonly done in Europe is referred to as ‘controlled’ recycling. ‘Uncontrolled’ recycling refers to products being recycled and processed with poor methods and no safety equipment on the streets in developing countries. This section treats controlled e-waste recycling, which is illustrated in Figure 3. In controlled e-waste recycling, usually two types of facilities are necessary. E-waste is first dismantled and mechanically processed (shredded) in one facility, called a *pre-processor*. The e-waste is there prepared for further recovery in a second facility, called an *end-processor*. The end processor for metals is called a smelter and for plastics a polymer recovery facility.

### 3.4.1 Pre-processor

The first step at the pre-processor is usually manual dismantling to take out certain parts or components. When recycling e-waste, dismantling is an essential process to enable reuse of components and the crucial removal of hazardous components. It is also common to dismantle highly valuable components and materials such as printed circuit boards (PCBs), cables, batteries, cathode ray tube (CRT) glass, liquid crystal displays (LCDs) and engineering plastics to make the following recovery steps of materials simpler (Cui & Forssberg, 2003). These components or materials can be reusable, valuable or hazardous and therefore sometimes also in need of special treatment.

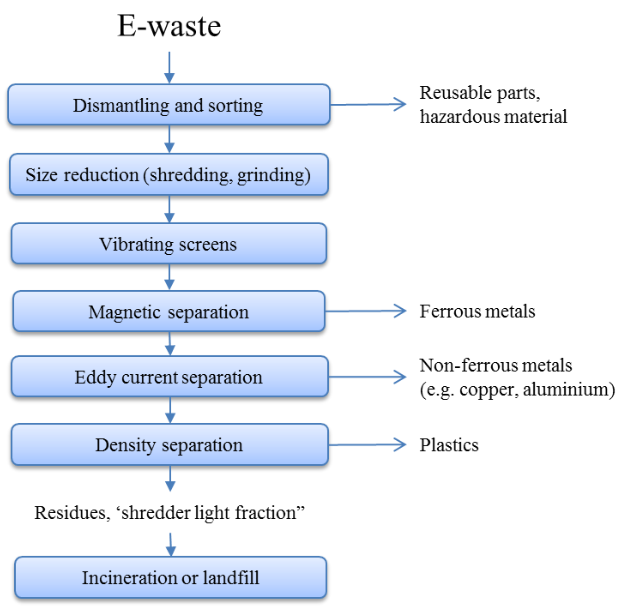


**Figure 3. The controlled e-waste recycling process (Cui & Forssberg, 2003).**

#### *The shredding process*

The second step at the pre-processor involves a shredding or crushing stage to break the product open. This allows for further separation and the smaller parts are sorted into output fractions depending on their weight, density, size, shape, electrical and magnetic properties. Common processes for these types of separation are screening, magnetic separation, eddy current separation, density or gravity separation. Magnetic separation is used for ferrous parts, eddy current separation for non-ferrous parts like copper and aluminium, density or gravity separation for plastics by floating media, water or airflow tables. In addition to this, manual or optical techniques may also be used (Naturvårdsverket, 2011).

Following further size reduction steps or screening, the final output streams from the pre-processor consists of whole components (such as PCBs, motors), a fraction of magnetic material, aluminium, copper and various plastics. This is sent on to a smelter for further processing. The generated waste fraction is referred to as “the shredder light fraction” and usually consists of plastics, glass wood and rubber. This is sent on to incineration, landfilling or for further processing.

### 3.4.2 End-processor

#### *Smelter*

After being manually and mechanically processed at the pre-processor, further upgrading of metals is made by metallurgical processes in a smelter. Metal fractions are refined by pyro-metallurgical processes (metal is melted) and hydro-metallurgical processes (metal is dissolved). In the last two decades, pyro-metallurgical refining together with electrolytic refining has become the most common method to recover non-ferrous; often valuable; metals from e-waste (Naturvårdsverket, 2011).

The general metallurgical industry can carry out this process, with the e-waste scrap as a small part of their input. A few industries are also processing large amounts of e-waste; these are referred to as “integrated smelters”. The integrated smelters can process many different kinds of materials containing copper and have metallurgical and chemical elements designed to function together. Boliden in Sweden, Umicore in Belgium, Noranda in Canada, Norddeutsche Affinerie AG in Germany and Dowa Eco-System in Japan are all examples of integrated smelters (IGES, 2009).

#### *Polymer recovery facility*

Following metals, the plastics contained in e-waste have the largest potential recycling value (Kang & Schoenung 2005). Despite this, very small fractions of the plastics collected are actually being recycled. Reasons for this is that plastics are complex materials, made up of multiple polymers and additives making the recycling process very complicated (Schlummer et al 2007). Before the plastics can be turned into new products, the various qualities need to be separated and unrecyclable fractions have to be removed before the recyclable plastics can be turned into new products. The plastics are separated by techniques such as sieving, density separation by density, air or electrostatics, combined with size reduction steps, such as grinding, milling and granulation (Kang & Schoenung 2005). Further grinding and washing is then conducted to remove paint and coatings. Other foreign materials are removed by magnetic separation and eddy-current separation, just as for general e-waste. The plastic that is recyclable are then melted, moulded and extruded into new products.

However, a large part of the plastics in e-waste are not recycled into new plastics but incinerated with energy recovery or simply landfilled. A substantial amount is also accompanying the metal fraction to the smelter where it is burned, thereby replacing some of the coke used.

For electronics plastics that cannot be recycled since they contain higher levels than allowed of restricted substances, the options are either landfill, incineration, or the use of ”chemical recycling”. In chemical recycling, restricted substances are removed. The landfill and incineration options are widely available, but the ability of chemical recycling to remove restricted flame retardants is still only on a pilot level. In the case of landfilling, flame retardant such as PBDEs, have been shown to leak into the environment. PBDEs in water can in sunlight be converted into brominated dioxins, which are highly toxic (ChemSec, 2012).

The European RoHS Directive states that only plastics with less than 1000 ppm of a group of flame retardants called Polybrominated Diphenyl Ethers (PBDEs), is allowed to be reused in electronics. An example of a company that recycles plastics from electronics is MBA Polymers. The company opened in 2005 the largest plant in the world for recycling plastics from electronics in Guangzhou, China. The company is able to meet the RoHS requirements by sorting out the plastics with bromine additives, by using technologies such as x-ray fluorescence (XRF) for identifying the bromine. MBA Polymer estimates that about 25-30 % by weight of the e-waste generated each year consists of plastics. Currently, less than 10 % of this plastic is being recycled (ChemSec, 2012).

### 3.4.3 Future developments in recycling technologies

For the coming 5-10 years; which can be estimated as the average time before a consumer product from Philips comes back for recycling; shredding is still expected to remain the main recycling processing technology in Europe. For the future, it is however likely that the amount of pre-sorting will increase, as will the materials price. Valuable parts will be taken out in manual dismantling to a further extent and there will be more plastic separation. This illustrates the importance of making products that are easy to take apart as well as considering how they are constructed and which materials are used. Technologies in material screening; where parts are being scanned to determined which material they consist of; are likely to develop where it is possible to distinguish materials based on their material structures on a molecular level. Markings with radio frequency identification (RFID) use a wireless system with a tag attached to an object and radio-frequency electromagnetic fields for automatic data identification and tracking. These or similar technologies are also a possible development, as well as more declarations on products. Marking on whether products contain hazardous substances as well as what types of metals or plastics the product contains, can also be expected to become more common (Smit, 2012).

More and more chemicals will also be restricted in the future, showing the importance of considering today what is put in products. Products that come back for recycling in 10 years will not be recycled if they contain concentrations of substances above certain limits. New health reports are continuously showing concerns for new substances, and attention is also given to the issues of illegal export of e-waste and the health and environmental issues it causes in third world countries. For the future it is important to take into account these substances already today, since it takes several years before a product comes back for recycling (Sivonen, 2012).

An additional aspect is the rare earth metals, which are not covered in this thesis, but probably will be recycled more in the future. To mention the subject briefly, the rare earth metals are fairly abundant all over the world but the capacity for extraction is mainly concentrated to China. China has the option to trade but has chosen to limit their exports since there is a value increase of the extracted metals in the countries they export to. By limiting their export, industry in other countries are threatened. The problem is therefore more related to politics, trading and extraction capacity, than the actual abundance of the rare earth metals on earth. The need for recycling of these metals is mainly for the short term, until other countries have reached higher extraction capacities. This can however take quite some time to achieve. These metals are also sometimes used in technologies that can contribute to a sustainable society in energy and transportation, such as technologies for sun and wind energy and electric cars.

Important to consider is that recycling of the rare earth metals is however far better for the environment than to extract them in the form of new raw material (Ljunggren Söderman, 2012). It avoids large amounts of waste associated with the mining of these metals, and saves both emissions and energy. It is up to Philips to decide if they should give particular attention to the rare earths in the future, but for now they are not taken into account. Philips also needs to consider whether the short term risk of not being able to access certain materials is a problem for Philips products.

### 3.4.4 Benefits of recycling e-waste

There are a number of benefits of recycling e-waste in society, involving for example resource recovery, energy savings and pollution avoidance. To highlight the various benefits of e-waste recycling, the most significant ones are described below.

#### *Resource recovery*

To recycle raw materials from end-of-life electronics in a controlled way is an important step to help mitigate the growing e-waste problem. If e-waste is recycled, it does not necessarily need to be seen as a burden but can instead become a potential for resources. It can be utilized as 'a mine above ground' that preferably not should be wasted. This is particularly important for regions like Europe where after many years of mining natural resources have been largely exploited. A large part of e-waste coming from Europe and North America is exported, often illegally, to Asia. The recycling operations performed there are highly primitive, lacking safety measures and often result in low yields with a lot of material being discarded. Next to terrible impacts on the environment and health in such regions, it is an enormous waste of resources (Hagelüken, 2006).

Electronic devices generally contain a wide variety of highly engineered materials that are made from valuable resources such as metals, plastics, and glass. Reusing and recycling consumer electronics conserves our natural resources that are used when manufacturing virgin materials. The recycled materials can then be used in new products and resources can thereby be saved by extracting fewer raw materials from the earth. This also includes less waste from the extraction processes of raw materials.

#### *Energy savings*

Recycling of materials from e-waste can also contribute to large energy savings, compared to the energy needed for producing entirely new materials. Recycling thus reduces the amount of energy needed in the manufacturing of virgin materials in new products (eWaste Center, 2010). As an example of potential savings, the production of 1 kg aluminium by recycling uses only 10% or less of the energy required for primary production. It has also been concluded that it costs more energy to manufacture one new aluminium can than it does to recycle 20 old aluminium cans (Arms, 2010).

#### *Pollution avoidance*

Pollution of the environment due to e-waste is generally caused by the hazardous substances often found in these products, and the emissions related to the manufacturing of materials and pollution in the form of waste from mining operations. Recycling of e-waste can help prevent the negative effects on the environment and people's health by avoiding hazardous disposal and stimulate safe management of toxic chemicals such as lead and mercury. It can also reduce emissions and avoid large amounts of waste associated with primary production.

The content of hazardous components in electrical and electronic equipment (EEE) is a major concern during the waste management phase, and recycling of EEE is not carried out to a sufficient extent

(WEEE Recast, 2012). Despite how safe and efficient landfills are claimed to be, there is always a risk of dangerous chemicals and heavy metals in the solid waste contaminating the ground water.

After the WEEE Directive came into force in 2003, hazardous substances contained in new EEE have been effectively reduced. Due to that products with hazardous substances are still in use, substances such as mercury, cadmium, lead, hexavalent chromium, polychlorinated biphenyls and ozone-depleting substances will still be present in e-waste for many years. The content of hazardous components in EEE is a major concern during the waste management phase, and due to these hazardous substances, it is very important that they are properly recycled.

Primary metal production often involves a significant environmental impact, particularly for precious and special metals which are mined from ores with low concentration of these metals. Large land areas are used for mining, waste water and sulphur dioxide ($SO_2$) is created and the energy use as well as $CO_2$ emissions are large. To recover metals from current recycling processes generates only a small part of these $CO_2$ emissions and also has significant benefits compared to mining in terms of land use and hazardous emissions. To give an example, the recycling of 1 kg aluminium prevents the residue of 1.3 kg of bauxite, the emissions of 2 kg $CO_2$ and 0.011 kg of $SO_2$ (StEP, 2009). Further, it also prevents the emissions linked to the production of the alloying elements used in aluminium.

### *Other benefits*

There are also several indirect benefits of conducting recycling. Communities can for example enjoy financial benefits by recycling in terms of reduced costs of waste management, garbage collection, and landfilling. Recycling can also be said to build community, since in society there is an emerging concern for recycling and the environment. People are working together to help promote recycling in local recycling programs, lobbies, and recycling organizations. Recycling also creates jobs for professional recycling companies including new markets for components that are dismantled (KDHE, 2012).

## 3.5 Health and safety aspects of electronics recycling

To avoid serious effects on human health and the environment caused by hazardous substances, it is essential to ensure that e-waste is properly taken care of. This needs to be done throughout the entire chain, from collection and handling to recycling and disposal. It also requires action in related areas such as research and development, information systems and regulations (Norden, 2008). To achieve a future reduction of the risks involved with e-waste treatment requires production of cleaner products, with less hazardous content. This also preferably needs to be combined with efforts in reducing the quantities of e-waste.

Information about hazardous substances in products is also vital to ensure that health and safety aspects are properly considered. Currently, there is for example no world-wide management system for information on substances in articles. This has consequences in decision-making of a number of actors, such as product designers, manufacturers, consumers, recyclers and regulators regarding decisions on substances in articles. A standardized global information system for substances in articles could support all actors in the supply chain in making better decisions from a health and safety point of view. Relevant information is an essential starting point for the protection of workers, the environment, and public health. If sufficient information is missing, correct risk management measures cannot be put in place.

The sections below describe problematic substances and what health and environmental risks electronic products pose, depending on whether they end up in controlled or uncontrolled recycling. Controlled recycling refers to products recycled in a facility with adequate safety measures and risk management, as is mainly done in developed countries. Uncontrolled recycling refers to recycling done on the streets in developing countries, without protection and safety equipment. It illustrates the variety of substances that are present in electronics and the importance to avoid that those substances end up in the environment.

### 3.5.1 Problematic substances in consumer electronics

Electronic components have been shown to contain numerous metals, metal oxides and polymers (KemI, 2012). Many of these are hazardous substances that may be released either during the use phase or during the handling and processing of a discarded product. The risks involved with hazardous substances for humans and the environment vary depending on the substance and how the waste is processed (Naturvårdsverket, 2011). E-waste also usually contains quite a few valuable components, for example precious metals and a number of plastics that can be profitable to extract during the end-of-life treatment processes.

The components usually found in electrical and electronic equipment that contain the highest amounts of hazardous substances are listed below (IGES, 2009). The adoption of RoHS will however have reduced these levels significantly in new products since it came into force in 2003.

- Mercury-containing components (gas discharge lamps, relays and switches)
- Batteries containing cadmium, lead, lithium, and mercury
- Printed circuit boards (PCBs) containing lead (in solder), antimony (in solder), beryllium (in connectors), cadmium (in contacts and switches), brominated flame retardants (in plastics)
- Cathode ray tubes (CRTs) containing antimony (in CRT glass), lead (in CRT glass), barium (in getter of electron gun) and phosphors composed of cadmium, zinc and rare earth metals
- Liquid crystal displays (LCDs)
- Plastics containing brominated flame retardants (BFRs, in various plastic parts) and plastics made of polyvinylchloride (PVC, in wire insulation)

The substances that are particularly problematic include a number of organic as well as inorganic compounds. Among the organic compounds, various brominated flame retardants and brominated or chlorinated dioxins are mentioned. Other substances of concern are brominated and chlorinated benzenes and phenols, polychlorinated biphenyls and naphthalenes (PCNs), polycyclic aromatic hydrocarbons (PAHs), nonylphenol, organophosphorus flame retardants, phthalate esters and freons. Among the inorganic compounds, substances to mention are antimony, arsenic, asbestos, barium, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, tin, yttrium, and zinc. A few of these are of concern due to toxicity and others since they are highly abundant in e-waste. Other chemicals present in e-waste that may be of concern are liquid crystals from liquid crystal displays (LCDs), toner dust from toner cartridges and nanoparticles from various products (Naturvårdsverket, 2011).

### 3.5.2 Risks in controlled recycling

To minimize the risks involved with hazardous substances in products, controlled recycling is to prefer over uncontrolled recycling, incineration or landfilling. Risks will however be present in all circumstances, since electronic products contain a mixed amount of compounds.

Controlled recycling generally poses lower risks both for the recycling workers, the local residents, and for the environment, since protective equipment is used and the risks are usually well managed. There are however risks involved with these activities as well. For the workers, the largest risk is dust exposal in dismantling, shredding and separation of the e-waste, and in the succeeding pyro-metallurgical processes (melting of metals). Exposure to volatile compounds such as mercury is also a risk for workers. The environmental risk is largest in the pyro-metallurgical processes and other high temperature operations such as incineration or plastic recycling processes. Chlorinated and brominated compounds as well as metals may then be emitted. It should be possible to limit these emissions by optimizing processes and treatment systems, but data shows that this is unfortunately not always achieved. Some sites are doing this very well under control, while high emission levels are sometimes found near other recycling sites (Naturvårdsverket, 2011).

### 3.5.3 Risks in uncontrolled recycling

The highest health and environmental risks regarding recycling of e-waste occur in uncontrolled recycling. This often takes place in developing countries where very simple methods are used. Two examples are manual disassembly and sorting together with heating and acid leaching of printed circuit boards (PCBs). Shredding, melting and extrusion of plastics, open burning of plastic coated wires and other components and collection of toners from toner cartridge are examples of other methods. These operations are very hazardous since they are carried out on the ground in the open air or in badly ventilated studios, without any personal protection for the workers. The environment as well as the inhabitants in such areas may therefore be highly exposed to the emissions generated, particularly via dust, fumes and smoke. This can have disastrous effects on the health of the local people as well as the local environment they live in.

The compounds of most concerns vary depending on material and methods used. However; lead, dioxins (chlorinated and brominated) and poly-brominated diphenyl ethers (PBDEs); seem particularly problematic. These compounds are highly toxic and sometimes emitted in large amounts during uncontrolled e-waste recycling. Lead and PBDEs due to that they are highly present in e-waste and dioxins since the formation conditions many times are perfect for it to form in the processes used. These have also been connected to various negative health effects observed among the people in these areas. There are significant indications that the emissions from uncontrolled e-waste recycling are increasing the local as well as the global pollution (Naturvårdsverket, 2011).

### 3.5.4 Risks in incineration and landfill

Risks also arise when e-waste is incinerated as general municipal solid waste. Numerous hazardous compounds may be released to the atmosphere via smoke and exhaust gases, both in the form of gases and bound to particles. These compounds may be those that were initially present, but more probably they are compounds that formed during the incineration processes. Since e-waste is a complex fuel, it can work as a precursor for various compounds in thermal processes. The conditions for dioxin formation are often ideal when e-waste is incinerated, which is caused by the abundance of polyvinyl chloride (PVC) plastics and brominated flame retardants (BFRs). Metals like copper and antimony can also help as catalysts in these reactions. In controlled incineration, which is done in facilities with emission control, these emissions may be minimized by process optimization and proper systems for treatment of flue gases and ashes (Naturvårdsverket, 2011).

However, when e-waste is openly burned as occurs in many developing countries, the emissions can be substantial. On top of dioxins, various other pollutants are released in large quantities. Examples of this are PAHs, chlorinated and brominated compounds, lead, copper, antimony, zinc, tin, arsenic, nickel, chromium, cadmium, barium and beryllium. Except from the atmospheric emissions, hazardous substances can also leak from the residual ashes to the ground and into the surroundings.

An environmental risk involved with e-waste in landfills, is that hazardous substances can start to leak to the surrounding environments. This often includes groundwater reservoirs and nearby surface water as well as evaporation into the atmosphere. Most substances start to leak eventually due to the long times spent in for example landfill. The leaking of some substances are however extra severe, for example the leakage of lead and certain other metals, as well as additives from plastics.

## 3.6 Initiatives in resource use and e-waste handling on a European level

### 3.6.1 GreenElec

GreenElec stands for Green Electronics and is an EU-project aimed to accomplish a more efficient use of resources by designing and manufacturing electronics that enable more effective recycling. A central issue related to this thesis consists of planning for efficient recovery of materials by taking into account the end-of-life already in the electronics design (GreenElec, 2012). This project is performed in the form of a PhD study and started in June 2012 at Delft University of Technology, the Netherlands. This study is very closely related to the topic of this thesis but will include an extensive research that just started, therefore it is not yet a result but meant to illustrate that initiatives are taken on EU level to emphasize the need for research in this area. Philips is taking part in this project and information on the findings of this thesis will be communicated to the PhD student at TU Delft.

### 3.6.2 StEP

The StEP (Solving the E-waste Problem) initiative is a joint step of several UN organizations to unite industry, governments and NGO's to facilitate sustainable e-waste handling. 'Recycling' and 'Redesign for better recyclability' are two of the five focal areas in this initiative which are closely related to this thesis (StEP, 2012). It is not a method or tool but an initiative to unite the actors in industry and government among others to improve the ways that e-waste are handled.

The main goals of the initiative are to standardize recycling processes globally to yield valuable components in e-waste and extend the life of products and markets for their reuse. It is also aimed to synchronize worldwide legislation and policy approaches to e-waste (Philips, 2012c).

## 3.7 Tools for environmental performance

The tools SimaPro and EcoScan are used at Philips to research and quantify environmental performance of their products.

### 3.7.1 SimaPro

SimaPro is a tool for LCA (Life Cycle Assessment) used to quantify the environmental impact of a product during its lifecycle. It takes into account all stages of the products life cycle. Transportation, production and use of raw material are also included, giving a very broad analysis of the environmental performance. SimaPro is used after a product is produced, to analyse the product's environmental impact in numbers. It is a time-intensive tool with hundreds of parameters that need to be filled in, and at Philips it is only used by experts and researchers. This tool requires a lot of knowledge, time and access to large amounts of specific data about production processes, raw material extraction and energy use (Aarts-Hornix, 2012). It is not a tool used by the product engineers and it does not provide any design advice other than quantified performance in a number of categories.

### 3.7.2 EcoScan

EcoScan is another tool used to quantify environmental performance which is based on SimaPro (see above). It is basically a simplified version of SimaPro, implying a slightly more user-friendly interface since its database links to SimaPro and therefore less numbers need to be entered. It still requires a lot of data and is also used after a product is finished, to give a quantified overview of the environmental impact in various stages of its lifecycle (Aarts-Hornix, 2012).

Philips Consumer Lifestyle conducts extensive case studies on energy usage, environmentally relevant materials, end-of-life, and composition of material and packaging. To quantify the environmental performance of a product, the products are disassembled and the materials, manufacturing process and weight of each component are documented. This has been done by researchers at Philips on approximately seventy consumer electronic products (Stevels, 2007). This information is then used to perform a life cycle assessment on the product with EcoScan. The version of Ecoscan used is based on Ecoindicator 95 (Goedkoop et al. 1996). Just as most LCA tools, EcoScan looks at the entire life cycle of the product. This includes extraction, manufacturing, packaging, usage and end-of-life. Environmental impacts from manufacturing include extraction and manufacturing processes. The tool also quantifies the impact of usage conditions, such as batteries or grid electricity. The packaging impacts accounts for the impact of plastic, cardboard and paper used in packing materials. The impact scenario for end-of-life treatment currently used in the calculations is disposal through incineration (Stevels, 2007).

## 3.8 Previous work on environmental tools at Philips

Starting in the early 1990s, a number of initiatives related to environmental improvements were initiated at Philips. This included work in the fields of disassembly, plastic recycling, reuse scenario for products and models for recycling effectiveness and costs. The topic of organizational development of take back and recycling systems was also included. Many of these initiatives were introduced at Philips by Ab Stevels, who worked in this field for many years, and also as a professor in Applied EcoDesign at Delft University of Technology. A detailed description of these initiatives can be found in his book 'Adventures in EcoDesign of Electronic Products' (2007). Examples of a number of projects conducted at Philips the last ten years are described below.

### 3.8.1 QWERTY/EE

The QWERTY/EE stands for "Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency" and presents an alternative for usual weight-based recycling percentages. It was developed in cooperation with Philips and Ab Stevels and concerns recyclability and eco-efficiency of consumer electronics, including take-back and recycling (Huisman, 2003). The QWERTY/EE concept contains a quantitative eco-efficiency approach for evaluating technological, design and policy strategies as well as economic effects of take-back and recycling. Extensive environmental and economic modelling of end-of-life processing is involved and applied to both products and scenarios. The outcome of this method indicates how policy making, system operation, technology and design need to be integrated to improve a product's end-of life performance. The concept and the resulting insights can be useful for policy makers, legislators, product designers, manufacturers, recyclers, take-back system operators and scientists. However, it requires detailed knowledge in recycling and its output is based on quantitative data. It is not used at Philips since it requires expertise from the developer to be applied, and it needs a quantified input to produce a quantified output.

### 3.8.2 PRI-tool

A tool on recyclability was built in Excel by a previous student at Philips, and named the Product Recyclability Indicator (PRI) tool (Peters, 2012). The PRI-tool consists of seven guidelines, each one containing a number of strategies on how to comply with each guideline. The seven guidelines are:

1. Do not use toxic or hazardous substances
2. Use recyclable materials
3. Minimize material diversity
4. Use material connections which allow liberation
5. Design a recyclable product construction
6. Enable easy and complete removal of toxic, hazardous, polluting components, operating liquids and gasses.
7. Enable easy logistics and encourage product collection

The entire PRI-tool consists of 43 strategies divided over seven categories called guidelines. The user is requested to "tick" a box to indicate compliance or non-compliance for each strategy. A list of all strategies can be found in Appendix D. Depending on the number of boxes ticked, a score on recyclability is generated. To generate a score, the tool contains a number of linked matrixes that are combined with a number of weighting factors. The weighting factors are mainly based on the student's expertise as a design engineer student, and a small part is based on input from three European recycling companies. Previous testing revealed that engineers found the tool useful and interesting to use, however they need a lot of support to actually be able to use it. The engineers that tested it were also already environmentally interested and positive to the tool, which might have influenced the result.

### 3.8.3 Other theses

Other theses have been made at Philips on topics closely related to DfR, however not with an outcome that is being used today. Bram Joosten designed in his thesis (2009) a tool with a focus on cradle-to-cradle and D4D (Design for Disassembly). It was consolidated into a tool that focuses on how to design and realize a tool to aid designers of consumer electronics to benchmark their designs from a D4D perspective. It provided insights into D4D and the principle of cradle-to-cradle but did not result in a tool that is currently in use. Another thesis by Marieke Brouwer (2010) treats the topic of sustainable materials choices and how to find a way to implement the software program called the "Granta CES Selector" in the department of domestic appliances. The outcome was a step-by-step plan that product engineers could use for making sustainable material choices. The plan included the use of the Granta CES Selector and when needed the use of the tool EcoScan (see section X) with material scenarios. This tool is however also not in use today.

## 3.9 Design for Recycling

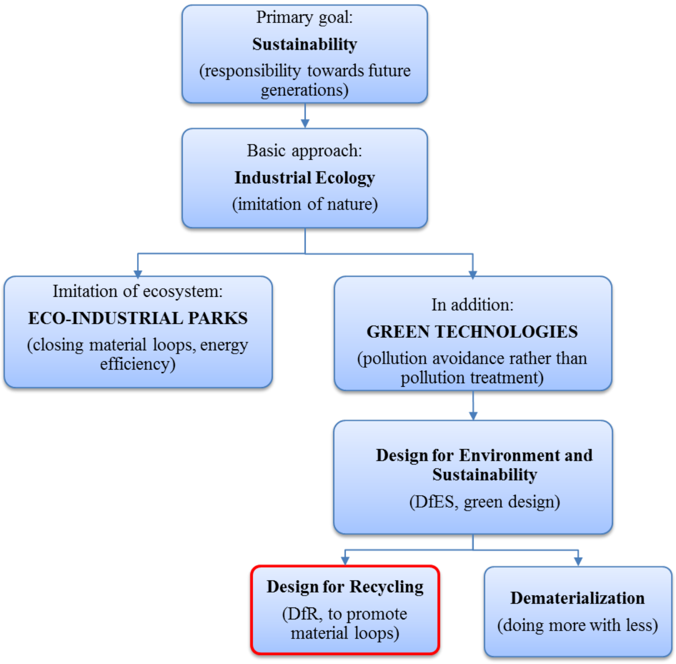


**Figure 4. Design for Recycling (DfR) and its relationship to sustainability and other environmental approaches (Design for Recycling PDF, 2010).**

### 3.9.1 Design for Recycling

Design for Recycling (DfR) can be seen as a part of Design for Environment and Sustainability (DfES), with the overhead goal being sustainability and responsibility towards future generations (Design for Recycling PDF, 2010). DfES requires the whole life-cycle to be accounted for in product design and DfR has been described as one of the central parts of DfES. The relationship between DfR, other environmental approaches and sustainability is illustrated in Figure 4.

DfR has been defined as design for ease of product recycling and maximum output. Particular attention has been given to the disassembly of a product during the recycling process (Kriwet et al 1993). The main mission of DfR is to account for how to recycle the product at the same time as it is being designed, to enable an easy recycling process. DfR has no formal rules, but it involves a number of general guidelines on hazardous materials, connections, construction and accessibility of parts.

DfR is a design methodology pointing towards a wide range of requirements of a product. It should be easy to dismantle and contribute to maintaining 'clean' and recyclable material-fractions (e.g. iron and copper should be easy to separate). Further requests are that parts and components that need separate treatment should be easily removable. As few different materials as possible should preferably be used, together with markings on materials in order to sort them properly, and surface treatments avoided with the purpose of maintaining clean material streams (Danish EPA, 2009). Another issue to consider is hazardous materials, keeping in mind that the product should not cause problems at its end-of-life phase. Where they have to be used, they should be easily found and removable. Materials and the way they are attached together is also a vital aspect, and the possibility of separation needs to be considered up front. Examples of materials to avoid combining are plastic moulded over metal or over a different plastic or metal coating on plastic films (Kriwet et al, 1995).

A product's design defines the selected materials as well as the complexity of their combinations and interactions within the product. There are numerous methods to join materials e.g. welded, glued, alloys and inserts. The possibility to separate different materials from each other, decides the quality of the recycling stream. This illustrates the importance of product design and choice of materials and joining technologies, to enable parts and materials that have been integrated and connected to also be separated (van Schaik & Reuter, 2009).

Product engineers play a key role in influencing the recyclability of a product. It has been claimed that up to 80% of a product's environmental impacts are set in the early stages of products development, for example in the concept creation phase (Danish EPA, 2009). Tools that exploit the skills of engineers in creative thinking and problem solving should be developed and used as an incentive to sustainable design in the early design stages (Attenborough, 2007). The influence of the stage in which the environmental impacts are considered is illustrated in Figure 5.

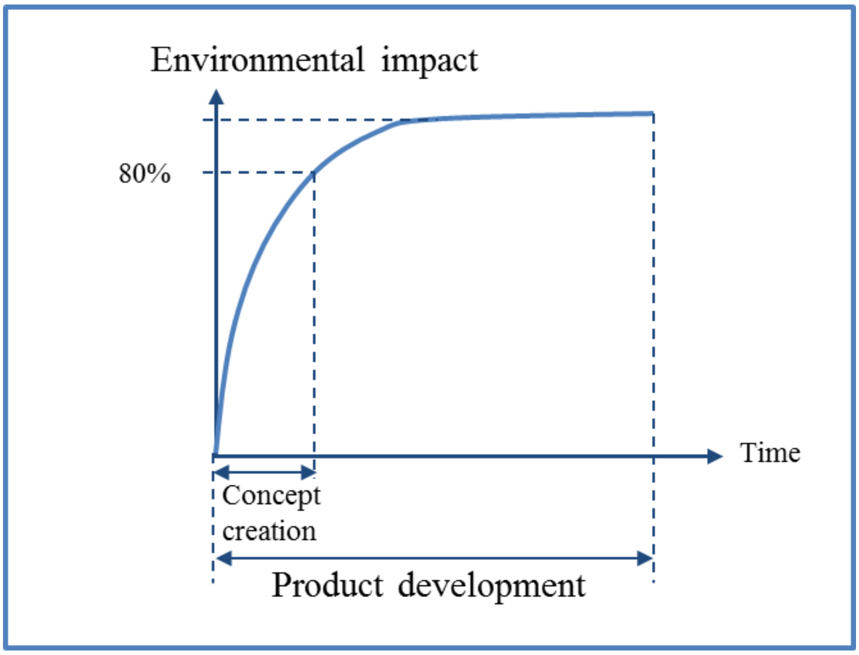


**Figure 5. The influence of the stage in which the environmental impacts are considered (Danish EPA, 2009).**

The efficiency with which products and components re-enter the flow into new products has been stated as highly dependent on product and process design (Graedel & Allenby, 2010). One of many challenges is that the product comes back first after 5-10 years, and the delayed effects on the recycling processes need to be considered (Kriwet et al, 1995). However, it should be noted that the products produced and sold in the past are still being recycled today, even though those products were not designed for recycling. The recycling process has the largest impact on how well the product can be recycled, but contributing to better product design is an important way to make the recycling process require less effort, time and costs (Smit, 2012).

Important is to keep in mind that DfR is a derivative of the more holistic concept of DfES or Eco-Design, aiming to minimize impacts of a product's entire life cycle. It should therefore be taken into account that DfR needs to be done in cooperation with further life cycle related efforts. The design results from performing DfR should not counteract the overall principles of life cycle impacts. Design for Recycling in product design cannot solve all issues with recyclability but needs to be combined with optimized and improved recycling technologies. It has also been shown that for some products, to enable easy manual disassembly in product design does not by default improve the recycling rate of a product. To improve environmental performance of recycling is highly dependent on the application of proper waste stream management, the market for secondary materials and collection logistics of enough financial scale. A product designer can contribute by improvements in design but this is far from the only initiative necessary to solve the e-waste problem (Stevels, 2007).

### 3.9.2 Material combinations

For successful electronics recycling, an important aspect is the combinations of materials. Materials can be perfectly recyclable separately, but when two materials are combined they can become impossible to separate. One of the materials end up as an impurity in the other material's recycling stream, degrading its properties (Graedel & Allenby, 2010). The purpose of this section is to illustrate how to select feasible combinations of materials, based on a material combinations matrix.

To identify which materials combinations are feasible, a material combinations matrix named the "THEMA" matrix have been developed by Castro (2005). The matrix indicates which materials should be avoided to combine based on the recycling process and how difficult it is to separate them once joined. The matrix shows three levels, "Must separate" "Should separate" and "Do not separate", and indicates for a number of common materials which combinations should be avoided and which ones are acceptable to combine. It is based on materials' thermo-dynamical properties and is illustrated in Figure 6. The input streams in the figure consist of a minor amount of material and will end up in the stream of the main material (the industrial stream) where it can cause a problem.

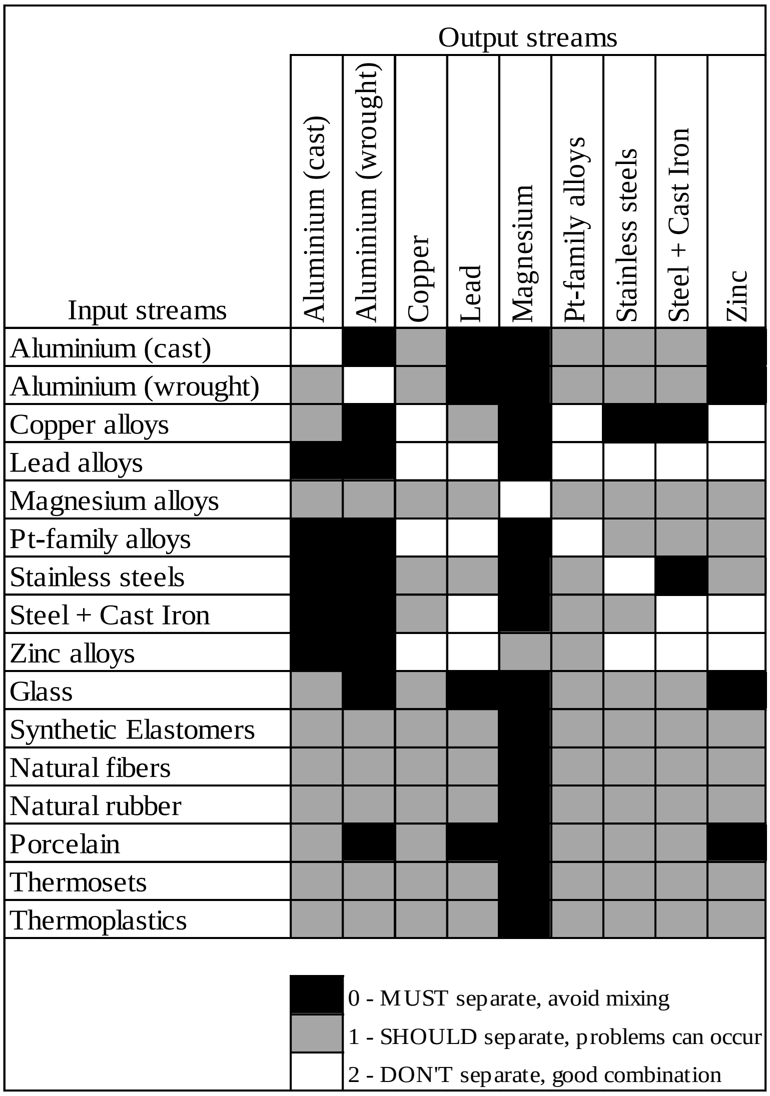


**Figure 6. The THEMA material combinations matrix, developed by Castro (2005).**

### 3.9.3 Reuse and Remanufacturing

Reuse and Remanufacturing are two important strategies for environmental improvement that are not part of this thesis, but should definitely be mentioned. Reuse can be described as the second hand use of a product that first has been discarded as waste and then reused again without considerably altering the physical form of the product or material. Reuse refers to the act of turning waste into a product again; the user has to have the intention to dispose of it before it can be termed as reuse. The process of Remanufacturing involves large amounts of similar products being brought into and disassembled in a central facility. The various product parts are separated by part type, followed by cleaning and repair or reuse inspection. New (remanufactured) products are then re-assembled using the recovered parts as far as possible, together with the addition of new parts where necessary.

The ‘waste hierarchy’ or ‘Lansink’s ladder’ are commonly used concepts to illustrate the preference for end of life strategies, see Figure 7. According to calculated environmental impact, the highest or most preferred level for end-of-life treatment (following reduce, sometime referred to as prevention) is reuse, followed by service of a product to extend its lifetime, remanufacturing, recycling and finally energy recovery by incineration or disposal by landfilling. The extension of a product’s life ranks highest, through reuse of the product and to reuse the product as a whole is an ideal solution for the product end-of-life. To extend the product's life by service on the product comes at second place, followed by reuse of parts and components through remanufacturing.

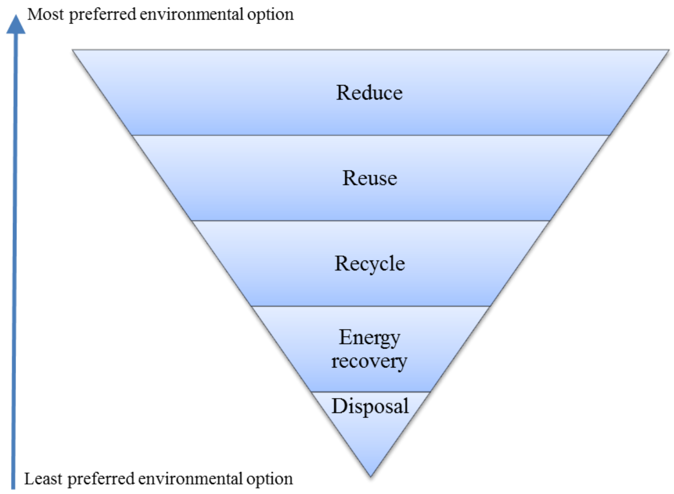


**Figure 7. The waste hierarchy or Lansink's ladder, illustrating the preference for end-of life treatment.**

To design for reuse and re-manufacturability are approaches that are closely related to the concept of Design for Recycling (DfR). Reuse and remanufacturing are most often better from an environmental impact view, but the logistic system required to perform such operations are not yet developed on a large enough scale to be generally applied. It is currently not comparable to the state-of-the-art recycling process where most electronics (of the electronics that are collected in Europe) end up, or many times cost-efficient enough to perform. For many products the use phase makes up the biggest environmental impact in its life-cycle. From a life-cycle perspective it is therefore many times better to recycle an old energy inefficient product than to have someone reuse it, since a new product often is much more energy efficient (Smit, 2012).

## 3.10 The Integrated Product Development (IPD) process

The Integrated Product Development (IPD) process is the model for product development at Philips Consumer Lifestyle. The IPD process is a model for cross-functional product development, introducing a common language and terminology together with a logic sequence of activities (de Wit, 2011). It is an approach to product development for managing progress and risks by using internal as well as external best practices. For an illustration of this process, see Figure 8.

In the project initiation phase, the proposal is made and the various costumer needs defined. In the assignment preparations phase, technical concepts and detailed requirements are set. This is followed by the project confirmation, where checks of the initial design are conducted and a project plan created. In the product implementation phase, the design is refined and validated and testing or debugging is performed. Process verification includes pilot runs and finalization of product and process release tests. The initial productions involves making and checking of initial quantities. This is followed by the mass volume and ramp up, where productions and quality issues are solved, and learning's documented.

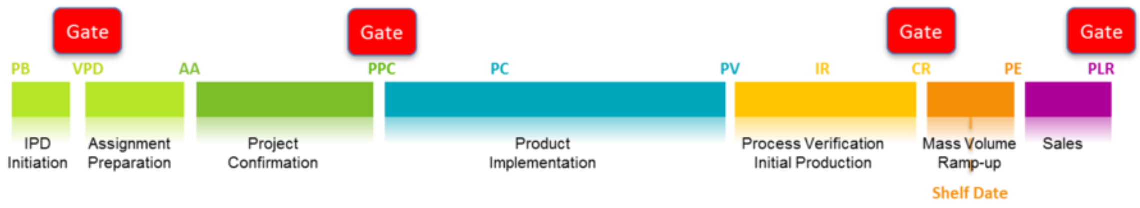


**Figure 8. The Integrated Product Development (IPD) process (de Wit, 2011).**

There are four 'gates' and ten 'milestones' in the IPD process, where a product has to fulfil certain requirements to pass through. The four gates can be seen as mandatory milestones that have to be fulfilled.

The milestones are named (in order from start to end of a project):

- PB (Project Briefing)
- VPD (Value Proposition Debriefing) – GATE
- AA (Assignment Agreed)
- PPC (Project Plan Committed) – GATE
- PC (Prototype Consolidated)
- PV (Product Validated)
- IR (Industrial Release)
- CR (Commercial Release) – GATE
- PE (Project End)
- PLR (Post Launch Review) – GATE

PB is the start of the project initiation, where consumer needs are mapped and a proposition is laid out. This is followed by the gate at milestone VPD, where requirements are frozen and initial trade-offs are made. After this, the assignment is prepared and technical concept and detailed requirements are set before the milestone of AA is reached. At AA, the product functions are frozen, as well as the architecture and requirements. Following this, a project confirmation is made where the initial design is created and checked and a project plan is created. Thereafter, the second gate at milestone PPC is reached, where the detailed design and the project plan is frozen, and the product is committed for launch. After this the product implementation starts, and it becomes difficult to make changes in the product design and specifications. The design is now refined and validated and at milestone PC the prototype is confirmed. Then follows PV, where pilot runs are made and product and process release tests are finished. At the next milestone; IR; the product and production process are released for start of mass production. Following IR is the gate at the CR milestone, where initial production is set up and initial quantities are checked and produced. At this gate, the first products are sent to the retailers and selling can start. When this gate is passed, mass volume ramp-up can start and production and quality issues are to be solved. Learning's are also documented. The milestone at PE is then reached where the project is closed, followed by a PLR, where the project is evaluated to establish accountability towards the original plan and to properly document the learning's for future projects (de Wit, 2011).

The structure of the IPD process was illustrated to be able to recommend where in this process guidelines on recyclability could be used. An insight after reviewing the IPD process is that the guidelines need to be embedded in this process for it to be successfully implemented, and preferably in the early stages of the process before the detailed design specifications are fixed.

## 3.11 Summary

The reviewed literature highlighted a number of important aspects. To start with, the concept of Extended Producer Responsibility (EPR) explains the changed role that producers have today and why there is a need to improve the products they put on the market. It illustrates that efforts are made on an EU-level to emphasize the responsibility of producers over the products they put on the market. Various legislations were illustrated, starting with the policy implementation of EPR for electrical and electronic equipment; the WEEE Directive. The WEEE Directive requires producers to fulfil certain requirements and supports this research in that the producers need to consider how they design their products and how it will be taken care of at the end of its life. EPR suggests increased responsibility of producers such as designing the products in a way that makes them easier to take apart, which is important to consider for a global producer of consumer electronics like Philips. Included in this are also collection targets for e-waste and the costs for recycling are partly put on the producer.

Chemical legislation was highlighted, to present what is already in place regarding restriction and regulation of substances. This covers REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) and its lists of candidate substances such as SVHCs (Substances of Very High Concern) and CARACAL (Competent Authorities for REACH and Classification, Labelling and Packaging). Further, RoHS (Restriction of Hazardous Substances) are also included. Company specific regulations; named Philips RSL (Regulated Substance List); are mentioned to highlight what is regulated by Philips on top of basic legislation. The findings from legislation and company specific requirements indicates which substances are likely to be banned in the future and which substances are already regulated by Philips even though they are not yet banned. It also shows which substances still can be expected to be restricted and therefore leaves room for improvement at Philips.

The process of electronics recycling was described to show the steps and processes that e-waste undergoes and to present expected future developments influencing the recycling process. From here it is shown that the amount of pre-sorting will likely increase, pointing at the importance of how products are constructed. The chemical content of products also influence whether the material will be accepted for recycling or not, with respect to the recycling process and concentration limits of substances.

Aspects on health and safety were considered by describing problematic substances in electronic products and how they pollute the environment and cause health problems. This is particularly important if the product ends up being recycled on the street in a developing country. An insight after this section was that it is necessary to include a health and safety perspective in the guidelines particularly regarding how hazardous or valuable materials are fixed in a product.

Design for Recycling (DfR) was defined and important aspects to consider in DfR highlighted. The fact that DfR is not on its own a solution for environmental improvement, but needs to be combined with other measures was also concluded. A matrix to make feasible material combinations was described and will be used to create a design strategy on material combinations. The most used materials in Philips products will be applied to this matrix to create design strategies for which combinations to avoid.

Two initiatives on a European level were described to illustrate that work is being done on a high level in this field. Two tools for environmental performance used at Philips were also reviewed as well as previous works in the form of Master theses and PhDs at Philips. The Integrated Product Development (IPD) process was described to show the frames of reference that guidelines for recyclability need to fit into, with the conclusion that a tool on recyclability preferably needs to be integrated into this process.

To conclude this section, there are a number of aspects Philips needs to consider regarding recyclability of their products, with the future developments of the recycling process in mind. These are mainly

- Chemical content and hazardous substances in materials and future legislation on chemicals
- How hazardous and valuable components are fixed in a product
- The use of recyclable materials in products
- How materials are combined and connected in a product

And for a successful implementation of guidelines and design strategies

- How to incorporate advice for increased recyclability into Philips day-to-day activities

# 4 Results

The results of this thesis consist of a number of partial results which corresponds to each of the four objectives initially set in this thesis. These partial results consist of findings from literature study, the analysis of the PRI-tool, the survey, product testing and from interviews with product engineers and architects.

## 4.1 Objective 1: Guidelines and design strategies for recyclability

The first objective of this thesis was to come up with a set of guidelines and design strategies for recyclability. This was achieved by a literature study together with expert interviews, and resulted in a list of 39 design strategies.

### 4.1.1 Findings from the literature review

As mentioned in the summary of the literature review section, the following features are recommended to be included as advice for recyclability at Philips.

- Chemical content and hazardous substances in materials and future legislation on chemicals
- How hazardous and valuable components are fixed in a product
- The use of recyclable materials in products
- How materials are combined and connected in a product

These four topics are chosen as guidelines or 'categories', each containing a number of design strategies on recyclability. The design strategies related to each of these four topics are presented in section 4.1.4.

A design strategy on how materials are combined in a product was developed with the THEMA matrix described in the literature review. The THEMA matrix was used to create a design strategy for feasible material combinations. It was simplified by analysing which materials are most commonly used in the products at Philips Consumer Lifestyle and then applying the matrix for these specific materials to generate design strategies on material combinations. A detailed description of this procedure can be found in Appendix E. The purpose was to create detailed advice for which materials to combine and which ones to avoid. It is meant as a support in making advice for recyclability as practical and tangible as possible, rather than stating that engineers generally should avoid a material; when it is not a problem as long as it is combined in an accurate way. This design strategy can be found in section 4.1.4 under guideline 4 (design strategy 4.4).

### 4.1.2 Evaluation of the PRI-tool

Firstly, the design strategies on chemicals in the PRI-tool were found to be almost entirely covered by current European legislation on substances, such as RoHS and REACH. The remaining content that was not covered by RoHS and REACH was found listed in Philips Regulated Substance List (RSL). A list with candidate substances to REACH, called SVHCs (Substances of Very High Concern), was also found to be covered by Philips own regulations. According to the tool requirements, substances that are already regulated are subject to legal requirements for compliance and do not add value to include in a tool for recyclability. One design strategy regarding chemicals from the PRI-tool was decided as suitable to include in this thesis, this refers to a list of substances called the CARACAL list, see design strategy 1.2 in section 4.1.4. This fits the purpose of preparing Philips for the future and is not yet covered by legislation or Philips own Regulated Substances List (RSL).

Secondly, the analysis of the remaining guidelines in the PRI-tool resulted in the selection of a number of design strategies, based on the areas mentioned above that Philips needs to improve in the future. From the PRI-tool, 26 design strategies (out of 39) were selected as relevant to include in the list. A detailed description on the selection can be found in Appendix F.

### 4.1.3 Findings from interviews

The design strategies were complemented with a number of new strategies that were suggested during interviews with experts and discussion of tool requirements within Philips. These were added to the list in section 4.1.4 where the source for each strategy is also mentioned.

### 4.1.4 List of collected guidelines

The guidelines collected from literature review, the PRI-tool, and interviews with experts are presented below. They have been selected based on the tool requirements set in agreement with Philips, see section 1.2. The source of each design strategy is mentioned in brackets. The design strategies are divided over four guidelines which have been reformulated into:

- Guideline 1: Do not use hazardous substances
- Guideline 2: Enable easy access and removal of hazardous or polluting components
- Guideline 3: Use recyclable materials
- Guideline 4: Use material combinations and connections that allow liberation

Below follows a description of each guideline and its corresponding design strategies with practical advice on product recyclability.

#### Guideline 1: Do not use hazardous substances

The purpose of the new guideline on chemicals is on preparing Philips for the future by phasing out substances that are very likely to become regulated. The purpose is also to add a health and safety perspective to product design in case they do not end up in controlled recycling. This includes avoiding using materials that contain certain chemicals in products, to prevent these chemicals from harming humans and the environment when controlled end-of-life treatment is not practised.

Therefore, a guideline on chemicals aiming to go beyond current legislation was created. It is based on preparing Philips for future legislation as well as including three chemical substances that are company specific for Philips to focus on (Philips, 2012d). These three substances are Phthalates, PVC (Polyvinylchloride) and BFRs (Brominated Flame Retardants).

**1.1 Do not use a total sum of Phthalates in a higher concentration than 1000 ppm per chemical compound (power cord exempted)** (Company specific regulation, Ton van Veen, 2012).

The Phthalates are plasticizers and are likely to be entirely banned in the future, and several phthalates are already on the list of SVHCs and in the Philips RSL. To avoid any higher concentrations than a total of 1000 ppm in any products, a design strategy on Phthalates is added. The limit of 1000 ppm was defined by Philips Sustainability Team (Ton van Veen, Senior Manager Sustainability). If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future.

| |
|---|
| **1.2 Do not use any Polyvinylchloride (PVC) in the product; ensure that it is 100% PVC free** (Company specific regulation, Ton van Veen, 2012).<br><br>To phase out PVCs in their products is a company specific strategy for Philips as an initiative to prepare for future legislation. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future. |
| **1.3 Do not use any Brominated Flame Retardants (BFRs) in the product; ensure that it is 100% BFR free** (Company specific regulation, Ton van Veen, 2012).<br><br>To phase out BFRs in their products is a company specific strategy for Philips as an initiative to prepare for future legislation. Several BFRs are already restricted and it is likely that more will become banned. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future. |

**1.4 Do not use any of the substances from the CARACAL list for electronics in concentrations above 1000 ppm (0.1 % per article) per substance** (PRI-tool, Peters 2012 combined with SinList 2012 & Tarja Sivonen, 2012).

Do not use substances that are listed for future restriction in the 'CARACAL list' (Competent Authorities for REACH and Classification and Labelling). These substances are mainly used in plastics as surfactants, solvents, stabilizers, plasticizers, anti-corrosions, pigments and coatings. Do not use in concentrations above 1000 ppm (0.1 % per article) per substance.

- PFOS, heptadecafluorooctane-1-sulfonic acid, perfluorooctane sulfonic acid
  ammonium heptadecafluorooctanesulfonate, ammonium perfluorooctane sulfonate
  potassium heptadecafluorooctane-1-sulfonate, potassium perfluorooctanesulfonate
- Bis (2-methoxyethyl) ether
- 2-ethoxyethyl acetate
- 1,2-dimethoxyethane
- Buta-1,3-diene
- Hexachlorobenzene
- 2-methoxypropyl acetate
- Thioacetamide
- N,N-dimethylformamide
- Hexachlorobuta-1,3-diene
- 1,2,3-trichlorobenzene
- 4,4'-(4-iminocyclohexa-2,5-dienylidenemethylene) dianiline hydrochloride
- 4,4'-methylenebis[2-chloroaniline]
- Diisobutyl phthalate

To phase out substances likely to become restricted in the future, the CARACAL list is added. The 'CARACAL list' is a list of substances that are not restricted yet, but gives a good indication of substances for future restriction and regulation. These substances are mainly used in plastics as surfactants, solvents, stabilizers, plasticizers, anti-corrosions, pigments and coatings. The substances on this list are not yet covered in Philips RSL. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future.

### Guideline 2: Enable easy access and removal of hazardous or polluting components

Guideline 2 contains advice for easy access and removal of hazardous components. The design strategies are described below.

| |
|---|
| **2.1 Do not permanently fix batteries in a product. Avoid glued, welded and enclosed solutions and prefer click/snap solutions, to prevent pollution of material streams and for health and safety reasons if the product does not end up in controlled recycling** (Feng Wang, 2012).<br><br>Strategy 2.2 focuses on not permanently fixing batteries in the product. Batteries are a problematic component that might end up polluting the recycling stream. To avoid pollution the battery needs to be removable via handpicking after the first shredding step. Therefore, a design strategy was added on how the battery is enclosed, and thereby how easy it is to remove. This is meant to emphasize the preference for click/snap solutions over glues or permanent attachments in design. Batteries can also explode in the shredding process which is a safety risk. |
| **2.2 Do not permanently fix valuable components (printed circuit boards (PCBs), cables, wires and motors). Avoid glued, welded and enclosed solutions and prefer click/snap solutions, to prevent pollution of material streams and for health and safety reasons if the product does not end up in controlled recycling** (Feng Wang, 2012).<br><br>Strategy 2.2 focuses on not permanently fixing valuable components in the product. It was added as a health and safety perspective to the tool, based on the fact that far from all e-waste actually ends up being shredded. A large part of e-waste still ends up in third world countries where it is recycled on the street under very primitive conditions. Components containing valuable materials are of particular interest to people performing this kind of recycling, which are for example cables, wires and motors containing copper, printed circuit boards containing numerous valuable metals such as gold, silver etc. To extract these valuable materials, methods like burning are common as well as pouring acids on the material to separate them. This releases many kinds of toxic fumes and poses a great health risk to humans. To account for these risks, designers are advised not to glue valuable components together but also choose for click/snap-solutions to enable easy removal. |
| **2.3 Provide drains for operating liquids and gasses and ensure those components (oil tank, compressor and hoses) can be easily removed** (PRI-tool, Peters, 2012).<br><br>To provide drains is considered important for the recycling process since drains make it possible to take out operating liquids and gasses and prevent them from polluting the material streams or the air. Therefore it is also important to consider the removal of these components in the design, and make sure they are easy to remove. |
| **2.4 Provide detachment possibilities for toxic, hazardous, and polluting components (dust bags, lamps, cord sets, cord winders) and for problematic materials (paper, cardboard, textiles, wood, foams and glass)** (PRI-tool, Peters, 2012. Modified due to overlap with 2.1 and 2.2).<br><br>Providing detachment possibilities for toxic, hazardous and polluting components are vital since they otherwise easily end up polluting the material streams. |

**2.5 If no drainage or detachment option is present, provide markings for destructive action** (PRI-tool, Peters, 2012).

A subordinate design strategy to 2.3 and 2.4, in case the request for drains or detachment possibilities for operating liquids or gasses or polluting components is not possible to fulfil. Markings for destructive action can help the first stage in the recycling process where the product breaks open. This usually happens when the product 'falls' onto the recycling belt in the first dismantling step. If it does not break open there, it can help to provide a marking or indication on where to manually apply force to enable taking out a polluting component.

**2.6 Use a module for hazardous components in the product structure to enable taking out a non-recyclable module instead of searching for several different hazardous parts** (Stena Technoworld, 2012).

To use one module where all the hazardous components are located makes the recycling process easier and more efficient. It is easier for the recycling workers to find one module in the manual dismantling step instead of taking time to find several components.

### Guideline 3: Use recyclable materials

Guideline 3 regards the use of recyclable materials, and was split up in three parts; plastics, metals and other materials. The design strategies in this guideline point towards avoiding materials that are difficult to recycle, and promoting the use of common materials that can easily be recycled.

#### *Plastic materials*

**3.1 Do not use thermosets since they end up in the waste fraction for burning; choose thermoplastics or another alternative instead** (PRI-tool, Peters 2012).

Thermosets are not (currently) possible to recycle, and are either burned or end up polluting material streams.

**3.2 When thermosets are necessary, use thermosets with a different density than the common recycled plastics (not in the density range of PP, PE, PS and ABS which is 0.888e3 – 1.070e3 kg/m3)** (PRI-tool, Peters 2012).

If thermosets are necessary, use a density that is not the same as common plastics, since then the thermosets will end up in the material stream of these plastics. The separation of plastics is done by density separation, usually in various flotation steps. The density will therefore determine which recycling stream the plastic ends up in.

| |
|---|
| **3.3 Do not use elastomers; they end up either polluting the plastic fraction or in the waste fraction for burning** (PRI-tool, Peters 2012).<br><br>Elastomers are not (currently) possible to recycle, and are either burned or end up polluting material streams. |
| **3.4 When elastomers are necessary, use elastomers with a different density than the common recycled plastics (not in the density range of PP, PE, PS and ABS which is 0.888e3 – 1.070e3 kg/m3)** (PRI-tool, Peters 2012).<br><br>If elastomers are necessary, use a density that is not the same as common plastics, since then the thermosets will end up in the material stream of these plastics. If elastomers are necessary, use a density that is not the same as common plastics, since then the elastomer will end up in the material stream of these plastics. The separation of plastics and similar materials is done by density separation, usually in various floatation steps. The density will therefore determine which recycling stream the plastic ends up in. |
| **3.5 Do not use polymer blends since they cannot be separated again, use one material instead. The blend PC-ABS is an exception that is ok to use, since it can be recycled as a whole** (PRI-tool, Peters 2012. Modified after contact with Stena Technoworld).<br><br>Polymer blends are generally very hard to separate, and therefore end up either being burned or polluting the material streams. An exception is the blend PC-ABS since this combination has been proven to be recycled well as a whole. The advice is generally to avoid polymer blends, but if a blend is necessary, choose for PC-ABS. |
| **3.6 Do not use more than 5 % master batch in plastics (flame retardants, stabilizers, fillers) since it impedes recycling. Glass fibres are here not included in the term master batch. Prefer an additive that changes the density of the plastic, to make it possible to filter it out when recycled** (PRI-tool, Peters 2012).<br><br>The more master batch in the plastic, the more polluted the material streams of the plastics will become. To avoid pollution of the streams, as low concentration as possible is preferred, with a maximum limit of 5 %. This is important today but also for the future, since stricter legislation on the concentrations in plastic recycling streams can be expected. This means that a plastic stream that has too high concentration of certain substances cannot be used as recycled plastics, but will instead be burned. Higher concentration of master batch also often means more hazardous fumes from burning. |

**3.7 When using plastics, use only common plastics (such as ABS, PE, PP, PS) since they can be recycled well** (PRI-tool, Peters 2012).

There are established recycling streams for these plastics, which mean that they very likely will be recycled. Other materials currently occur in too small volumes in the waste stream to make it economically possible to recycle them.

**3.8 Do not use biodegradable plastics, since it will pollute the plastic stream when degrading. Bio-based plastics such as PP made from corn are ok to use** (PRI-tool, Peters 2012).

Biodegradable plastics starts to degrade after a while, thereby polluting the material stream in the recycling process. It is therefore recommended not to use these types of plastics in products. Bio-based plastics have on the contrary the same properties as regular plastics and are therefore approved to use since they come from a bio-based source instead of oil.

**3.9 Do not use coatings on plastics such as painting, lacquering, plating, and galvanizing, since it can result in changed density of the plastic. A density difference < 1 % of the materials weight is ok. Avoid plating since it is always a problem as it connects plastic and metal** (PRI-tool, Peters 2012).

All forms of coatings pollute the material streams or make the recycling process difficult. Coatings change the density of the plastics, which makes it likely to end up in the wrong material stream. The coating material itself also pollutes the streams. However, if the density difference after coating is less than 1 %, it is likely that the plastic will end up in the material stream it is supposed to end up in. Printing of small text, numbers or lines for level-indication are not a problem, but in fact better than using a sticker for the same purpose.

### *Metals*

**3.10 When using metals, ensure that they have characteristic metal properties such as ferrous metals that are magnetic and non-ferrous metals that are non-magnetic** (PRI-tool, 2012).

For metals, make sure that metals have characteristic properties to make the separation of materials easier in the recycling process. The separation of metals in the recycling process is done by magnetic separation. If the metal is ferrous and magnetic it will be taken out by the magnets in the process and end up in the ferrous stream. If it is ferrous but non-magnetic, it will end up with the other non-ferrous materials such as aluminium and thereby pollute these streams.

**3.11 Do not use permanent magnets, they get stuck in the magnet separation of metals and cannot be recycled** (Stena Technoworld, 2012).

Permanent magnets (not electro-magnets but magnets that are permanently magnetic) create problems by getting stuck in the large magnets used for metal separation in the recycling process. There they have to be manually removed which causes disturbance in the recycling process.

### *Other materials*

**3.12 Do not use composites, they end up in burning, landfill or polluting other fractions since the different materials in the composite cannot be separated** (PRI-tool, Peters 2012).

**3.13 Do not use ceramics (cement, concrete, alumina and silicon) since they cannot be recycled, only down-cycled** (PRI-tool, Peters 2012).

**3.14 Do not use paper, cardboard, wood, textiles and foams, since these will be removed by manual effort and burned or land filled** (PRI-tool, Peters 2012).

This strategy was added since these materials cause a problem in the recycling process, since they have to be manually taken out otherwise they end up polluting various streams.

**3.15 Do not use adhesives, glues, stickers, labels, PSA (Pressure Sensitive Tapes; electrical, masking, box sealing tapes). If safety stickers and labels are necessary make them easily removable in the recycling process, but not in the use phase** (PRI-tool, Peters 2012).

Stickers and other adhesives pollute the material streams of the material they are attached to. If a sticker is necessary, choose a material as similar as possible to the host material (for example a PP-based sticker for a part made of PP material).

**3.16 Do not use operating liquids and gasses which stay present in the product at the end of life of the product. It may pollute the material streams and require extra effort to remove.**

**Unpressurized water or air is ok to use** (PRI-tool, Peters 2012).

**3.17 Use as few different materials as possible since the fewer materials the purer fraction in the end. Same with components, the fewer components the easier it is to dismantle by hand and less material is usually used** (Stena Technoworld, 2012).

Strategy 3.17 was added to increase the recyclability of products by using as few materials as possible. If it is possible to only use two types of plastic for all the parts in a product, do not use more than that.

### Guideline 4: Use material combinations and connections that allow liberation

Guideline 4 treats the choice of material combinations and connections, aiming to enable easy liberation of materials and connections. It was also divided into three parts; plastic, metal and other materials.

#### *Plastics*

**4.1 Do not mould different material types together by 2K or xK processes (different plastic materials injected into the same mould), unless the material types are the same and only differ in colour and additives. To mould red PP containing antioxidants on black PP containing talc is ok, but avoid moulding a thermoplastic elastomer onto PP, like toothbrushes** (PRI-tool, Peters 2012).

It is very difficult to separate materials that have been joined by 2K or xK processes. Therefore these joined materials will end up as waste or (depending on density) they will pollute other plastic streams.

**4.2 Prefer snap-fits for plastic components (particularly housing), to allow easy liberation of materials** (PRI-tool, Peters 2012).

Plastic snap-fits usually make it easy to remove the housing and open up the product, since they break and the housing is often cracked open in the first dismantling step. This helps the workers since they do not need to break open the product themselves. Plastic snap-fits are also an upside in case the product goes straight into the shredder; they will then follow the plastic host component into the plastic stream. With a metal screw there is for example always a risk that it goes either with a plastic part into the plastic stream or that a plastic part goes with the screw into the metal stream.

### *Metals*

**4.3 Do not fix ferro metals to non-ferro metals in parts or fasteners. For example, to design for separation, avoid using a screw (ferro metal) to attach a plastic part to an aluminium part (non-ferro)** (PRI-tool, Peters 2012).

If ferro and non-ferro materials are joined and the product goes into shredding it is very likely that either the ferro or the non-ferro stream will be polluted. The materials are shredded to small pieces and either the screw will go with the host component to the non-ferro stream or the non-ferro part will follow the screw into the ferrous stream.

**4.4 Do not permanently fix aluminium, copper (including brass), stainless steel or steel together in the following combinations:**

**- If the main material in a component is Al (cast), do not attach a part of stainless steel or steel onto it.**

**- If the main material in a component is Al (wrought), do not attach a part of Al (cast), copper, stainless steel or steel onto it.**

**- If the main material in a component is stainless steel, do not attach a part of copper onto it.**

**- If the main material in a component is steel, do not attach a part of copper or stainless steel onto it** (THEMA matrix, Castro, 2005. Modified according to the most used materials at Philips).

This design strategy concerns recyclers' perspective of material combinations in products. Based on thermodynamics, a decision model called THEMA was developed (Castro, 2005). This model indicates which combinations of materials are feasible and which ones should preferably be avoided. Depending on the main material in a component, smaller amounts of other materials will end up polluting that stream. Some materials are easy to separate while some are very problematic. The THEMA model was consolidated into a matrix, and adapted to only contain the materials that are most used by Philips CL, see Appendix E. The outcome of this matrix was formulated into a number of strategies related to which material combinations are important to avoid. A good and easily separable material combination will result in streams that are less contaminated as well as less waste, since many streams containing a pollutant that is hard to extract will simply end up as a waste fraction.

**4.5 If the main material is copper, do not permanently fix a part of iron, lead, antimony or bismuth to it** (Stena Technoworld, 2012).

An addition to the above mentioned design strategy

***Other materials***

**4.6 Use a detachable power cord instead of a permanently fixed one** (Roel Verbrugge, 2012 & personal observation during study visit at Coolrec).

This would make the manual disassembly step a lot easier, since the power cords are cut off one by one by the workers. The cords are separately recycled and the copper is recovered. When cut off, a part of the cord is always lost and goes with the product into the shredder. The copper in that part is lost and the plastic in the power cord is usually not the most pure plastic but commonly contains PVC which pollutes the recycling streams.

**4.7 Do not use fasteners that are not compatible with the connecting components. Fasteners are recycled together with the host component; therefore choose plastic fasteners for plastic and metal fasteners for metal to avoid polluting other material streams or end up in the waste fraction** (PRI-tool, Peters 2012).

The fastener often ends up with the main component it is attached to. If a screw is attached to plastic, then either the plastic part will go into the metal stream or the screw will end up in the plastic stream.

**4.8 Do not use connections that enclose a material permanently to avoid polluting the material streams. Avoid moulding-in inserts into plastic, rivets, staples, press-fit, bolts, bolt and nut, screws, brazing, welding and clinching** (PRI-tool, Peters 2012).

Enclosing a material permanently makes it harder to separate the different materials. The processes mentioned are typical processes that tightly enclose one material into another, and are therefore recommended to be avoided.

**4.9 If connections are applied that enclose materials permanently, apply gaps and or break-lines to the enclosing material to enable liberation during shredding** (PRI-tool, Peters 2012).

If a material has to be enclosed, apply a break line in the plastic or create a marking on where to apply force to get it out.

**4.10 Cluster materials of the same type. Ensure that wires connected to PCBs, displays, switches and motors are most strongly attached to the part containing the most weight of metals (usually the motor) to enable clustered manual material separation** (PRI-tool, Peters 2012).

If parts containing similar materials are clustered, they are likely to stick together and end up being sorted together. This is good for components that contain similar materials, for example PCBs, displays, switches and motors.

| |
|---|
| **4.11 Use the same type of fasteners in the product and make sure it can be disassembled with a standard tool. Construct the product so that disassembly of the product can be done from one side, without the need for turning/twisting the product** (Stena Technoworld, 2012).<br><br>Same type of fasteners avoid that several different tools need to be used in dismantling, which saves time. A standard tool is to prefer, and dismantling from one side speeds up the process and makes it easier for the workers. |
| **4.12 Avoid over-dimensioning of the fasteners as well as the parts in the product; do not use more fasteners or larger parts than necessary** (Stena Technoworld, 2012).<br><br>To make it easier and faster to disassemble or break open the product, if two fasteners are enough, do not use more than that. For parts and material in general, avoid using more material or larger parts than necessary. |

In total, the four guidelines above consist of 39 design strategies. With this list, the first objective of coming up with a set of guidelines and practical design strategies for recyclability has been met. This amount does not yet meet the requirement of an easy and user-friendly tool and it would be quite time-consuming for an engineer to go through the entire list. Some of the strategies are also probably more important than others, and makes a larger contribution to increasing the recyclability of a product. Due to this, a selection of the most important advice was necessary, see section 4.2.

## 4.2 Objective 2 & 3: Selection of the most important guidelines and design strategies & Creation of a user-friendly tool for engineers

The next step was to find out which of the above mentioned design strategies are the most important to use as advice for product engineers. This was done by asking a number of recycling companies and experts in this field to provide their opinion on the guidelines and design strategies in the form of a survey. Section 4.2 and its subchapters thus treat the results from the second and third objective of this thesis, which was to select the most important design strategies for recyclability and to create a user-friendly tool.

### 4.2.1 Survey results

The survey received ten responses from recycling companies and experts in recycling. Each design strategy was given a score by each survey respondent and these scores were calculated into an average score for each design strategy. The score from the survey reflects the importance of each design strategy. The design strategies are presented in Figure 9, with their corresponding average scores indicated in the rightmost column.

The respondents could give a score between 1 and 5 for each design strategy, where 5 represents the most important. Some design strategies received mixed scores while others were quite uniform. It is difficult to say why the responses differ; perhaps due to personal preferences or a difference in background or knowledge. There is no clear pattern on which design strategies received a particularly mixed score, but the ones with quite a high score such as 4 and above were indeed given a high score among almost all respondents. The same goes naturally for the ones with a very low score.

The outcome of the survey provided the average scores for each design strategy that reflects their importance in this thesis. For a strategy to be considered important, an average received score of 3 from the survey was chosen, to fulfil the requirement of a user-friendly list of guidelines by only including the most important ones. See the Method section (2.4-2.5) for details. All design strategies that received an average score of 3 and above in the list of design strategies in Figure 9, were selected.

It was also considered to investigate if more design strategies should be included, by testing six of Philips products to see how they perform on recyclability today. This is described in section 4.2.3.

| Strategy number | Design strategies for recyclability | Survey score |
|---|---|---|
| **1.1** | Do not use a total sum of Phthalates in a higher concentration than | **2** |
| **1.2** | Do not use any PVC (Polyvinylchloride) in the product; ensure that it | **2.6** |
| **1.3** | Do not use any BFR’s (Brominated Flame Retardants; PBDEs, | **3.2** |
| **1.4** | The ‘CARACAL list’ (Competent Authorities for REACH and | **3** |
| **2.1** | Do not permanently fix batteries in a product. Avoid glued, welded and | **4.2** |
| **2.2** | Do not permanently fix valuable components (PCBs, cables, wires and | **4** |
| **2.3** | Provide drains for operating liquids and gasses and ensure those | **3.2** |
| **2.4** | Provide detachment possibilities for toxic, hazardous, and polluting | **4.6** |
| **2.5** | If no drainage or detachment option is present, provide markings for | **3.111111** |
| **2.6** | Use a module for hazardous components in the product structure to | **3.7** |
| **3.1** | Do not use thermosets since they end up in the waste fraction for | **2.8** |
| **3.2** | When thermosets are necessary, use thermosets with a different density | **2.555556** |
| **3.3** | Do not use elastomers, they end up either polluting the plastic fraction | **2.6** |
| **3.4** | When elastomers are necessary, use elastomers with a different density | **2.888889** |
| **3.5** | Do not use polymer blends like PC-ABS since it cannot be separated | **2.666667** |
| **3.6** | Do not use more than 5% master batch in plastics (flame retardants, | **2.8** |
| **3.7** | When using plastics, use only common plastics (such as ABS, PE, PP, | **4.3** |
| **3.8** | Do not use biodegradable plastics, since it will pollute the plastic | **2.4** |
| **3.9** | Do not use coatings on plastics such as painting, lacquering, plating, | **3.3** |
| **3.10** | When using metals, ensure that they have characteristic metal | **2.8** |
| **3.11** | Do not use permanent magnets, they get stuck in the magnet separation | **2.8** |
| **3.12** | Do not use composites, they end up in burning, landfill or polluting | **2.6** |
| **3.13** | Do not use ceramics (cement, concrete, alumina and silicon) since they | **1.8** |
| **3.14** | Do not use paper, cardboard, wood, textiles and foams, since these will | **2** |
| **3.15** | Do not use adhesives, glues, stickers, labels, PSA (Pressure Sensitive | **2.4** |
| **3.16** | Do not use operating liquids and gasses which stay present in the | **2.9** |
| **3.17** | Use as few materials as possible since the fewer materials the purer | **3** |
| **4.1** | Do not mold different material types together by 2K or xK processes | **3.4** |
| **4.2** | Prefer snap-fits for plastic components (particularly housing), to allow | **2.9** |
| **4.3** | Do not fix ferro metals to non-ferro metals in parts or fasteners. For | **3.333333** |
| **4.4** | Do not permanently fix Aluminum, Copper, Stainless steel or Steel | **4.3** |
| **4.5** | If the main material is Copper, do not permanently fix a part of Iron, | **3.666667** |
| **4.6** | Use a detachable power cord instead of a permanently fixed one. | **1.8** |
| **4.7** | Do not use fasteners that are not compatible with the connecting | **2.3** |
| **4.8** | Do not use connections that enclose a material permanently to avoid | **3** |
| **4.9** | If connections are applied that enclose materials permanently, apply | **2.888889** |
| **4.10** | Cluster materials of the same type. Ensure that wires connected to | **2.2** |
| **4.11** | Use the same type of fasteners in the product and make sure it can be | **2.8** |
| **4.12** | Avoid overdimensioning of the fasteners as well as the parts in the | **1.7** |

**Figure 9. The list of design strategies on recyclability that was sent as a survey to recycling companies and experts. The average scores that each design strategy received in the survey are indicated in the rightmost column. The score reflects the importance of each design strategy, and was measured on a scale from 1-5, where 5 is most important.**

### 4.2.2 Additional review

An additional review of the list of design strategies presented in section 4.1.4 was done after the survey had already been carried out, by an expert in waste management (Ljunggren Söderman, 2012). This review resulted in a number of comments on the design strategies, which are important to consider before making the final selection of advice on recyclability. The main comments gained in this review are stated below:

- Regarding design strategy 3.11 (Section 4.3, Guideline 3) Permanent magnets in products are sometimes motivated since they are light, strong, takes less space. This should be a trade-off depending on the type of product and what alternatives exist.
- Paper, cardboard and wood in products is to prefer from a total life-cycle perspective. From a total environmental impact point of view, it is better to use wood and paper than for example plastics.
- To provide markings of plastics is highly recommended. In Europe, the plastic parts are currently not manually sorted but first shredded, while in Asia it is common to have manual sorting of for example plastic parts. To provide markings is therefore a way to make the product easier to identify, which does not require much effort.

After the results from the survey were evaluated, the above comments were considered. Regarding permanent magnets, it might be motivated to use them, very much depending on what the alternatives are. If this advice ends up in the final selection of design strategies, it will be re-evaluated. If there are no better alternatives to permanent magnets for Philips products, it is not relevant to advice to avoid them. The comment on permanent magnets resulted in the knowledge that it can be motivated for some products depending on the existing alternatives.

The result of the second comment regarding design strategy 3.14 on paper, cardboard and wood, (Section 4.3, Guideline 3), is that it will not be recommended even if it reaches the final selection. This is due to the fact that it is important to not give advice that contributes to a higher total environmental impact. A much better design strategy is instead design strategy 2.4 (Section 3.4, Guideline 2) with the focus on making paper, cardboard and wood easily removable instead of advising to avoid them. Design strategy 2.4 will therefore entirely replace design strategy 3.14.

Finally, to provide markings on plastic is an important comment, which is done for many years at Philips and already part of existing design manuals. This requirement is therefore not added to the guidelines, since it is already included in the current design manuals. Markings are often required to meet certain types of labelling for products, such as the European Eco-label. It is also expected from NGOs (non-governmental organizations) that products have this type of markings.

### 4.2.3 Testing on products

The outcome of the product testing is illustrated in Figure 10, where the design strategies that each product currently cannot comply with are indicated with an ‘X’. The design strategies are sorted from a high to a low importance, based on their received survey score.

| | | | X = not compliant | | | | | |
|---|---|---|---|---|---|---|---|---|
| Strategy number | **Design strategies for recyclability** | Survey score | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** |
| **2.4** | Provide detachment possibilities for toxic, hazardous, | **4.6** | | | | | | |
| **3.7** | When using plastics, use only common plastics (such | **4.3** | | **X** | | **X** | | |
| **4.4** | Do not permanently fix Aluminum, Copper, Stainless | **4.3** | | | **X** | | **X** | **X** |
| **2.1** | Do not permanently fix batteries in a product. Avoid | **4.2** | | | | | | |
| **2.2** | Do not permanently fix valuable components (PCBs, | **4** | | **X** | | | | |
| **2.6** | Use a module for hazardous components in the | **3.7** | | | | | | |
| **4.5** | If the main material is Copper, do not permanently fix | **3.667** | | | | | | |
| **4.1** | Do not mould different material types together by 2K | **3.4** | | **X** | | | **X** | **X** |
| **4.3** | Do not fix ferro metals to non-ferro metals in parts or | **3.333** | **X** | | **X** | | **X** | **X** |
| **3.9** | Do not use coatings on plastics such as painting, | **3.3** | | **X** | **X** | | **X** | **X** |
| **1.3** | Do not use any BFR’s (Brominated Flame Retardants; | **3.2** | | | **X** | **X** | **X** | **X** |
| **2.3** | Provide drains for operating liquids and gasses and | **3.2** | | | | | | |
| **2.5** | If no drainage or detachment option is present, | **3.111** | **X** | | | | | |
| **1.4** | The ‘CARACAL list’ (Competent Authorities for | **3** | **X** | **X** | **X** | | | |
| **3.17** | Use as few materials as possible since the fewer | **3** | | **X** | | | | |
| **4.8** | Do not use connections that enclose a material | **3** | | **X** | | **X** | **X** | **X** |
| **3.16** | Do not use operating liquids and gasses which stay | **2.9** | | | | | | |
| **4.2** | Prefer snap-fits for plastic components (particularly | **2.9** | **X** | | | **X** | | |
| **3.4** | When elastomers are necessary, use elastomers with a | **2.889** | | **X** | **X** | **X** | **X** | **X** |
| **4.9** | If connections are applied that enclose materials | **2.889** | **X** | **X** | | **X** | **X** | **X** |
| **3.1** | Do not use thermosets since they end up in the waste | **2.8** | | **X** | | | | **X** |
| **3.6** | Do not use more than 5% master batch in plastics | **2.8** | | | | **X** | **X** | **X** |
| **3.11** | When using metals, ensure that they have | **2.8** | | | | **X** | **X** | **X** |
| **3.11** | Do not use permanent magnets, they get stuck in the | **2.8** | | | | **X** | | |
| **4.11** | Use the same type of fasteners in the product and | **2.8** | | | | | **X** | **X** |
| **3.5** | Do not use polymer blends like PC-ABS since it | **2.667** | | **X** | | | | |
| **1.2** | Do not use any PVC (Polyvinylchloride) in the | **2.6** | | | **X** | | **X** | **X** |
| **3.3** | Do not use elastomers, they end up either polluting | **2.6** | | **X** | **X** | **X** | **X** | **X** |
| **3.12** | Do not use composites, they end up in burning, | **2.6** | | | | | | |
| **3.2** | When thermosets are necessary, use thermosets with a | **2.556** | | **X** | | | | |
| **3.8** | Do not use biodegradable plastics, since it will | **2.4** | | | | | | |
| **3.15** | Do not use adhesives, glues, stickers, labels, PSA | **2.4** | | | | **X** | **X** | **X** |
| **4.7** | Do not use fasteners that are not compatible with the | **2.3** | **X** | **X** | **X** | | **X** | **X** |
| **4.10** | Cluster materials of the same type. Ensure that wires | **2.2** | | | | **X** | **X** | **X** |
| **1.1** | Do not use a total sum of Phthalates in a higher | **2** | | | | | | |
| **3.14** | Do not use paper, cardboard, wood, textiles and | **2** | | | | **X** | | |
| **3.13** | Do not use ceramics (cement, concrete, alumina and | **1.8** | | | **X** | **X** | **X** | **X** |
| **4.6** | Use a detachable power cord instead of a permanently | **1.8** | **X** | | **X** | **X** | **X** | **X** |
| **4.12** | Avoid overdimensioning of the fasteners as well as the | **1.7** | | | | | | |

**Figure 10. The testing of six Philips products showing which design strategies on recyclability the products cannot currently comply with. The design strategies are sorted from a high to a low importance based on their received survey score. A product that cannot comply with a design strategy is indicated with an ‘X’ in the corresponding box.**

As mentioned in section 4.2.1, all design strategies with an average score of 3 and above, will be selected. On top of this, the guidelines just below this limit that received a score between 2.5 and 3 were reviewed, see Figure 11. If the vast majority (more than three out of six) of the products tested were not compliant on these strategies, they were either included or; if suitable; combined with another strategy. This was done to ensure that the ones near the chosen limit were not neglected, but considered for inclusion once more depending on how Philips products currently perform on recyclability. The ones that are just below 3 can still be seen as relatively important and if a number of products cannot comply with those today, they are worth including as advice for future improvements.

The design strategies where more than three out of six products cannot comply will be included in the final selection. Those design strategies are highlighted in Figure 11.

| | | | X=not compliant | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Strategy number | **Design strategies for recyclability** | Survey score | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | |
| **4.8** | Do not use connections that enclose a material permanently to avoid polluting | **3** | | **X** | | **X** | **X** | **X** | **LIMIT** |
| **3.16** | Do not use operating liquids and gasses which stay present in the product at the | **2.9** | | | | | | | Not applicable, concluded not to be used in Philips' products |
| **4.2** | Prefer snap-fits for plastic components (particularly housing), to allow easy | **2.9** | **X** | | | **X** | | | No, too few are non-compliant |
| **3.4** | When elastomers are necessary, use elastomers with a different density than | **2.889** | | **X** | **X** | **X** | **X** | **X** | Yes, combined with 3.3 |
| **4.9** | If connections are applied that enclose materials permanently, apply gaps and or | **2.889** | **X** | **X** | | **X** | **X** | **X** | Yes, combined with 4.8 |
| **3.1** | Do not use thermosets since they end up in the waste fraction for burning; choose | **2.8** | | **X** | | | | **X** | No, too few are non-compliant |
| **3.6** | Do not use more than 5% master batch in plastics (flame retardants, stabilizers, | **2.8** | | | | **X** | **X** | **X** | No, too few are non-compliant |
| **3.10** | When using metals, ensure that they have characteristic metal properties, such as | **2.8** | | | | **X** | **X** | **X** | No, too few are non-compliant |
| **3.11** | Do not use permanent magnets, they get stuck in the magnet separation of metals | **2.8** | | | | **X** | | | No, too few are non-compliant |
| **4.11** | Use the same type of fasteners in the product and make sure it can be | **2.8** | | | | | **X** | **X** | No, too few are non-compliant |
| **3.5** | Do not use polymer blends like PC-ABS since it cannot be separated into PC and | **2.667** | | **X** | | | | | No, too few are non-compliant |
| **1.2** | Do not use any PVC (Polyvinylchloride) in the product; ensure that it is 100% | **2.6** | | | **X** | | **X** | **X** | No, too few are non-compliant |
| **3.3** | Do not use elastomers, they end up either polluting the plastic fraction or in the | **2.6** | | **X** | **X** | **X** | **X** | **X** | Yes, combined with 3.4 |
| **3.12** | Do not use composites, they end up in burning, landfill or polluting other | **2.6** | | | | | | | Not applicable, concluded not to be used in Philips' products |
| **3.2** | When thermosets are necessary, use thermosets with a different density than | **2.556** | | **X** | | | | | No, too few are non-compliant |

**Figure 11. A review of the design strategies that received a survey score between 2.5 and 3 was made, based on how the products tested perform on recyclability today. If more than half of the products tested (more than three of six) cannot currently comply with a design strategy, it will be included in the final selection. Design strategies where more than half of the products cannot comply are highlighted, and will be included.**

### 4.2.4 Guidelines and design strategies for recyclability

This list of guidelines and design strategies makes up the final result of this thesis, and is illustrated in Figure 12. The selected design strategies reflect the opinion of ten recycling companies and experts on what advice should be given to engineers to improve the recyclability of products. The final list consists of 14 design strategies and represents the most important advice to increase recyclability of an electronic product. Please note that the design strategies have here been re-numbered.

This list also represents the result of the third objective, which is a user-friendly tool for engineers on recyclability. The list contains the most important 14 points of advice on recyclability that should be integrated into the already existing product development process.

| **Guidelines and design strategies for recyclability** | | | | |
|---|---|---|---|---|
| | **GUIDELINE 1: Do not use hazardous substances** | **Compliance** | | |
| **1.1** | **Do not use any BFR's (Brominated Flame Retardants; PBDEs, TBBPA, PBBs, HBCDs, etc.) in the product. Make it 100% BFR-free.** | **Yes** | **No** | **Partly** |
| | To phase out BFRs is a company specific strategy of Philips, as an initiative to prepare for future legislation. These substances are likely to be restricted in the future and therefore it is desired to already now stop using them. Several BFRs are already restricted and it is likely that more will become banned. The substances on this list are not yet covered in Philips RSL. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future. Important is that not a worse alternative is selected, if you have ideas for a replacement for BFR fulfilling the same function - contact a materials expert or the sustainability department. | | | |
| **1.2** | Do not use substances that are listed for future restriction in the 'CARACAL list' (Competent Authorities for REACH and Classification and Labelling). These substances are mainly used in plastics as surfactants, solvents, stabilizers, plasticizers, anti-corrosions, pigments and coatings. Do not use in concentrations above 1000ppm, (0,1% per article) per substance.<br>**-PFOS, heptadecafluorooctane-1-sulfonic acid, perfluorooctane sulfonic acid, ammonium heptadecafluorooctanesulfonate, ammonium perfluorooctane sulfonate potassium heptadecafluorooctane-1-sulfonate, potassium perfluorooctanesulfonate**<br>**- Bis (2-methoxyethyl) ether - 2-ethoxyethyl acetate**<br>**- 1,2-dimethoxyethane - Buta-1,3-diene**<br>**- Hexachlorobenzene - 2-methoxypropyl acetate**<br>**- Thioacetamide - N,N-dimethylformamide**<br>**- Hexachlorobuta-1,3-diene - 1,2,3-trichlorobenzene**<br>**- 4,4'-(4-iminocyclohexa-2,5-dienylidenemethylene) dianiline hydrochloride**<br>**- 4,4'-methylenebis[2-chloroaniline] - Diisobutyl phthalate** | | | |
| | The 'CARACAL list' is a list of substances that are not restricted yet, but are a good indication of substances for future restriction and regulation. These substances are likely to be banned in the future and therefore it is important to already now stop using them. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future. The substances on this list are not yet covered in Philips RSL. | | | |

| GUIDELINE 2: Enable easy access and removal of hazardous or polluting components | | | | |
|---|---|---|---|---|
| 2.1 | **Use click/snap solutions to fix <u>batteries</u> in a product. Avoid permanent fixing such as glued, welded and enclosed solutions.**<br><br>Batteries can cause problems in the recycling process if they are not manually removed before they go into the shredder. If not removed, they pollute the material streams and can explode during the recycling process. Batteries are also seen as dangerous by consumers, and therefore it is important to make them easily removable. | **Yes** | **No** | **Partly** |
| 2.2 | **Use click/snap solutions to fix <u>valuable components</u> (PCBs, cables, wires and motors) in a product. Avoid permanent fixing such as glued, welded and enclosed solutions.**<br><br>Valuable components can pose a health and safety risk since a large part of all e-waste still ends up in third world countries where it is recycled on the street under very primitive conditions. These components are often extracted by methods such as burning cables to extract the copper and pouring acids on PCBs to get out the valuable metals.This releases many kinds of toxic fumes and poses a great health risk to humans and an environmental risk since the local surroundings often suffer from these activities. To account for these risks, designers are advised not to glue valuable components together but to choose for click/snap-solutions to enable easy removal. If the valuable components are easier to take out it contributes to less negative health and environmental impacts. It also has a positive impact in controlled recycling, since if the valuable materials can be easily separated, less of it gets lost into other material streams and more can be recycled into new materials. | | | |
| 2.3 | **Use drains for operating liquids and gasses and enable easy removal of components such as oil tank, compressor and hoses.**<br>Drains are important to provide to avoid polluting the material streams in the recycling process, since drains make it possible to take out operating liquids and gasses and prevent them from polluting the material streams or the surrounding air. Therefore it is important to consider the removal of these components in the design, and make sure they are easy to find and take out. In case the request for drains is not possible to fulfil, markings for destructive action can help the first stage in the recycling process where the product breaks open. This usually happens when the product falls onto the recycling belt in the first dismantling step. If it does not break open there, a marking or indication on where to manually apply force to enable taking out a polluting component is helpful. | | | |
| 2.4 | **Use detachment possibilities for polluting components/materials (dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams and glass).**<br><br>To provide detachment possibilities for hazardous and polluting components are vital since they otherwise easily end up polluting the material streams. The easier it is to take out these materials the easier it is to keep the material streams pure. In case the request for detachment possibilities is not possible to fulfil, markings for destructive action can help the first stage in the recycling process where the product breaks open. This usually happens when the product falls onto the recycling belt in the first dismantling step. If it does not break open there, a marking or indication on where to manually apply force to enable taking out a polluting component is helpful. | | | |
| 2.5 | **Use a module for hazardous components in the product structure to enable taking out <u>one</u> non-recyclable module instead of searching for several different hazardous parts.**<br><br>To use one module where all the hazardous components are located makes the recycling process easier and more efficient. It is easier for the recycling workers to find one module in the manual dismantling step instead of taking time to find several components. It saves time and effort in the process which reduses costs significantly. | | | |

| GUIDELINE 3: Use recyclable materials | | | | |
|---|---|---|---|---|
| 3.1 | **Use only common plastics in the product such as ABS, PE, PP and PS.** Common plastics can easily be recycled and are always to be used as a first choice. If another material is needed ensure the reasons are motivated and supported. There are established recycling streams for these plastics, which mean that they very likely will be recycled. Other materials currently occur in too small volumes in the waste stream to make it economically viable to recycle them. | **Yes** | **No** | **Partly** |
| 3.2 | **Do not use coatings on plastics such as painting, lacquering, plating, and galvanizing, since it can result in changed density of the plastic. A density difference < 1% of the materials weight is ok. Always avoid plating since it is a problem as it connects plastic and metal.** Avoid coatings if possible since all forms of coatings pollute the material streams or makes the recycling process difficult. Coatings change the density of the plastics, which makes it likely to end up in the wrong material stream. The coating material itself also pollutes the streams. Printing of numbers or lines for level-indication (which are small compared to the product as a whole) are not a problem, in fact that is better than using a sticker for the same purpose. | | | |
| 3.3 | **Do not use elastomers. When elastomers are necessary, use elastomers with a different density than the common recycled plastics (not in the density range of PP, PE, PS and ABS which is 0.888e3 – 1.070e3 kg/m3).** If elastomers are necessary, use a density that is different from common plastics, since then the elastomer will end up polluting the material streams of these plastics. The separation of plastics and similar materials is done by density separation, usually in various floatation steps. The density will therefore determine which recycling stream the plastic ends up in. | | | |

| | GUIDELINE 4: Use material combinations and connections that allow liberation | | | |
|---|---|---|---|---|
| 4.1 | **Do not mold different material types together by 2K or xK processes (different plastic materials injected into the same mould) such as molding a thermoplastic elastomer onto PP (e.g. toothbrush). If the material types are the same and only differ in colour and additives it is ok to use, for example molding red PP containing antioxidants on black PP containing talc.** | **Yes** | **No** | **Partly** |
| | Avoid molding different material types together since the end result will not be recyclable. It is very difficult to separate materials that have been joined by 2K or xK processes. Therefore these joined materials will end up as waste or (depending on density) they will pollute other plastic streams. | | | |
| 4.2 | **Do not fix ferro metals to non-ferro metals in either parts or fasteners. For example, do not use a screw (ferro metal) to attach a plastic part to aluminum (non-ferro).** If ferro and non-ferro materials are joined and the product goes into shredding it is very likely that either the ferro or the non-ferro stream will be polluted. The materials are shredded to small pieces and either the screw will go with the host component to the non-ferro stream or the non-ferro part will follow the screw into the ferrous stream.This pollutes the material streams. | | | |
| 4.3 | **Do not permanently fix Aluminum, Copper (including Brass), Stainless steel or Steel together in the following combinations:**<br>**- If the main material in a component is Al (cast), do not attach a part of Stainless steel or Steel onto it.**<br>**- If the main material in a component is Al (wrought), do not attach a part of Al (cast), Copper, Stainless steel or Steel onto it.**<br>**- If the main material in a component is Stainless steel, do not attach a part of Copper onto it.**<br>**- If the main material in a component is Steel, do not attach a part of Copper or Stainless steel onto it.**<br>**- If the main material is Copper, do not permanently fix a part of Iron, Lead, Antimony or Bismuth to it.**<br>These combinations are based on thermodynamical properties of the materials, indicating which materials are feasible to combine and which ones are not.Depending on the main material in a component, smaller amounts of other materials will end up polluting that stream. Some materials are easy to separate while some are very problematic. A good and easily separable material combination will result in streams that are less contaminated as well as less waste, since many streams containing a pollutant that is hard to extract will simply end up as a waste fraction. The combinations listed here are a shortened version of the full list, adapted to the most used materials in Philips products. This list should also be considered when selecting fasteners. | | | |
| 4.4 | **Do not use connections that enclose a material permanently. Avoid methods such as: molding-in inserts into plastic, rivets, staples, press-fit, bolts, bolt and nut, brazing, welding and clinching.** To avoid using connections that enclose a material permanently helps to avoid polluting the material streams. Enclosing a material permanently makes it harder to separate the different materials. The processes mentioned are typical for tightly enclosing one material into another, and are therefore recommended to be avoided. | | | |

**Figure 12. The final list of the four guidelines containing the 14 most important design strategies for recyclability.**

## 4.3 Objective 4: Suggestions for practical implementation at Philips

The following section describes the findings to answer the fourth objective of giving suggestions for implementation at Philips.

### 4.3.1 Integration into the IPD process

The IPD (Integrated Product Development) process was described in the literature study with the aim to illustrate where guidelines on recyclability can be used. The guidelines should preferably be used in the early design phase, where changes in the design are still possible and therefore the potential for improvement is higher than if done late in the development process. If done later, there is a large risk that the product design is already fixed and it would be too costly to make any changes.

To improve the recyclability of a product, the engineer should be able to make decisions on the main choices of construction and materials. These choices are usually done early in the process. There are however a number of challenges with using a tool early in the product development process. A problem with using guidelines on materials and substances at this stage is that the engineer does not always have access to proper material lists yet. Detailed material lists can sometimes be difficult to obtain from suppliers and sometimes they are not received until later in the project. The later in the project, the more specific information the engineer has but the more difficult it is to make changes.

These findings influenced the final suggestions for implementation in terms of that it provided understanding of challenges that engineers may face. Implementation in the early stage is recommended despite the difficulties described above. The advice on recyclability is very much aimed at awareness and therefore it is still useful to emphasize this in the early stage when there is still potential for changes. It can also serve as a motivation for engineers to push suppliers towards providing proper lists already at the start of a project to help them make informed decisions regarding material choices.

### 4.3.2 Results from interviews with engineers

During the interviews with engineers, the list of guidelines and design strategies were presented and discussions took place around the content of these as well as on how to practically implement guidelines or a tool on recyclability.

The feedback from engineers was mainly positive and practical hands-on design strategies were particularly appreciated. They prefer to have examples on which materials are ok to use and which ones are not. The more specific a design strategy is the more likely is it that they will follow it. If it states “do not use a material” then they prefer to know which material to pick instead. Chemical content seems to be the most difficult to handle, since most engineers lack detailed knowledge about chemicals, and the responsibility of chemical management reaches over several departments. It is a joint responsibility of the quality department, the purchasing department and the engineers in each department. They are working closely together, but from the engineers interviewed it is not seen as the direct responsibility of the engineers.

The product architects were also mentioned in the interviews as someone who has the overall responsibility and makes decisions regarding for example product structure and material choices. Therefore, interview sessions were also scheduled with the architects, see section 4.3.3.

Ideas on how to implement the tool in the daily work were raised, and suggestions favoured implementing it into a document or process that already exists. One idea is to implement it into the IPD process (see literature review) to make it a part of the existing product development process. It could there be integrated into the documentation process as a checklist on recyclability. To use it at the "gate" called PPC (Project Plan Committed) could be a useful way to integrate it into the early phase of the already existing development process. The ideal place for a tool to be used would be in the early design stage, before the product design becomes too fixed and specifications are difficult and costly to change.

Another idea is to add the tool to a list of 'do's and don'ts' that exists within each department. The list is basically a list of requirements that are specifically adapted to the products of each department.

### 4.3.3 Results from interviews with architects

The main response from the session with product architects involved a positive attitude and interest in how their products can influence the recyclability. An important insight was that the design strategies discussed instantly seemed to raise awareness. Several design strategies received responses indicating that the architects were not aware of that certain materials, combination of materials or certain components used in their products actually cause problems in the recycling process.

Other comments were that content regarding chemicals are difficult; mainly due to the fact that most engineers lack knowledge in chemicals and that they do not always have information from suppliers regarding specific chemicals. The ones covered in current legislation such as RoHS and REACH as well as Philips Regulated Substances List (RSL) are agreed through supplier contracts. But chemicals for future legislation that are not yet covered in these contracts are difficult to monitor. Substances such as PVCs and BFRs are they however familiar with.

Regarding which materials or material combinations to avoid, it would be preferred to have a list of approved substances or materials. For example, if a design strategy states "do not use material A", then add a list of which ones are an approved alternative. In short, as practical and detail "hands-on" advice as possible is appreciated.

The comments also involved questions on whether this will be mandatory requirements or whether it will be used for education. Architects were also asking if and how a scoring will be applied to these guidelines.

A thought on the implementation was whether the guidelines should be applied for all products or if they should only be applied to Philips line of environmentally better performing products called the "Green products". The guidelines could there be made part of the green product requirements. It could for example be set as a requirement to comply with 50 % of the guidelines in 2015, with 60 % in 2016 etc. or a requirement for all products integrated into the product development process documentation system as checklists in the beginning and at the end of a project.

Final comments from the architects were that they believe that awareness among the engineers is the first step in implementing guidelines on recyclability. A first step could be to organize workshops and training sessions, preferably with a dismantling session or a practical way to visualize the content of the guidelines. For the site in Drachten where the product architects in this session are located, it was suggested to do a first introduction by a presentation in an upcoming "Quarterly Town-hall meeting" where a lot of engineers can be reached at the same time, to generate a first attention to this topic.

### 4.3.4 Implementation of the guidelines

How to implement the guidelines and design strategies has been thoroughly discussed with the Sustainability department at Philips Consumer Lifestyle as well as with product engineers and architects. It has been discussed whether they should be used as an assessment tool with a score, or if they should be used as a checklist for improvement or as education and training material.

The possibility to assign a value or apply a scoring to the design strategies, depending on how important they are, has been considered. This would mean that a product could be awarded a score on recyclability, depending on their performance. Scores or values have however not been applied, since the products at Philips are so diverse, and it is significantly harder for some products to comply with the design strategies. This is due to the complexity and performance requirements of various types of products.

For now, a scale of compliance is therefore chosen, indicating whether a product is compliant, non-compliant or partly compliant (see the scale in Figure 12). This can also be expanded to a scale with percentage, to indicate more specifically to what extent the product complies. An example of a scale with percentage is shown in Figure 13. As a start, it is however recommended to look at the ones that a product currently cannot comply with and focus on how to improve on those points.

| NO | 0-25% | 25-50% | 50-75% | 75-100% | YES |
|---|---|---|---|---|---|

**Figure 13. Example of a scale for product compliance in recyclability.**

It has also been elaborated on who should be responsible for the guidelines. An idea was first to split the responsibility over several people, since the list contain very wide subjects, but on the other hand there is a risk that the list gets lost somewhere in between. I would recommend dividing the list into two parts but still having one person responsible, for example the product architect. The part regarding chemicals probably needs to be communicated to the purchasing department while the other part can be communicated to the engineers. If further advice is needed, the quality department or materials experts might also need to be consulted. Important is that one person has the overall responsibility, ensuring that the information or support needed is collected and provided by the appropriate department or expert.

A suggestion on how to implement the guidelines is presented below as a number of recommended steps.

A first step should be to attract attention and awareness for recyclability in product design. A practical step for this can be a presentation where a lot of employees attend, for example in a large quarterly meeting where the company results for each quarter are presented. This could be a good first step to generate attention and also to show the support from the management in this subject.

As a second step, it is recommended to organize workshops with engineers. In these workshops awareness for recyclability can be raised, and the meaning of the design strategies can be visualized by conducting dismantling of products during these sessions. It could also be interesting to organize a workshop and exchange ideas with various stakeholders involved in a product's life cycle, such as representatives from suppliers, product engineer as well as representatives from the recycling industry.

After a first awareness has been raised, the guidelines should as a third step be discussed in each product team, together with the product architect who has the overall responsibility of the product. Here, discussions on which design strategies could be implemented should be introduced. The final implementation of guidelines on recyclability preferably consists of that each product team set their own requirements of their products. The goal should be to always improve the recyclability compared to a previous model of the product.

Finally, the guidelines are suggested to be incorporated in the form of a checklist into the existing IPD (Integrated product Development) process. It could there be integrated into the early design phase such as at the PPC gate where a checklist is filled in (see Figure 14), together with a corresponding checklist at the end of the project. At the end of the project the list can be checked again to evaluate and confirm what was actually implemented in terms of compliance to the guidelines.

Updates of the guidelines are also necessary, particularly regarding chemical substances since legislation on new substances are continuously added.

| Project Confirmation | | |
|---|---|---|
| Name | Status | Start Date |
| Evidence Sheet | Completed | [None] |
| Project Progress Report | Completed | [None] |
| Recyclcbility confirmation | Routed for Approval | [None] |
| IPD model agreed | Completed | [None] |
| PPC Gate Decision Proposal | Not Started | [None] |

**Figure 14. Example of a way to integrate recyclability into the product development process.**

# 5 Discussion

First, the methods used in this thesis are briefly discussed, followed by a discussion on the resulting guidelines and the suggested implementation at Philips. Finally, potential sources of errors are described as well as recommendations and advice on future work.

## 5.1 Discussion on the methods

To compare the methods in this thesis with the PRI-tool, more recycling companies were involved (six compared to three). The recycling companies were in this thesis involved by directly ranking practical design strategies, compared to the PRI-tool that investigated which 'consequence' in the recycling process is most important to prevent. A number of experts in the field of recycling were also consulted, which was not done in the development of the PRI-tool.

The choice of research methodologies used in this thesis and the number of respondents and experts involved will likely influence the results. The research methodologies used in this thesis were literature study, interviews, survey and product testing. The result of this research reflects the opinions of a limited number of people involved in the field of recycling. The testing represents six products from various departments at the company. The interviews, the survey and the product testing are recommended to be conducted on a larger scale; to ensure the results accurately reflects the most important choices in product design.

### 5.1.1 Sources of errors

The amount of survey participants in the survey of the guidelines in this thesis was limited to ten, which makes the potential for errors larger than if the responding population would be bigger. The number is limited due to the time of the project but also to the fact that there are not that many experts in the field of recycling, it is for example not considered possible to find 100 experts to ask. However, ten responses still should give at least an indication of valuable advice since it was noticed that several guidelines were indeed highly graded by most respondents. Some design strategies however received a mix of grades ranging from 1-5. Possible reasons for this may be a difference in opinion on what is important in product design and the recycling process as well as different interests or varying degrees of knowledge.

The respondents consisted of a mix of academic experts and general recycling companies. The general recyclers are all in the category of pre-processors, meaning that they receive and process whole products. If the recyclers were a mix of pre-processors and end-processors (smelters or plastic recoveries), the result may have been expected to differ more since a plastic recovery might consider the design strategies on plastics more important and the other way around regarding metals for a smelter representative.

The experts have varying expertise in slightly different areas; however all of them are experienced in the field of recycling, eco-design and environmental impacts. Their varying knowledge or preferences might have influence on the results.

## 5.2 Discussion on the results

The discussion on the achieved results is divided into a discussion on the guidelines followed by a discussion on the implementation.

### 5.2.1 Discussion on the guidelines

As mentioned in the introduction, this thesis continues the work of a previous student, which was named the PRI-tool. The research of this thesis adds to the work of the PRI-tool in several ways. This tool or set of guidelines can be seen as more user-friendly since only the most important design strategies are chosen, the list of guidelines is thereby significantly shorter. It differs in chemical content since this thesis does not include mandatory legislation in the guidelines, or the company specific regulations found in Philips RSL (Regulated Substances List). This set of guidelines focuses on improving for the future, from the perspective of the recycling process.

In the developed set of guidelines, providing information to consumers about parts and contents of products has been excluded. This information is usually provided in the form of stickers or attached product documents. This is not due to a lack of importance, but has instead been put aside to consider for the marketing department, and not for the product engineers. The guidelines presented here are strictly focussed on improving the recyclability by design of a product and not on increasing the chances of a product ending up in recycling by providing information to the customer.

Regarding the chemical content in design strategy 1.2, this can be difficult for an engineer to understand. It is therefore recommended to cooperate with the purchasing or quality department regarding this matter, or contact a materials expert at Philips if necessary. For the future, it may be of interest to add the chemical requirements to the contracts that suppliers sign, referred to as a 'code of conduct'. Cooperation between departments regarding these topics will therefore most likely be necessary.

This report can provide an indication of what is important in product design to increase the recyclability of the product, with a focus on current recycling technologies. Hopefully it can be used as input for similar research in this area, such as GreenElec or StEP, see section 3.6 in the literature review.

### 5.2.2 Discussion on the implementation

For engineers to understand the importance of recyclable product design, I find an interesting option is to send product teams in small groups to recycling companies, where they are placed at a dismantling belt to dismantle their own products. Doing this could provide hands-on experience in a practical way where engineers can actually see where their products end up and how they are taken apart. This is however a cost and organizational matter which needs to be further investigated.

As always when implementing changes in an organization it is important to have support from the management. This means that it needs to be introduced from the top and spread throughout the organization, showing that this is important. It is necessary to incorporate the guidelines in the bigger picture such as emphasizing that sustainability is a part of the company's vision. Further, it is also important to clearly communicate the purpose and the goal of implementing these guidelines.

# 6 Conclusions

A number of conclusions can be drawn from the insights gained in this thesis; the most significant ones are described below.

- There appears to be a lack of knowledge in the area of recyclability among engineers and architects. There is a strong drive in being creative and innovative to deliver high performing products, but it is sometimes not known that certain materials or constructions impact the recyclability.

- However, there is a large interest in how to make the products recyclable. The response from engineers and architects has been very positive and they seem willing to change as long as they know how to change and which materials are allowed. For example, if a design advice states "Do not use material A", it should preferably be complemented with "instead use material B, C or D". There is thus a preference for detailed lists of approved materials.

- It was found difficult to implement some kind of scoring to quantify the recyclability. This is due to that the products at Philips are so diverse, and there is a large difference in complexity between a coffee machine and for example a shaver. The coffee machine can meet quite a lot of the requirements in the guidelines for recyclability, while for a shaver this might be technically impossible to achieve. Thereby it does not really make sense to have a score, if certain products; due to their complexity; will never be able to reach 100%. A coffee machine may reach quite a high score, while a shaver might not be able to reach higher than 50%. This might be due to that the shaver has many demands to meet regarding function, weight and material properties, and due to these it may never have the chance to comply with all requirements. If the products are not comparable, it does not actually give a valuable answer to assign a score to how a product performs.

- Therefore, a suggestion was to give the responsibility to each department to set their own department specific targets for which design strategies they will chose to improve on compared to a previous product model. They can set the goals themselves, and document it in the product development process.

- It was found that chemicals are already managed well at Philips, and on top of mandatory legislation there is also a list of company specific regulation termed the Philips RSL (Regulated Substances List). This list contains substances that are regulated on top of mandatory legislation. This confirms that the PRI-tool that was developed by a previous student, and had its main focus on chemicals, did not provide a fully accurate content regarding chemicals. The chemicals are already managed well and what of higher interest is to prepare for future upcoming legislation that are not yet on any lists of legislation, but likely will be within a few years. To already now phase out certain substances and thereby be prepared with alternatives for replacement already before legislation come into force, can create a competitive advantage for a company like Philips.

- It seems to be important to have one person responsible for the guidelines. If several departments are to split the responsibility, there is a risk that information is lost in between. Even if that person does not have all the knowledge necessary, it is that person's responsibility to get the information needed. Recommended from both engineers and higher management was in this case to give this responsibility to the product architect, alternatively the project manager.

- It seems important to not enforce these guidelines in terms of making them mandatory. Product engineers are already under a lot of pressure from time, costs and other demands, and often trade-off between these demands are necessary. An approach where the focus is on increased awareness and stimulating creativity is thereby to prefer. Visual support of what the guidelines mean, such as dismantling sessions, is likely helpful in illustrating the impact of different choices in design. Important is to communicate why it is important, that it is part of Philips vision to become more sustainable.

- Finally, product design cannot solve everything, but it can make the recycling process easier, and mitigate harmful effects on human health and the environment. It can contribute to keeping the material streams more pure and thereby enable the materials to be recycled and used again. Thereby the environmental impact may be reduced, since waste material, energy use and emissions from mining raw materials can be reduced. To solve the entire e-waste problem, the design of recyclable products needs to be combined with efforts in several other areas. Examples of such areas are collection and organizational efforts as well as changes in people's consumption behaviour. The recycling process in itself also contains large improvement potentials, with new technologies for separation and additional steps to identify, sort and separate materials from each other.

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Wang, F. (2012). PhD student at Delft University of Technology, Delft. Researcher at UNU Institute for Sustainability and Peace (UNU-ISP), Bonn. Personal contact regarding health and safety aspects as well as review of the guidelines. July, 2012.

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# Appendix A - Small household appliances

The following products are in the category small household appliances at Philips Consumer Lifestyle.

- Vacuum cleaners
- Carpet sweepers and other appliances for cleaning
- Appliances used for sewing, knitting, weaving and other processing for textiles
- Irons and other appliances for ironing, mangling and other care of clothing
- Toasters
- Fryers
- Coffee machines and grinders
- Equipment for opening or sealing of containers or packages
- Electric knives
- Appliances for hair-cutting and hair-drying
- Appliances for tooth brushing
- Appliances for shaving, massage and other body care appliances
- Clocks, watches and equipment for measuring, indicating or registering time
- Scales

# Appendix B - List of experts interviewed

*Aarts-Hornix, Eefje.* Research Engineer, Photonic Materials and Devices, Philips Research Eindhoven. Contacted regarding design for recyclability guidelines and SimaPro and EcoScan tool.

*Balkenende, Ruud.* Principal Research Scientist, Photonic Materials and Devices, Philips Research Eindhoven. Contacted regarding design for recyclability guidelines.

*Dirksen, Mark-Olof.* Function Developer, Materials and Finishing, Technical Expert Group, Philips CL Drachten. Contacted regarding the design for recyclability tool and regarding testing with engineers in Drachten.

*Fan, Ginny.* Senior Manager Sustainability, Mechanical Commodity Cluster, Philips CL Eindhoven. Contacted regarding material declarations in BOMcheck to search for substances present in Philips' products.

*Huisman, Jaco.* Scientific Advisor at United Nations University Bonn, Director at OsevenfortytwO and Associate Professor at Delft University of Technology. Regularly contacted regarding design for recyclability guidelines.

*Ljunggren Söderman, Maria.* Senior researcher at IVL Swedish Environmental Research Institute and assistant professor at Chalmers University of Technology, Gothenburg, Sweden. Contacted regarding feedback on the guidelines and design strategies, particularly regarding her expertise in environmental system analysis in waste management and recycling.

*Peters, Harm.* Master student on "Generating design for recyclability guidelines" at University of Twente. Harm is a previous student at Philips who worked on a tool for recyclability and whose project this Thesis continues. The outcome of his project is referred to as the Product Recyclability Indicator (PRI) tool, and he interviewed and regularly contacted for questions about his tool.

*van Schaik, Antoinette.* Owner, MARAS - Material Recycling and Sustainability, The Hague, The Netherlands. Contacted regarding design for recyclability guidelines and resource efficiency.

*Scheijgrond, Jan-Willem.* Senior Director Environmental Health and Safety, Philips Corporate Sustainability Office. Contacted regarding rare earth metals and regarding design for recyclability guidelines.

*Setayeh, Sepas.* Materials and Finishing Engineer, Chemistry and Polymers, Philips CL Drachten. Contacted regarding chemicals in products and chemical legislation around SVHCs.

*Sivonen, Tarja.* Senior Manager Sustainability, Philips Eindhoven. Contacted regarding chemical legislation, RoHS and REACH including SVHCs and upcoming legislation.

*Soichez, Valerie.* Incident Handling and Regulatory Manager SCR, Philips Eindhoven. Contacted regarding chemicals in products and chemical legislation.

*Stevels, Ab.* Professor in Applied EcoDesign at Delft University of Technology, Delft. Contacted regarding advice for recyclability and discussion around experiences in implementing Eco-design.

*Wang, Feng.* PhD student on the direction of modelling and eco-efficiency assessment of e-waste collection and recycling systems at Delft University of Technology, and researcher at UNU Institute for Sustainability and Peace (UNU-ISP) on various e-waste topics mainly focusing on e-waste management in developing countries like China. Contacted regarding health and safety aspects on design for recycling, and for general feedback on survey design and design for recyclability guidelines.

*Wilkens*, *Bernard.* Senior Manager Regulatory SCR, Philips Eindhoven. Contacted regarding chemicals in products and chemical legislation.

## Appendix C - Study visit at Coolrec

A study visit to Coolrec was conducted, to the facility where the first manual dismantling step is conducted. Coolrec is one of Europe's largest companies in waste electrical and electronic equipment (WEEE) recycling. The first manual step consists of a conveyor belt which electronics fall onto from about one meter height, and break open. On the conveyor belt they are manually dismantled by eight workers, who ensure that certain parts and materials are taken out and that power cords are manually cut off. The products spend about 30 seconds on the belt before they end up falling down a few meters into a big container. This container is further transported to their second plant, to go through the next step in the recycling process.

The material/components taken out in the first dismantling step at Coolrec are (for household appliances): power cords, batteries, filters, dust bags, coffee pads, and liquid crystal displays (LCDs) over 100 $cm^2$. For other appliances, a number of additional materials are taken out, such as wood, oil containing materials, hazardous waste (for example capacitors, mercury switches, radioactive material, smoke detectors, toner, cartridges, printer ribbons, appliances containing asbestos, general waste and cathode ray tubes (CRT) for TVs or flat panel displays) (Verbrugge, 2012).

To see this step in reality was very valuable and provided a very good insight into problems encountered when recycling electronics. The manual dismantling workers are facing many difficult challenges in finding and being able to remove problematic components in a very short time. It gave a good insight in the first dismantling step and what needs to be manually removed before the product is sent to the second step in the recycling, which is normally shredding.

An observation of this manual dismantling line is the enormous effort of cutting off all the power cords. To have detachable power cords would make the dismantling step easier and faster, as well as prevent that there is always a piece of cord that is left and goes along with the product. The cords contain copper inside and this metal is thereby lost. The plastic around the copper is usually not the purest plastic material and might thereby end up polluting the recycling streams of other plastics. A question is therefore if detachable power cords could be used like usually seen in laptop chargers and TV's. Harm Jan Visser, who is an expert in safety requirements at Philips' Safety, Compliance and Regulatory department, was contacted regarding this matter. The question asked was why certain products such as computers and TV's have this cord but household appliances not. The answer from Harm Jan was that the detachable cord is generally more expensive compared to the connected cord. For TV and PC's this is less of an issue because the appliances are more expensive on the market. For a household product the proce has larger impact since these products are generally cheaper. Another reason is that TV's, PC's and other IT and Audio equipment have an internal or connected power supply which allows for the complete voltage range to be able to be used all over the world (100-240 V). In this sense the appliance is electrically more or less universal, and the only variable component for the product is the mains plug. For household appliances this universal voltage is not feasible because of certain technical issues and the fact that it would lead to higher power consumption (Visser, 2012).

Most products that Philips Consumer Lifestyle puts on the market are allowed to be fitted with a cord-set which can be unplugged from the appliance. But this solution comes with requirements from the product standards. In order to unplug a cord-set from an appliance an appliance-connector needs to be built-in. This appliance connector has to comply with a different standard, and adding this appliance connector will require redesign and re-certification of products. This is also a reason for why it is not currently used.

Concerning the potential improvement gained in the manual dismantling process with a detachable power cord, it is however added as a design strategy to the tool. This is done to see whether it is graded as important by recyclers by conducting a survey of the design strategies. If the detachable power cord could be made in a more cost-efficient way it might be something to strive towards for the future also for household appliances.

## Appendix D - Guidelines and strategies from PRI-tool

(Peters, 2012)

**G1. Do not use toxic or hazardous substances**

**S1.1.** Do not use toxic and hazardous substances incorporated in RoHS and REACH at all, unless it's technically impossible to avoid minute amounts.
**S1.2.** Do not use hazardous or toxic substances facing authorization (SVHC list)
**S1.3.** Do not use potential toxic or hazardous substances (maybe)
**S1.4.** Do not use at all: (I) toxic or hazardous halogens: (chlorine, bromine, fluorine, iodine, perfluorinated compounds), (II) toxic metals: (antimony compounds, beryllium compounds, glass containing heavy-metal) and (III) endocrine disruptors: (phthalates, alkylphenols, bisphenol A).
**S1.5.** Ensure the product does not contain substances assigned the following risk phrases or combinations thereof: R40, R45, R46, R50, R51, R52, R53, R60, R61, R62, R63 as defined in Council Directive 67/548/EEC and its amendments.

**G2. Use recyclable materials**

**S2.1**. Do not use thermosets.
**S2.2.** When thermosets are necessary, use thermosets with a different density than the common recycled plastics.
**S2.3.** Do not use elastomers.
**S2.4.** When elastomers are necessary, use elastomers with a different density than the common recycled plastics.
**S2.5.** Do not use composites.
**S2.6.** Do not use ceramics.
**S2.7.** Do not use paper, cardboard, wood, textiles and foams.
**S2.8.** Do not use polymer blends.
**S2.9.** Do not use more than 5% master batch in plastics.
**S2.10**. Do not use coatings such as painting, lacquering, plating, galvanizing, etc., when they are not compatible with the recycling process.
**S2.11.** Do not use adhesives, glues, stickers, labels, PSA tapes.
**S2.12.** Do not choose fasteners made of materials not compatible with the connecting components
**S2.13.** Do not use bioplastics.
**S2.14.** Do not use operating liquids and gasses which stay present in the product at the end of life of the product.

**G3. Minimize material diversity**

**S3.1.** Do not use more than 5% master batch in plastics.
**S3.2.** When using metals, ensure the ferrous metals used are magnetic.
**S3.3.** When using metals, ensure the non-ferrous metals used are non-magnetic.
**S3.4.** When using plastics, use only common plastics.
**S3.5.** Do not use polymer blends.
**S3.6.** Do not use coatings such as painting, lacquering, plating, galvanizing, etc., when they are not compatible with the recycling process.

**G4. Use material connections which allow liberation**

**S4.1.** Do not use adhesives, glues, stickers, labels, PSA tapes.
**S4.2.** Do not use 2K or xK processes.
**S4.3.** Prefer snap-fits for plastic components whenever technical possible.
**S4.4.** Do not use connections that enclose a material permanently.

**S4.5.** If connections are applied that enclose materials permanently, apply gaps and or break-lines to the enclosing material.
**S4.6.** Do not fix ferro to non-ferro, concerns parts as well as fasteners.
**S4.7.** Cluster materials of the same type.

**G5. Design a recyclable product construction**

**S5.1**. Ensure the hardness of all components is compatible with shredding process. Maximum 59HRC (Hardness Rockwell Cone)
**S5.2**. If component exceeds max hardness, enable fast and easy removal of the component within 2, 3.5 or 5 seconds*. Provide detachment possibilities, and ensure that they can be detected and accessed easily.
**S5.3**. If component exceeds max hardness, enable fast and easy removal of the component within 2, 3.5 or 5 seconds*. Provide marking for destructive action, ensure that it can be detected and accessed easily.

**G6. Enable easy and complete removal of toxic, hazardous, polluting components, operating liquids and gasses.**

**S6.1**. Provide drains for operating liquids and gasses.
**S6.2**. Provide detachment possibilities for toxic, hazardous, and polluting components.
**S6.3**. Provide detachment possibilities for problematic materials.
**S6.4**. If no drainage and/or detachment option is provided, provide marking for destructive action.

**G7. Enable easy logistics and encourage product collection**

**S7.1**. Encourage the consumers to begin the recycling process.
**S7.2.** Encourage collectors to separate the appliances by product category and by brand.
**S7.3**. Provide information relevant to recycling.
**S7.4**. Design the product in a way that it can be transported easily after usage.

# Appendix E - Materials in Philips CL products

The main materials used at Philips Consumer Lifestyle are illustrated in Figure 15. The most used materials (> 5 % per product) are identified below.

| Product A | | | Product B | | | Product C | |
|---|---|---|---|---|---|---|---|
| Al | 1% | | Al | 18% | | Al | 1% |
| Cu | 10% | | Cu | 7% | | Cu | 5% |
| SS | 27% | | SS | 12% | | SS | 12% |
| PP | 37% | | PA 30%GF | 7% | | Steel | 11% |
| ABS | 5% | | PP | 18% | | PP | 40% |
| PVC | 2% | | ABS | 24% | | ABS | 25% |
| Logic board | 1% | | Silicon | 2% | | PVC | 4% |
| PA6.6 | 13% | | PVC | 2% | | Logic board | 1% |
| POM | 4% | | Logic board | 2% | | POM | 1% |
| | | | PA6.6 | 6% | | PS | 2% |
| | | | POM | 1% | | PET | 5% |
| | | | PC | 2% | | PE | 6% |
| | | | | | | insulation | 1% |
| | | | | | | SBR rubber | 3% |

| Main materials used (>5%): |
|---|
| Al |
| Cu |
| SS |
| PP |
| ABS |
| PA6.6 |
| Steel |
| PET |
| PE |
| PA 30%GF |

**Figure 15. The main materials used in products at Philips Consumer Lifestyle (van Veen, 2012).**

Al – Aluminium
Cu – Copper
SS – Stainless Steel
PP – Polypropylene
ABS – Acrylonitrile Butadiene Styrene
PA6.6 – Polyamide Nylon 6.6
Steel
PET – Polyethylene terephthalate
PE – Polyethylene
PA30%GF – Polyamide 30% Glass Fibres

The materials most used at Philips CL that are relevant for the THEMA matrix are:

- Aluminium (Al)
- Copper (Cu)
- Stainless Steel (SS)
- Steel

The THEMA material combinations matrix is illustrated in Figure 16 (Castro, 2005).

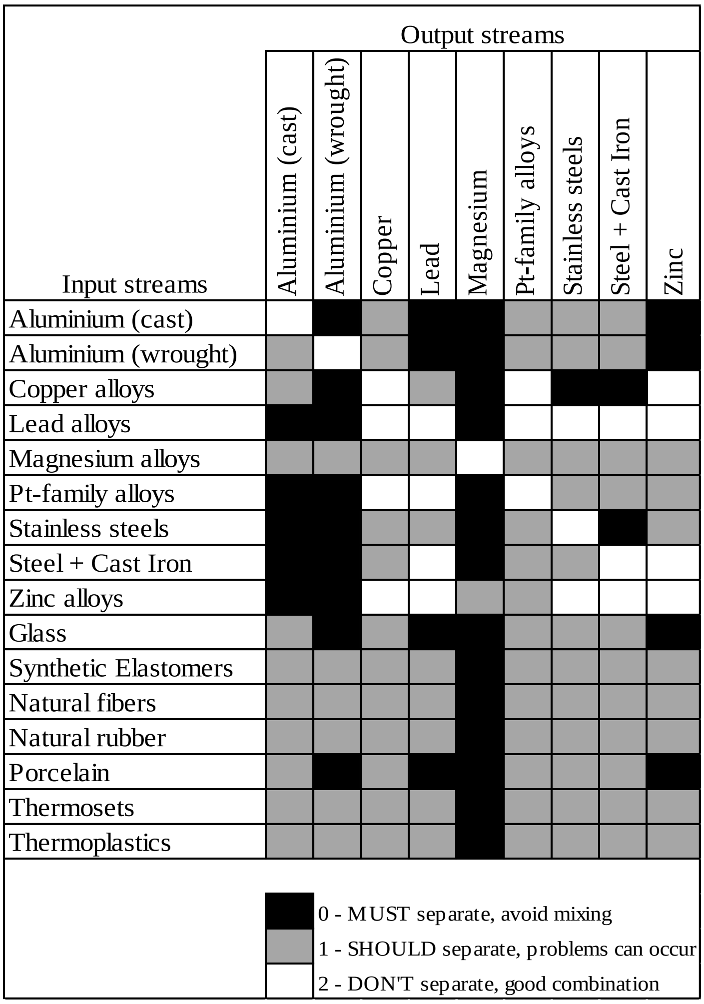


**Figure 16. THEMA material combinations matrix (Castro, 2005).**

The input streams consist of a minor amount of material and will end up in the stream of the main material (the industrial stream) where it can cause a problem.

A simplified version of the THEMA matrix is constructed for the most used materials at Philips Consumer Lifestyle, see Figure 17.

| | Industrial streams | | | | | |
|---|---|---|---|---|---|---|
| Input stream | | Al cast | Al wrought | Cu | SS | Steel |
| (contaminant) | Al cast | | ■ | | | |
| | Al wrought | | | | | |
| | Cu | | ■ | | ■ | ■ |
| | SS | ■ | ■ | | | ■ |
| | Steel | ■ | ■ | | | |

**Figure 17. Matrix adapted to the most used materials at Philips.**

The material combinations identified in this matrix resulted in the formulation of a design strategy with the following advice.

Do not permanently fix aluminium, copper, stainless steel or steel together in the following combinations:

- If the main material in a component is Al (cast), do not attach a part of stainless steel or steel onto it.
- If the main material in a component is Al (wrought), do not attach a part of Al (cast), copper, stainless steel or steel onto it.
- If the main material in a component is stainless steel, do not attach a part of copper onto it.
- If the main material in a component is steel, do not attach a part of copper or stainless steel onto it.

## Appendix F - Selection of strategies from the PRI-tool

A selection of guidelines and strategies from the PRI-tool was made. A lot of information from literature studies on eco-design principles, design for disassembly and design for recycling was collected in that tool by a previous student at Philips. The PRI-tool consisted of 43 design strategies (of where a few appear several times, the actual number is 39) divided over 7 guidelines. To capture relevant findings of that tool it was necessary to extract which ones are suitable for the purpose and requirements of this thesis. For a description of the purpose and the desired tool requirements, see the Introduction section of this thesis. To briefly describe it, the main focus when selecting the below design strategies is on the recycling process and improving for the future; mandatory legislation will not be included.

Below, the guidelines and design strategies of the PRI-tool (Peters, 2012) are described. Each strategy is indicated with "selected" or "not selected", with a short motivation or description.

**1. Do not use toxic or hazardous substances**

***S1.1.*** *Do not use toxic and hazardous substances incorporated in RoHS and REACH at all, unless it's technically impossible to avoid minute amounts.*

***NOT SELECTED***

This strategy is not considered relevant since RoHS and REACH are mandatory legislation, and this thesis aims to improve for the future.

***S1.2.*** *Do not use hazardous or toxic substances facing authorisation.*

***NOT SELECTED***

This strategy refers to the Candidate list or list of SVHCs. These substances are already included in Philips RSL (Regulated Substances List).

***S1.3****. Do not use potential toxic or hazardous substances.*

***SELECTED***

This refers to a list named CARACAL, which contains substances that are candidates to the previous strategy, meaning they are two steps ahead regarding upcoming future legislation. This fits with the tool requirements of this thesis.

***S1.4.*** *Do not use at all: (I) toxic or hazardous halogens: (chlorine, bromine, fluorine, iodine, perfluorinated compounds), (II) toxic metals: (antimony compounds, beryllium compounds, glass containing heavy-metal) and (III) endocrine disruptors: (phthalates, alkylphenols, bisphenol A).*

***NOT SELECTED***

These groups of substances are already included in previously mentioned lists, creating an overlap.

***S1.5****. Ensure the product does not contain substances assigned the following risk phrases or combinations thereof: R40, R45, R46, R50, R51, R52, R53, R60, R61, R62, R63 as defined in Council Directive 67/548/EEC and its amendments.*

***NOT SELECTED***

These groups of substances are already included in previously mentioned lists, creating an overlap.

**2. Use recyclable materials**

***S2.1.*** *Do not use thermosets.*

***SELECTED***

Thermosets are not (currently) possible to recycle, and are either burned or end up polluting material streams, thereby relevant for the recycling process.

***S2.2.*** *When thermosets are necessary, use thermosets with a different density than the common recycled plastics.*

***SELECTED***

The separation of plastics is done by density separation, usually in various flotation steps. The density will therefore determine which recycling stream the plastic ends up in, thereby relevant for the recycling process.

***S2.3***. *Do not use elastomers.*
***SELECTED***
Elastomers are not (currently) possible to recycle, and are either burned or end up polluting material streams.

***S2.4.*** *When elastomers are necessary, use elastomers with a different density than the common recycled plastics.*
***SELECTED***
The separation of plastics and similar materials is done by density separation, usually in various floatation steps. The density will therefore determine which recycling stream the plastic ends up in, thereby relevant for the recycling process.

***S2.5.*** *Do not use composites.*
***SELECTED***
They end up in burning, landfill or polluting other fractions since the different materials in the composite cannot be separated. Relevant for the recycling process.

***S2.6.*** *Do not use ceramics.*
***SELECTED***
Ceramics (cement, concrete, alumina and silicon) cannot be well recycled, and is (in the context of this thesis and the products concerned here) thereby not a material to recommend.

***S2.7.*** *Do not use paper, cardboard, wood, textiles and foams.*
***SELECTED***
These materials cause a problem in the recycling process, since they have to be manually taken out otherwise they end up polluting various streams.

***S2.8.*** *Do not use polymer blends.*
***SELECTED***
Polymer blends are generally very hard to separate, and therefore end up either being burned or polluting the material streams. Relevant for the recycling process.

***S2.9.*** *Do not use more than 5% master batch in plastics.*
***SELECTED***
The more master batch in the plastic, the more polluted the material streams of the plastics will become. To avoid pollution of the streams, as low concentration as possible is preferred, with a maximum limit of 5%. This is important today but also for the future, since stricter legislation on the concentrations in plastic recycling streams can be expected. This means that a plastic stream that has too high concentration of certain substances cannot be used as recycled plastics, but will instead be burned. Higher concentration of master batch also often means more hazardous fumes from burning.

***S2.10.*** *Do not use coatings such as painting, lacquering, plating, galvanizing, etc., when they are not compatible with the recycling process.*
***SELECTED***
All forms of coatings pollute the material streams or make the recycling process difficult. Coatings change the density of the plastics, which makes it likely to end up in the wrong material stream. The coating material itself also pollutes the streams.

***S2.11.*** *Do not use adhesives, glues, stickers, labels, PSA tapes.*
***SELECTED***

Stickers and other adhesives pollute the material streams of the material they are attached to.

***S2.12.*** *Do not choose fasteners made of materials not compatible with the connecting components.*
***SELECTED***
The fastener often ends up with the main component it is attached to. If a screw is attached to plastic, then either the plastic part will go into the metal stream or the screw will end up in the plastic stream.

***S2.13.*** *Do not use bioplastics.*
***SELECTED***
Biodegradable plastics starts to degrade after a while, thereby polluting the material stream in the recycling process.

***S2.14.*** *Do not use operating liquids and gasses which stay present in the product at the end of life of the product.*
***SELECTED***
It may pollute the material streams and require extra effort to remove in the recycling process.

**3. Minimize material diversity**
***S3.1.*** *Do not use more than 5% master batch in plastics.*
***SELECTED (redundant)***
The more master batch in the plastic, the more polluted the material streams of the plastics will become. To avoid pollution of the streams, as low concentration as possible is preferred, with a maximum limit of 5%. This is important today but also for the future, since stricter legislation on the concentrations in plastic recycling streams can be expected. This means that a plastic stream that has too high concentration of certain substances cannot be used as recycled plastics, but will instead be burned. Higher concentration of master batch also often means more hazardous fumes from burning.

***S3.2.*** *When using metals, ensure the ferrous metals used are magnetic.*
***SELECTED***
To prevent metals end up in the wrong metal fraction.

***S3.3.*** *When using metals, ensure the non-ferrous metals used are non-magnetic.*
***SELECTED***
To prevent metals end up in the wrong metal fraction. To be combined with 3.2.

***S3.4.*** *When using plastics, use only common plastics.*
***SELECTED***
There are established recycling streams for these plastics, which mean that they very likely will be recycled. Other materials currently occur in too small volumes in the waste stream to make it economically possible to recycle them. Relevant for the recycling process.

***S3.5****. Do not use polymer blends.*
***SELECTED (redundant)***
Polymer blends are generally very hard to separate, and therefore end up either being burned or polluting the material streams. Relevant for the recycling process.

***S3.6.*** *Do not use coatings such as painting, lacquering, plating, galvanizing, etc., when they are not compatible with the recycling process.*
***SELECTED (redundant)***
All forms of coatings pollute the material streams or make the recycling process difficult. Coatings change the density of the plastics, which makes it likely to end up in the wrong material stream. The coating material itself also pollutes the streams.

**4. Use material connections which allow liberation**

***S4.1.*** *Do not use adhesives, glues, stickers, labels, PSA tapes.*

***SELECTED (redundant)***

Stickers and other adhesives pollute the material streams of the material they are attached to.

***S4.2.*** *Do not use 2K or xK processes.*

***SELECTED***

It is very difficult to separate materials that have been joined by 2K or xK processes. Therefore these joined materials will end up as waste or (depending on density) they will pollute other plastic streams.

***S4.3.*** *Prefer snap-fits for plastic components whenever technical possible.*

***SELECTED***

Plastic snap-fits usually make it easy to remove the housing and open up the product, since they break and the housing is often cracked open in the first dismantling step. This helps the workers since they do not need to break open the product themselves. Plastic snap-fits are also an upside in case the product goes straight into the shredder; they will then follow the plastic host component into the plastic stream. With a metal screw there is for example always a risk that it goes either with a plastic part into the plastic stream or that a plastic part goes with the screw into the metal stream.

***S4.4.*** *Do not use connections that enclose a material permanently.*

***SELECTED***

Enclosing a material permanently makes it harder to separate the different materials. The processes mentioned are typical processes that tightly enclose one material into another, and are therefore recommended to be avoided.

***S4.5.*** *If connections are applied that enclose materials permanently, apply gaps and or break-lines to the enclosing material.*

***SELECTED***

If a material has to be enclosed, apply a break line in the plastic or create a marking on where to apply force to get it out.

***S4.6.*** *Do not fix ferro to non-ferro, concerns parts as well as fasteners.*

***SELECTED***

If ferro and non-ferro materials are joined and the product goes into shredding it is very likely that either the ferro or the non-ferro stream will be polluted.

***S4.7.*** *Cluster materials of the same type.*

***SELECTED***

If parts containing similar materials are clustered, they are likely to stick together and end up being sorted together. This is good for components that contain similar materials, for example PCBs, displays, switches and motors.

**5. Design a recyclable product construction**

***S5.1****. Ensure the hardness of all components is compatible with shredding process. Maximum 59HRC (Hardness Rockwell Cone)*

***NOT SELECTED***

Several recycling companies have expressed that this is not a problem in the recycling process.

***S5.2****. If component exceeds max hardness, enable fast and easy removal of the component within 2, 3.5 or 5 seconds*. Provide detachment possibilities, and ensure that they can be detected and accessed easily.*

***NOT SELECTED***

Several recycling companies have expressed that this is not a problem in the recycling process.

***S5.3***. *If component exceeds max hardness, enable fast and easy removal of the component within 2, 3.5 or 5 seconds*. Provide marking for destructive action, ensure that it can be detected and accessed easily.*
***NOT SELECTED***
Several recycling companies have expressed that this is not a problem in the recycling process.

**6. Enable easy and complete removal of toxic, hazardous, polluting components, operating liquids and gasses.**
***S6.1.*** *Provide drains for operating liquids and gasses.*
***SELECTED***
To provide drains is considered important for the recycling process since drains make it possible to take out operating liquids and gasses and prevent them from polluting the material streams or the air.

***S6.2.*** *Provide detachment possibilities for toxic, hazardous, and polluting components.*
***SELECTED***
Providing detachment possibilities for toxic, hazardous and polluting components are vital since they otherwise easily end up polluting the material streams.

***S6.3.*** *Provide detachment possibilities for problematic materials.*
***SELECTED***
Providing detachment possibilities for problematic components are vital since they otherwise easily end up polluting the material streams. To be combined with 6.2.

***S6.4.*** *If no drainage and/or detachment option is provided, provide marking for destructive action.*
***SELECTED***
In case the request for drains or detachment possibilities for operating liquids or gasses or polluting components is not possible to fulfil. Markings for destructive action can help the first stage in the recycling process where the product breaks open. This usually happens when the product 'falls' onto the recycling belt in the first dismantling step. If it does not break open there, it can help to provide a marking or indication on where to manually apply force to enable taking out a polluting component.

**7. Enable easy logistics and encourage product collection**
***S7.1.*** *Encourage the consumers to begin the recycling process.*
***NOT SELECTED***
Suitable for Marketing department, this thesis focuses on making the recycling process easier.

***S7.2.*** *Encourage collectors to separate the appliances by product category and by brand.*
***NOT SELECTED***
Suitable for Marketing department, this thesis focuses on making the recycling process easier.

***S7.3.*** *Provide information relevant to recycling.*
***NOT SELECTED***
Suitable for Marketing department, this thesis focuses on making the recycling process easier.

***S7.4.*** *Design the product in a way that it can be transported easily after usage.*
***NOT SELECTED***
Suitable for Marketing department, this thesis focuses on making the recycling process easier.

This selection resulted in 28 selected design strategies. The ones suitable to combine were combined, resulting in that a final number of 26 design strategies from the PRI-tool that will be considered in this thesis.

## Appendix G – Product testing

*Confidential information.*

For information on the products tested please contact Eelco Smit, Senior Manager in Sustainability, Philips Consumer Lifestyle, at eelco.smit@philips.com.