

Design for Recycling of Electronic Products

How to bridge the gap between design methods and recycling practices

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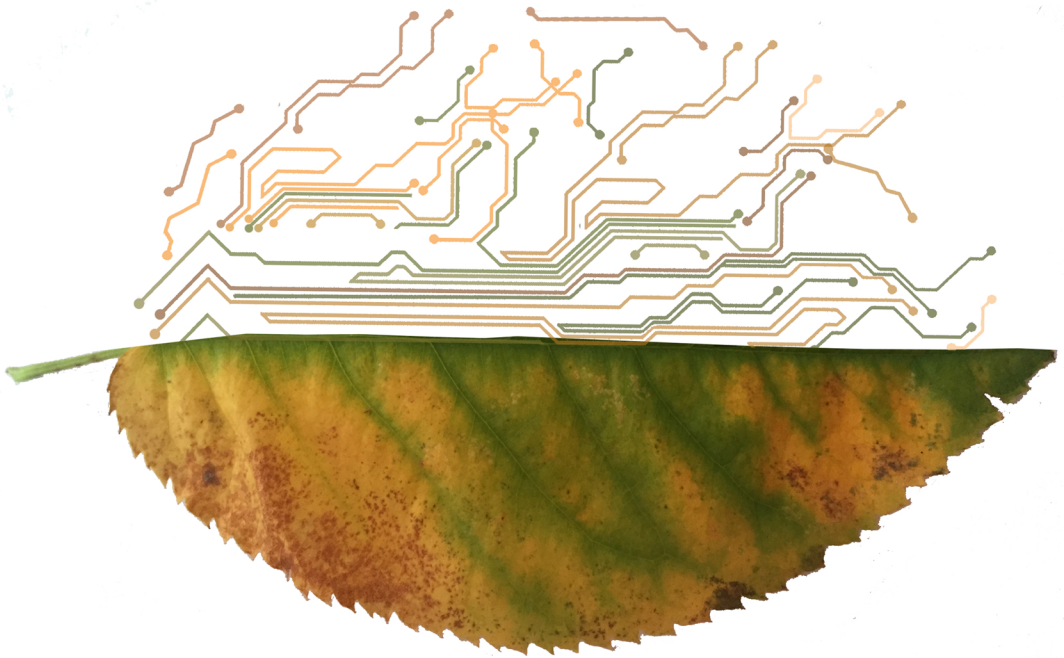
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Design for Recycling of Electronic Products:

How to bridge the gap between design methods and recycling practices



Farzaneh Fakhredin

**Design for Recycling of Electronic Products:
How to bridge the gap between design methods and
recycling practices**

**Design for Recycling of Electronic Products:
How to bridge the gap between design methods and recycling
practices**

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for the purpose of obtaining the degree of doctor
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by the authority of the Rector Magnificus prof. dr. ir. T. H. J. J. van der Hagen
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to be defended publicly on
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Doctoral dissertation, Delft University of Technology, Delft, The Netherlands

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To Alireza, Sima, Farzad & Mohammad

Table of contents

Summary	i
Samenvatting	v
خلاصه رساله	ix
List of abbreviations	xi
Chapter 1: Introduction	1
1.1 Introduction	1
1.2 Background	2
1.2.1 The e-waste challenge	2
1.2.2 Description of the e-waste recycling process	3
1.2.3 Definition of key terms	5
1.2.4 Product design and the efficiency of the recycling process	6
1.3 Problem statement	6
1.4 Research objectives and questions	7
1.5 Research design and scope	8
1.6 Thesis outline	11
1.7 References	13
Chapter 2: Literature review on characteristics of design for recycling	
Methods	15
2.1 Introduction	15
2.2 Research method	16
2.3 Results	17
2.4 Discussion and conclusion	39
2.5 References	40
Chapter 3: Identifying product design features that affect disintegration of electronic products during recycling	43
3.1 Introduction	43
3.2 Research method	45
3.3 Manual disintegration of LED-LCD displays	50
3.4 Mechanical disintegration of LCD screens and LED lamps	64
3.4.1 Mechanical disintegration of CCFL-LCD modules obtained after partial dismantling – large scale test	64
3.4.2 Mechanical disintegration of LED lamps - small scale tests	66
3.4.3 Mechanical disintegration of LED lamps- large scale test	71
3.5 Discussion and conclusion	79
3.6 References	81
Chapter 4: Effectiveness of design for recycling methods in improving the recyclability of electronic products	83
4.1 Introduction	83
4.2 Research method	84
4.3 Displays: application of design for recycling and evaluation of manual disintegration	87
4.3.1 Redesigned LED LCD TV	87
4.3.2 Redesigned medical displays	91
4.4 LED lamps: application of design for recycling and evaluation of mechanical disintegration	97
4.4.1 Fracture lines	97
4.4.2 Stacked design without inner connections	98
4.4.3 Brittle housing	100
4.4.4 Bulb redesign	102
4.5 Discussion	104
4.5.1 Recyclability	104
4.5.2 Environmental and economic impact	105
4.5.3 Design practice and use of DfR guidelines	107

4.6 Conclusion	108
4.7 References	109
Chapter 5: Examining the current corporate design for recycling practices of product developers and designers	111
5.1 Introduction	111
5.2 Research method	112
5.2.1 Interview development	112
5.2.2 Analysis of interview data	113
5.2.3 Roundtable discussion	114
5.3 Roozenburg and Eekels' product innovation process description	115
5.4 Results	117
5.4.1 Companies' approach to the design process and decisions	117
5.4.2 Investigating current design for recycling practices	120
5.4.3 Needs and wishes of designers regarding incorporation of DfR in the early design stage	121
5.4.4 The result of the roundtable discussion	125
5.5 Discussion and conclusion	125
5.6 References	127
Chapter 6: Understanding the effects of societal and business context of companies on implementation of design for recycling	129
6.1 Introduction	129
6.2 Research method	130
6.3 Results: drivers for implementation of design for recycling	132
6.3.1 External drivers	132
6.3.2 Internal drivers	136
6.4 Results: barriers for implementation of design for recycling	138
6.4.1 External barriers	138
6.4.2 Internal barriers	141
6.5 Discussion	143
6.6 Conclusion	144
6.7 References	145
Chapter 7: Conclusions and recommendations	149
7.1 Introduction	149
7.2 Answers to the research questions	150
7.2.1 First study (Chapter 2)	150
7.2.2 Second study (Chapter 3)	151
7.2.3 Third study (Chapter 4)	152
7.2.4 Forth study (Chapter 5)	152
7.2.5 Fifth study (Chapter 6)	153
7.3 Thesis contributions	154
7.3 Recommendations for design practice and future research	155
7.4 References	158
Acknowledgments	159
About the Author	163

Summary

Rapid economic growth, combined with an increasing demand for electronic products and the broader context of the information age, have considerably expanded the number of electronic devices produced worldwide. As a result, the amount of waste from electrical and electronic equipment, known as 'electronic waste' ('e-waste'; WEEE) is also increasing rapidly. According to the global e-waste monitor report for 2017, it is expected that the global volume of e-waste will increase by 24% between 2014 and 2021, reaching 52.2 million tons by 2021. The amount of e-waste that is being produced and the amount of toxic, scarce and valuable material found in it makes the reduction and optimal processing of e-waste an important topic.

One of the most widely discussed strategies for reducing the impacts of e-waste is design for recycling (DfR). DfR aims to ensure that, wherever feasible and appropriate, products are designed to facilitate recycling and to ensure that the recycled material keeps as much of its value as possible. It is often claimed that the development and use of DfR methods could assist designers to achieve this goal. However, there is a clear gap between what is claimed in theory, and the recycling practices that show electronics are still not optimally disintegrated and separated in actual recycling processes. Consequently, the aim of this thesis is to uncover the various reasons of mismatch between the theory and practice of DfR through a number of research studies.

The work reported in this thesis was carried out in the framework of the GreenElec EU project (2012-2015). GreenElec aimed for a combined effort from suppliers, producers, designers, recyclers and knowledge institutes to improve the recyclability of electronics. The work described here explicitly addresses the role of product design as studied in the GreenElec project. The following topics were explored in this context: which DfR methods are available; how recycling is carried out in practice and is this taken into account by the DfR methods available; how effective are those DfR methods; how and when do designers use these methods; and what opportunities and limitations are associated with the actual application of DfR methods.

Chapter 2 analyses the characteristics of existing DfR methods. The analysis shows that control over product features is needed to improve product recyclability. These features include the product structure (geometrical arrangement and modular features), materials used and connection technologies. However, with respect to electronics, the effectivity of DfR methods has rarely been tested in practice.

Chapter 3 reports on an in-depth investigation and offers a description of how electronic products behave in the actual recycling process, with a specific focus on the partial manual disintegration of displays and the mechanical disintegration of LED lamps. The results of the recycling tests are discussed in relation to product design by looking into product features that facilitate or hamper subsequent recovery of materials. The results obtained from the disintegration tests showed that the products studied broke down, to a large extent, in a way that is not favourable to optimal disintegration and separation of materials. This led to the identification of a number of critical design features, including the materials, connections and product structure, which all affect the recyclability of electronics and require specific attention. Comparing the investigation findings of Chapter 3 with the literature findings of Chapter 2

showed that there is evidently a gap between the aims of DfR methods and the results obtained from disintegration tests of electronic products in practice.

To determine whether the discrepancy between the DfR aims and the actual recycling results was due to ineffectiveness of the guidelines or the result of not applying the guidelines in practice, a few products were developed while specifically taking DfR guidelines into account. Chapter 4 reports on the results of these tests, revealing to what extent actual product recyclability can be improved if designers do take into account existing DfR methods. To test this, designers at Philips Lighting, Barco and TP Vision were explicitly asked to take a set of DfR guidelines into account and redesign electronic products accordingly. This chapter reports on the application of guidelines to displays for optimal *manual* disintegration, and on the application of guidelines to LED lamps for optimal *mechanical* disintegration. The guidelines applied were based on the product design features mentioned in the literature review chapter as well as results obtained from the initial disintegration tests.

The redesigns were manufactured and subsequently subjected to the same recycling treatment as described in Chapter 3 (i.e. manual disintegration and separation for the displays and shredding and automated separation for the LED lamps). The evaluation of the recyclability of the redesigns shows that the application of design guidelines leads to disintegration that enables significantly better subsequent separation: fragments that are homogeneous or consist of materials that can be recovered from the same recycling process. The evidence suggests that the guidelines are based on the correct understanding of recycling processes and are to a large extent comprehensive. From this observation, it was concluded that the major factor limiting product recyclability is the limited degree in which DfR guidelines are applied. Apparently, the guidelines available are not properly taken into account in practice.

Chapter 5 provides an insight into the reasons why current DfR methods are not properly taken into account, based on interviews with a number of designers from Barco, Philips Lighting and TP Vision who were involved in GreenElec. These designers had been working on the redesigns and were thus, at the time of the interviews, well aware of DfR guidelines and their use. Based on the interviews, it became clear that suitable methods, especially for the early design stage, are not readily available to designers in a structured way. However, more importantly, all of the designers interviewed stated that companies do not focus on recyclability. According to the designers, compliance with directives and some company-specific additional sustainability demands, especially regarding potentially hazardous materials, is usually the main sustainability focus for their companies. This implies that taking into account recyclability is not explicitly demanded in the design brief. These designers, therefore, did not have a direct incentive to take DfR into account. The designers also explained that they could explore ideas to improve product recyclability by framing it more in terms of direct company interest, such as design for improved assembly or design for minimum value loss at end-of-life. This, of course, only has a limited impact, as it only affects products in which these designers are directly involved.

In Chapter 6, the findings of the previous chapters are placed in a broader societal and business context with the aim of understanding the reasons why DfR methods are rarely applied in the design of electronic products. The analysis shows that businesses are influenced by internal and external drivers of recyclability. Legal compliance is the most important external driver for business to act upon design for recycling. Despite the obligations to deal with the waste they generate, companies do not have a direct financial incentive to improve

recyclability. As producers are allowed to deal with the waste generated in a collective scheme of extended producer responsibility, the burden is shared across producers in such a way that direct responsibility is lacking. The conclusion – that the way extended producer responsibility is currently operationalized gives no incentive to improve the recyclability of electronic products – is strongly supported by the recycling results obtained in Chapter 3.

Despite the importance attributed to DfR, this thesis shows that the influence of product designers who work in a business context is relatively modest. The findings of this thesis put the responsibility for successful product recycling into the hands of government and company strategic management. Government needs to create boundary conditions, and companies need to make a strategic decisions to include DfR in their operational processes. With these conditions in place, designers are very capable of developing easy-to-recycle products. The thesis also shows that the DfR methods currently available are useful and effective, and that heuristic DfR guidelines work well when applied in the early stages of the design process.

Samenvatting

Als gevolg van de combinatie van snelle economische groei met een toenemende vraag naar elektronische producten in de bredere context van het informatietijdperk is het aantal elektronische apparaten dat wereldwijd wordt geproduceerd aanzienlijk gestegen. Dat heeft ertoe geleid dat de hoeveelheid afval afkomstig van elektrische en elektronische apparatuur ('e-afval' of WEEE) eveneens snel toeneemt. Volgens het Global E-waste Monitor-rapport voor 2017 zal naar verwachting het wereldwijde volume aan e-afval tussen 2014 en 2021 met 24% toenemen naar 52,2 miljoen ton. Gezien de hoeveelheid geproduceerd e-afval en de hoeveelheid toxisch, zeldzaam en waardevol materiaal dat dit bevat is de reductie en optimale verwerking van e-afval een belangrijk onderwerp.

Een van de meest besproken strategieën voor het beperken van de gevolgen van e-afval is 'Design for Recycling' (DfR), oftewel ontwerpen gericht op recyclebaarheid. DfR is erop gericht om, voor zover dat haalbaar en passend is, producten zodanig te ontwerpen dat recycling wordt gefaciliteerd en wordt gegarandeerd dat het gerecyclede materiaal zo veel mogelijk waarde behoudt. Hoewel in de literatuur wordt betoogd dat de toepassing van DfR-methodes de efficiëntie van recycling van elektronische producten vergroot, laat de praktijk zien dat de recycling van elektronische producten nog altijd niet optimaal verloopt en dikwijls met grote verliezen gepaard gaat. Daarom wil dit proefschrift aan de hand van een aantal onderzoeken de verschillende oorzaken inzichtelijk maken voor de slechte aansluiting tussen DfR in theorie en DfR in de praktijk.

Het in dit proefschrift beschreven werk is uitgevoerd in het kader van het EU-project GreenElec (2012-2015). Het doel van GreenElec was een gezamenlijke inspanning door leveranciers, fabrikanten, ontwerpers, recyclebedrijven en kennisinstellingen om de recyclebaarheid van elektronica te verbeteren. Het hier beschreven werk heeft expliciet betrekking op de rol van productontwerp zoals bestudeerd binnen het GreenElec-project. In deze context zijn de volgende onderwerpen onderzocht: welke DfR-methodes er beschikbaar zijn; hoe recycling in de praktijk wordt uitgevoerd en hoe hiermee rekening wordt gehouden in de beschikbare DfR-methodes; hoe effectief die DfR-methodes zijn; hoe en wanneer ontwerpers die methodes toepassen; en welke kansen en beperkingen er zijn met betrekking tot de daadwerkelijke toepassing van DfR-methodes.

In hoofdstuk 2 worden de kenmerken van bestaande DfR-methodes geanalyseerd. Uit die analyse blijkt dat controle over productkenmerken noodzakelijk is om de recyclebaarheid van producten te verbeteren. Tot die kenmerken behoren de productstructuur (geometrische indeling en modulaire kenmerken), de gebruikte materialen en verbindingstechnologieën. Voor elektronica is de effectiviteit van DfR-methodes echter nauwelijks in de praktijk onderzocht.

In hoofdstuk 3 wordt verslag gedaan van een diepgaand onderzoek en wordt een beschrijving gegeven van de manier waarop elektronische producten zich binnen het daadwerkelijke recyclingproces gedragen, met specifieke aandacht voor de gedeeltelijk handmatige desintegratie van beeldschermen en de mechanische desintegratie van ledlampen. De resultaten van de recyclingtests worden besproken in relatie tot productontwerp door te kijken naar producteigenschappen die de terugwinning van materialen faciliteren of juist belemmeren. Uit de resultaten van de desintegratietest bleek dat de onderzochte producten

in hoge mate werden opgebroken op een manier die niet bevorderlijk is voor de optimale desintegratie en scheiding van materialen. Dat heeft geleid tot de identificatie van een aantal kritieke ontwerpmerken, waaronder de materialen, verbindingen en productstructuur, die allemaal van invloed zijn op de recyclebaarheid van elektronica en specifieke aandacht behoeven. Uit een vergelijking tussen de bevindingen van het onderzoek uit hoofdstuk 3 en die van het literatuuronderzoek uit hoofdstuk 2 kwam naar voren dat er een kloof bestaat tussen de doelstellingen van DfR-methodes en de resultaten van het onderzoek naar de desintegratie van elektronische producten in de praktijk.

Om vast te stellen of de discrepantie tussen de doelstellingen van DfR en de daadwerkelijke recyclingresultaten het gevolg is van ineffectieve richtlijnen of het niet toepassen van die richtlijnen in de praktijk, zijn er enkele producten ontworpen met specifieke inachtneming van de DfR-richtlijnen. In hoofdstuk 4 worden de resultaten van deze tests beschreven, waaruit blijkt in welke mate de daadwerkelijke recyclebaarheid van producten kan worden verbeterd als ontwerpers rekening houden met bestaande DfR-methodes. Om dat te toetsen werd aan ontwerpers bij Philips Lighting, Barco en TP Vision expliciet gevraagd om rekening houdend met een set DfR-richtlijnen elektronische producten te herontwerpen. In dit hoofdstuk wordt verslag gedaan van de toepassing van richtlijnen op beeldschermen voor optimale *handmatige* desintegratie en de toepassing van richtlijnen op ledlampen voor optimale *mechanische* desintegratie. De gehanteerde richtlijnen waren gebaseerd op de productontwerpkenmerken genoemd in het hoofdstuk over het literatuuronderzoek en de resultaten van de eerste desintegratietests.

De herontworpen producten zijn geproduceerd en vervolgens onderworpen aan dezelfde recyclingbehandeling zoals beschreven in hoofdstuk 3 (d.w.z. handmatige desintegratie en separatie voor de beeldschermen en versnippering en automatische separatie voor de ledlampen). Uit de evaluatie van de recyclebaarheid van de herontworpen producten blijkt dat de toepassing van ontwerprichtlijnen leidt tot desintegratie die een significant betere separatie mogelijk maakt, doordat de fragmenten homogeen zijn of bestaan uit materialen die met hetzelfde recyclingproces kunnen worden teruggewonnen. Het bewijs wijst erop dat de richtlijnen zijn gebaseerd op een correct begrip van recyclingprocessen en in hoge mate compleet zijn. Naar aanleiding daarvan is geconcludeerd dat de belangrijkste belemmering voor de recyclebaarheid van producten de geringe toepassing van DfR-richtlijnen is. Kennelijk wordt er in de praktijk niet afdoende rekening gehouden met de beschikbare richtlijnen.

Hoofdstuk 5 geeft inzicht in de redenen waarom er onvoldoende rekening wordt gehouden met actuele DfR-methodes, op basis van gesprekken met ontwerpers van Barco, Philips Lighting en TP Vision die betrokken waren bij GreenElec. Dit waren de ontwerpers die aan het herontwerp hadden gewerkt en dus, ten tijde van de gesprekken, goed op de hoogte waren van de DfR-richtlijnen en de toepassing daarvan. Uit de gesprekken kwam naar voren dat er, met name voor de vroegste ontwerpfasen, geen geschikte methodes structureel voorhanden zijn voor ontwerpers. En wat nog belangrijker is: alle geïnterviewde ontwerpers gaven aan dat bedrijven zich niet focussen op recyclebaarheid. Volgens de ontwerpers is het naleven van verordeningen en een aantal aanvullende, bedrijfsspecifieke duurzaamheidseisen – met name met betrekking tot potentieel gevaarlijke materialen – meestal het belangrijkste aandachtspunt van bedrijven wat betreft duurzaamheid. Dat impliceert dat rekening houden met recyclebaarheid geen expliciet deel uitmaakt van de

ontwerpeisen. Als gevolg daarvan hadden deze ontwerpers geen directe reden om rekening te houden met DfR. De ontwerpers gaven verder aan dat zij ideeën gericht op een betere recyclebaarheid van producten konden verkennen door deze meer te presenteren als van direct belang voor het bedrijf, bijvoorbeeld ontwerpen voor betere assemblage of ontwerpen voor een minimaal waardeverlies aan het einde van de productlevensduur. Dat heeft uiteraard slechts een beperkt effect, aangezien het alleen gevolgen heeft voor de producten waarbij deze ontwerpers direct zijn betrokken.

In hoofdstuk 6 worden de bevindingen uit de voorgaande hoofdstukken in een bredere maatschappelijke en commerciële context geplaatst om inzicht te krijgen in de redenen waarom DfR-methodes zelden worden toegepast bij het ontwerpen van elektronische producten. Uit de analyse bleek dat bedrijven worden beïnvloed door zowel interne als externe drijfveren voor recyclebaarheid. Naleving van de regelgeving is voor bedrijven de belangrijkste externe drijfveer voor DfR. Hoewel zij verplicht zijn het door hen gegenereerde afval af te handelen, hebben bedrijven geen directe financiële prikkel om de recyclebaarheid te verbeteren. Doordat fabrikanten het gegenereerde afval mogen afhandelen in het kader van een gezamenlijke aanpak op basis van uitgebreide producentenverantwoordelijkheid wordt de last zodanig onder de fabrikanten verdeeld dat er geen directe verantwoordelijkheid is. De conclusie dat de manier waarop uitgebreide producentenverantwoordelijkheid momenteel in de praktijk wordt gebracht geen prikkel geeft om de recyclebaarheid van elektronische producten te verbeteren, wordt sterk ondersteund door de recyclingresultaten behaald in hoofdstuk 3.

Dit proefschrift toont aan dat, ondanks het belang dat aan DfR wordt toegeschreven, de invloed van productontwerpers werkzaam in een commerciële context relatief bescheiden is. Volgens de bevindingen uit dit proefschrift ligt de verantwoordelijkheid voor succesvolle productrecycling bij de overheid en het strategisch management van bedrijven. De overheid moet randvoorwaarden scheppen en bedrijven moeten strategische beslissingen nemen om DfR onderdeel te maken van hun operationele processen. Als aan die voorwaarden wordt voldaan, zijn ontwerpers zeer goed in staat om gemakkelijk recyclebare producten te ontwikkelen. Deze dissertatie maakt daarnaast zichtbaar dat de momenteel beschikbare DfR-methodes bruikbaar en effectief zijn, en dat heuristische DfR-richtlijnen goed functioneren wanneer zij tijdens een vroege fase van het ontwerpproces worden toegepast.

خلاصه رساله

رشد سریع اقتصادی، به همراه افزایش نیاز برای محصولات الکترونیکی و گستردگی عصر اطلاعات، تعداد لوازم الکترونیکی تولید شده در جهان را بطور قابل توجهی افزایش داده است. از این رو، تعداد پسماندهای این محصولات که به زباله های الکترونیکی نیز شناخته میگردند، افزایش یافته است. بنابر گزارش دیدبان جهانی زباله های الکترونیکی، انتظار میرود تا میزان زباله های الکترونیکی در جهان از سال ۲۰۱۴ تا ۲۰۲۱، تا ۲۴ درصد افزایش یابد، و به رقم ۵۲.۲ میلیون تن در سال ۲۰۲۱ برسد. حجم بالای زباله های الکترونیکی تولید شده در جهان و وجود مواد سمی، نادر و ارزشمند درون این زباله های الکترونیکی بر اهمیت کاهش تولید این محصولات و بازیافت آنها می افزاید.

طراحی برای بازیافت یکی از متداول ترین راههای کاهش تاثیر زباله های الکترونیکی است که بطور گسترده مورد بحث قرار گرفته است. هدف این مدل از طراحی این است که در صورت امکان، محصولات به نحوی طراحی شوند که بازیافتشان ارتقاء یابد، و همینطور مواد مصرف شده ارزش خود را در حین بازیافت حفظ کنند. در حالی که منابع علمی مختلف ادعان دارند بر اینکه استفاده از روشهای طراحی برای بازیافت میتواند راندمان بازیافت را افزایش دهد، اما در واقعیت محصولات الکترونیکی هنوز به طور بهینه در فرآیندهای بازیافت تجزیه و از هم جدا نمیشوند. از این رو، این پایان نامه به بررسی دلایل مختلف عدم هماهنگی بین تئوری و واقعیت طراحی برای بازیافت محصولات الکترونیکی میپردازد.

این پژوهش بخشی از پروژه GreenElec است که در اتحادیه اروپا انجام گرفته است (۲۰۱۲-۲۰۱۵). پروژه GreenElec به دنبال ایجاد یک تلاش مشترک بین عرضه کنندگان، تولید کنندگان، طراحان، بازیافت کنندگان و موسسات دانش بنیاد بود تا بازیافت محصولات الکترونیکی را بهبود بخشد. این پایان نامه به شکل ویژه، به نقش طراحی محصول میپردازد. موضوعات مورد بحث بدین قرار میباشند: چه روشهای طراحی برای بازیافت در حال حاضر موجود میباشند، بازیافت چگونه در عمل صورت میگیرد و آیا روشهای موجود در طراحی برای بازیافت از آن آگاه است، چگونه و چه زمانی طراحان از این روشها استفاده میکنند، و در نهایت چه فرصتها و محدودیتهایی در مورد استفاده از روشهای طراحی برای بازیافت وجود دارد.

فصل دوم این پایان نامه، ویژگی های روشهای موجود برای طراحی برای بازیافت را تحلیل میکند. این تحلیل نشان میدهد که داشتن آگاهی از مشخصات محصول لازمه ی ارتقاء بازیافت محصول است. این ویژگی ها از جمله ساختار محصول (آرایش هندسی و ویژگی های مولار)، مواد استفاده شده و تکنولوژی اتصالات است. شایان ذکر است که در مورد محصولات الکترونیکی، کارایی روشهای طراحی برای بازیافت هنوز مورد ارزیابی قرار نگرفته است.

فصل سوم به بررسی رفتار محصولات الکترونیکی در فرایند بازیافت میپردازد. تمرکز این فصل بصورت ویژه روی جداسازی دستی نمایشگرها و جداسازی مکانیکی لامپ های کم مصرف است. ویژگی های مختلف در طراحی این محصولات که باعث بهبود یا اشکال در فرایند بازیافت میشود مورد بحث قرار گرفته است. نتایج این مطالعه نشان داد که این محصولات به قطعاتی خرد شدند که مطلوب بازیافت نبودند. از این رو نقش مواد مورد استفاده، اتصالات و ساختار طراحی بعنوان مهمترین عوامل در بازیافت محصولات الکترونیکی محرز گردید. مقایسه نتایج فصل ۳ با ادبیات موضوع در فصل ۲ نشان داد که اختلافی نمایان بین نتایج عملی و آنچه که اهداف روشهای طراحی برای بازیافت در تئوری ادعا میکنند وجود دارد.

برای بررسی اختلاف بین اهداف و نتایج طراحی برای بازیافت، تعدادی محصول طراحی شد تا آزمایش شود که مشکل از عدم کارایی راهنماها است یا عدم اجرای آنها. از این رو، فصل چهار به نتایج آزمایشهایی میپردازد که در آنها طراحان راهنماهای طراحی برای بازیافت را در نظر گرفته بودند. از طراحان در بخش Philips Lighting، Barco و TP Vision خواسته شد که محصولاتی را با توجه به راهنماهای طراحی برای بازیافت طراحی کنند. این فصل استفاده راهنماها برای از هم جداسازی نمایشگرها را به شکل دستی و لامپ ها را به شکل مکانیکی بررسی میکند. این راهنماها برگرفته از فصل ادبیات موضوع و همینطور آزمایشهای اولیه از هم جداسازی میباشند.

بازطراحی محصولات بر اساس راهنماهای بازیافت که پیشتر در فصل ۳ آمد (جداسازی دستی نمایشگرها و مکانیکی لامپ ها) انجام شدند. بررسی بازیافت پذیری طراحی های جدید نشان داد که بکارگرفتن راهنماها، قطعات را به شکل بهتری از هم جدا میکند (در حین بازیافت). به این معنی که قطعات یکدست تری با همان روش بازیافت قبلی بدست آمد. این نشان داد که راهنماها بر اساس اصول صحیحی از درک بازیافت تهیه شده اند. این مساله نشان داد که دلیل اصلی عدم بازیافت پذیری محصولات استفاده نکردن از راهنماها است. بعبارت دیگر، راهنماها به شکل صحیحی مورد اعتنا واقع نشده اند.

فصل پنج نگاهبست به درون این مساله که چرا راهنماهای طراحی برای بازیافت مورد استفاده قرار نمیگیرند. این مساله از طریق مصاحبه با تعدادی از طراحان Barco, Philips Lighting و TP Vision که در پروژه GreenElec بودند انجام شد. این طراحان در زمان مصاحبه در جریان بازطراحی محصولات (که شرح آن در فصل قبلی داده شد) بودند. از مصاحبه ها چنین نتیجه گرفته شد که روشهای مناسب برای طراحان در مراحل اولیه طراحی وجود ندارد. همینطور به عقیده طراحان، شرکتها توجه لازم را به اصول بازیافت مبذول نمی نمایند. به گفته طراحان، مهمترین اصول در نظر گرفته شده برای پایداری محصولات تنها به پرهیز از استفاده از مواد سمی محدود میگردد. این نشان می دهد که بازیافت پذیری در شرح خواسته های طراحی محصولات مورد توجه قرار نمیگیرد. از این رو، طراحان انگیزه ای برای رعایت اصول طراحی برای بازیافت احساس نمیکنند. طراحان اذعان کردند که آنها این توانایی را دارند که نحوه طراحی را برای بهبود بازیافت ارتقاء دهند. اما بایستی گفت که این تلاش به چند محصول که تحت طراحی این طراحان است محدود میگردد.

در فصل ۶، نتایج فصول قبل با توجه به جنبه های شرکتی و جامعه شناختی عدم استفاده از اصول طراحی برای بازیافت بررسی شد. تحلیل ها نشان داد که شرکت ها تحت عوامل خارجی و داخلی برای بازیافت پذیری محصولاتشان قرار دارند. پابندی به قوانین اتحادیه اروپا مهمترین عامل خارجی برای در نظر گرفتن طراحی برای بازیافت در شرکتهاست. اما این عامل، انگیزه مالی برای شرکتها ایجاد نمیکند تا محصولاتشان را بازیافت کنند. در واقع با اینکه تولید کنندگان اجازه دخالت در امور پسماندهای محصولاتشان را دارند، اما مسئولیت مستقیمی متوجه شان نیست. این نتیجه (عدم منفعت مالی جهت ایجاد انگیزه برای شرکتها) توسط نتایج فصل ۳ هم ثابت شده است.

علیرغم اهمیت بالای طراحی برای بازیافت، این پایان نامه نشان میدهد که نقش طراحان در این فرایند نسبتا کم است. نتایج تحلیل های این پایان نامه به نقش بالای دولت و مدیریت استراتژیک شرکتها اذعان دارد. دولت بایستی الزاماتی را قرار دهد، و شرکتها باید اصول استراتژیک طراحی برای بازیافت را در فرایند کاریشان قرار دهند. بعد از حصول این شرایط، طراحان قادر خواهند بود تا محصولاتی با بازیافت پذیری بالا را طراحی نمایند. این پایان نامه همچنان نشان داد که راهنماهای موجود برای طراحی برای بازیافت مفید و کارا هستند وقتی که در مراحل اولیه طراحی مورد استفاده قرار بگیرند.

List of abbreviations

ABS	Acrylonitrile Butadiene Styrene
ABS/PC	Acrylonitrile Butadiene Styrene/ Polycarbonate
AC	Alternating current
CCFL	Cold Cathode Fluorescent Lamp
CPR	Collective Producer Responsibility
CRT	Cathode Ray Tube
DC	Direct Current
DfR	Design for Recycling
EC	European Commission
EEE	Electrical and Electronic Equipment
ENIAC JU	Electronic Numerical Integrator and Computer Joint Undertaking
EPR	Extended Producer Responsibility
EU	European Union
e-waste	electronic waste
IPR	Individual Producer Responsibility
ISO	International Standards Organization
IT	Information Technology
KJ method	Kawakita Jiro method
LCD TV	Liquid Crystal Display
LED	Light Emitting Diode
NGO	Non-Governmental Organization
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ether
PBT	Polybutylene terephthalate
PC	Polycarbonate
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PP	Polypropylene
RoHS	Restriction of Hazardous Substances
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WEEE	Waste Electrical and Electronic Equipment
wt	weight

Chapter 1: Introduction

1.1 Introduction

The topic of this thesis is design for recycling (DfR) of electronic products. More than ever before, electronic products are intruding into our everyday life, both in the household and in industry, resulting in increasing numbers of electronic products ending up in waste streams (also known as electronic waste, or e-waste). Electronic products contain a wide range of materials, such as iron, steel, lead, plastics, glass, aluminium, copper and precious metals. Materials are assembled using different types of connections, such as click or snap-fit joints, adhesive tape, screws, glue and soldering. Furthermore, different arrangements and positioning of materials, as well as the connections between them, lead to different kinds of product structures. These characteristics can make the recycling process for electronic products more or less difficult.

Design is seen as pivotal in the creation of products that can facilitate the recycling process. For this reason, in the past two decades there has been considerable research on DfR, resulting in a large number of methods and tools being developed. The aim of these methods is to assist designers in assessing the recyclability of their designs and to select adequate product design features that facilitate the recycling process. However, these methods do not seem to have been very effective; particularly not in the case of electronic products. This is because, despite the considerable number of methods developed thus far, and what they claim in theory, electronic products are still not being optimally disintegrated and separated in actual recycling processes. Consequently, the aim of this thesis is to uncover the various reasons for the mismatch between the theory and practice of DfR by undertaking a number of studies.

Section 1.2 provides background materials that readers of this thesis might need to be familiar with to understand the research problem addressed by this thesis. Section 1.3 states the central problem dealt with in this thesis. The problem statement subsequently leads to the formulation of the research objectives and questions (Section 1.4). Section 1.5 describes the research design and scope of this thesis. Finally, Section 1.6 will present an outline of the thesis.

1.2 Background

1.2.1 The e-waste challenge

Electronic products are part of our everyday life. Many people – in households, businesses and the public sector – benefit from electronic products on a daily basis in the realms of education, health, entertainment, government, commerce, welfare and safety. Living in the digital age, combined with rapid economic growth, urbanization and industrialization, has considerably expanded the number of electronic products manufactured worldwide (Balde et al., 2017). In Europe, the number of electronic products on the market increased by 3.4% over the period 2010 to 2015 (Eurostat, 2017). As a result, the number of electronic products that end up in waste streams (electronic waste or e-waste) is also increasing. As reported by Balde et al. (2015), 11.6 Mt of e-waste was generated in Europe in 2014. This makes Europe the third largest producer of e-waste worldwide, with 15.6 kg of e-waste produced for every inhabitant in that year. It is expected that the overall amount will rise to 12 Mt by 2020 (European Commission, 2018). The increasing e-waste stream contains a broad variety of products. The European Union's WEEE directive (2012) grouped the products in the e-waste stream into six different categories. Table 1.1 summarizes the e-waste categories, providing some product examples for each category.

Table 1.1- e-waste categories and examples of products in each category as defined by the WEEE directive (2012)

E-waste categories	Examples of products per category
1. Temperature exchange equipment	Refrigerators, freezers, air conditioners, heat pumps, dehumidifier, radiators
2. Screens and monitors	Televisions, laptops, notebooks, LCD photo frames, medical displays
3. Lamps	Fluorescent lamps, high intensity discharge lamps, low pressure sodium lamps and LED lamps
4. Large equipment	Washing machines, clothes dryers, dish washers, cookers, electric stoves, large printing machines, copying equipment, photovoltaic panels, etc.
5. Small equipment	Vacuum cleaners, microwaves, irons, toasters, electric kettles, clocks and watches, electric shavers, scales, appliances for hair and body care, calculators, radio sets, video cameras, electrical and electronic toys, etc.
6. Small IT and telecommunication equipment	Mobile phones, GPS devices, pocket calculators, routers, personal computers, printers, telephones, etc.

These electronic products are different in size, design features (material composition and connections) and grade of electronics used, also differing for each model and changing over time (Balde et al., 2015). Each product is composed of several to many discrete elements, such as the housing, printed circuit boards and internal parts. The parts are made of different materials, such as common metals (e.g. iron and steel, copper, aluminium), precious metals (e.g. silver, gold, platinum and palladium), plastics (e.g. acrylonitrile butadiene styrene, polycarbonate, ABS/PC blends, high-impact polystyrene and polystyrene), hazardous materials (e.g. mercury, lead, cadmium), glass, ceramics and more (Balde et al., 2015; Wang, 2014). Furthermore, the materials are held together by different types of connections, such as snap-fit and click connections, bolts, rivets, screws, glue, soldering, brazing, welding and molding (Kaya, 2016; van Schaik & Reuter, 2010; Güngör, 2006).

The wide range of different materials and connections present in electronic products can make their recycling difficult. In the future, the recycling of electronic products may become even more difficult, as electronic products are becoming increasingly complex and miniaturized, while the diversity of materials used in electronic products is expanding considerably (Graedel et al., 2015; Greenfield & Graedel, 2013; Reck & Graedel, 2012).

Below, subsection 1.2.2 describes the three major steps in the recycling process, while subsection 1.2.3 defines the key terms used in this thesis. Subsequently, subsection 1.2.4 explains the issues related to product design that may negatively affect the efficiency of the recycling process.

1.2.2 Description of the e-waste recycling process

Generally speaking, the treatment of electronic products in the recycling process is composed of three stages (also known as sub-processes): 1. disintegration, 2. separation and 3. material recovery.

The disintegration stage consists of manual disintegration (also known as dismantling) and/or mechanical disintegration (also known as shredding or roller milling). A dismantled product does not need to be reassembled, and maintaining product functionality is not important (Xanthopoulos & Iakovou, 2009; Imtananavich & Gupta, 2006; Veerakamolmal & Gupta, 2002; Das & Naik, 2002; Nakashima et al., 2002; Zeid et al., 1997). Examples of dismantling are: cutting off power cords or destructively opening a product's housing to remove batteries, cables and parts containing mercury.

Usually, the dismantling stage entails the removal of some parts or subassemblies which are hazardous, valuable or which may damage or negatively affect the shredder. Doing this prevents contamination of all materials with toxic materials, improves recovery of valuable parts and reduces damage. Therefore, product dismantling – before shredding – may reduce losses. The outcome of the dismantling stage is that specific parts and subassemblies are removed from the product and are subsequently subjected to shredding or, sometimes, go directly to the separation stage (see Figure 1.1). Dismantling involves manual labour, which is often not economically attractive. Dismantling is, therefore, not generally applied, although this depends on the type of product (Tanskanen & Takala, 2006).

Most electronic products are directly, or after partial dismantling, mechanically disintegrated. This causes breakdown of the product into small fragments. A fragment is a piece that is broken off or detached. Fragments can consist of a single material or of a mixture of materials. The process can be carried out using equipment such as large hammer mills, crush augers, roller mills and large-scale granulators. Each technique has its own parameter settings, which affect the disintegration of products and the resulting average fragment size.

In the separation stage, a batch of fragments is sorted into various fractions for subsequent recovery. The chemical composition of the fractions depends on the nature of the separation process and on the composition of the fragments that are separated. Common e-waste fractions are ferrous materials, non-ferrous materials, printed circuit boards, glass and plastic. Common separation techniques include magnetic separators, using ferromagnetism to separate magnetic from non-magnetic materials; eddy-current separators, using electromagnetic

induction to separate non-ferrous metals; and sink-float or wind-sifter separators, using density to separate non-conducting materials (Tempelman et al., 2014).

At the material recovery stage, the various fractions separated from e-waste are further treated using hydro-metallurgical, pyro-metallurgical, electro-metallurgical or bio-metallurgical processes, or a combination of them (Khaliq et al., 2014), to recover metals. Currently, hydro-metallurgy and pyro-metallurgy are the two major recovery routes for e-waste that contains metals. The hydro-metallurgical processes mainly focus on recovery of precious metals (Au, Ag, Pt) from e-waste (Cui & Zhang, 2008; Quinet et al., 2005). The pyro-metallurgical processes focus on recovery of base metals (Al, Cu, Zn, Sn, Pb) as well as precious metals (Cui & Jørgen Roven, 2011; Hagelūken, 2006a;2006b). The recovery of valuable and base metals from e-waste is the main economic stimulus for the e-waste recycling industry (Cui & Zhang, 2008).

At present, e-waste recycling is mainly subjected to pyro-metallurgical processing. This is done by smelting. Smelting works by separating the metals from the other materials present by heating the fraction to a high temperature in the presence of a reducing agent (usually a source of carbon) to cause the metals to melt. Smelting the metal-containing fractions produces a metal or a metallic mixture and a stony waste called slag (Khaliq et al., 2014). However, not all metals can be recovered from the same smelting process. Metals that are not compatible with a particular smelting process are dissolved into the major metal or are lost in the slag material. ‘Non-compatible’ implies that at least one of the metals cannot be recovered and will be lost. Non-compatible materials can also adversely affect the recovery rate of other materials.

Similarly, the glass and recyclable plastic fractions will be remelted and become new sheets and granulates for reuse (Reuter et al., 2013). Bulk plastics such as PP and ABS are often recovered. Most other plastics, which often contain filler materials to tune their properties, are usually incinerated. Figure 1.1 illustrates the stages in the e-waste recycling process. The red rounded rectangles show the sub-processes and the green parallelograms show the input and output flow of products, parts or materials for each sub-process. The recycling process has one main input stream, which consists of the intact or damaged products entering the recycling process, and several output streams. Each output stream is the input stream to the next recycling process, as is shown with orange arrows.

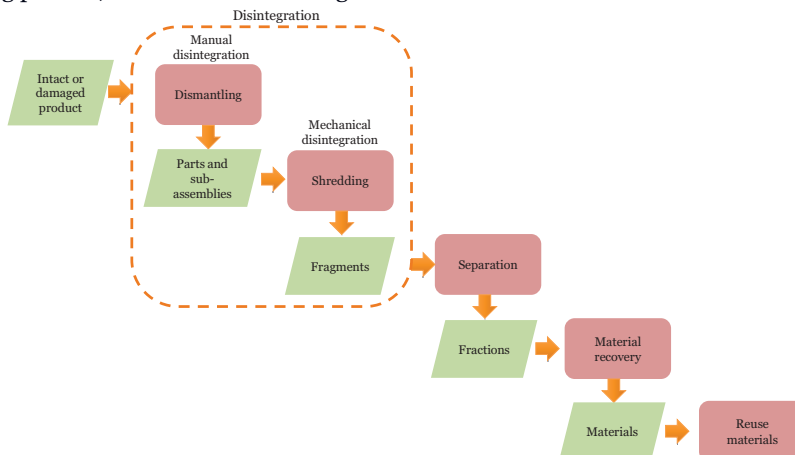


Figure 1.1- Stages in the e-waste recycling process

1.2.3 Definition of key terms

Table 1.2 provides definitions of the key terms that are frequently used in this thesis. It is important to note that these key terms are defined in the literature in many different ways and from different perspectives. Table 1.2 includes the terms that are most relevant to this thesis and defines how they are used here.

Table 1.2- Definition of key terms

Key terms	Definitions
Recycling	The reprocessing of discarded products for recovery of materials, which involves collection, sorting, processing and conversion into raw materials which can be used in the production of new products. (Adapted from <i>Oxford Dictionary of Environment and Conservation</i>)
Recovery	Recovery includes any activities that facilitate the closure of material loops, including reuse of components, remanufacturing of products and recycling of material. Adapted from Tojo (2004). In this thesis, which focuses on recycling, ‘recovery’ refers to the material that is actually available for reuse after the recycling processes, excluding collection.
Yield	The efficiency of a recycling process is described as its yield (Graedel et al., 2011). The yield of each sub-process is the ratio of the input into that sub-process and its output. The yield is usually expressed as a weight fraction.
WEEE recycling rate	“The WEEE recycling rate is the weight ratio of the WEEE-fraction that goes to the recovery/recycling plant divided by the weight of WEEE collected. So, it doesn’t include the efficiency of the recovery/recycling facility.” (Tytgat, 2013)
Recovery rate (or recycling efficiency)	The material fraction actually recovered from the amount that enters the recycling facility.
Recyclability	“The affordance a product has for recovering as much components and materials as possible (quantity) with the highest possible purity (quality) by the least amount of effort (ease) with existing recycling technologies.” (Peters et al., 2012)

1.2.4 Product design and the efficiency of the recycling process

The efficiency of the recycling process depends on the purity of the fractions after separation. In reality, the fractions are never 100% pure but are contaminated with other materials. This is partly because of inefficiencies in the recycling facilities and technology, but also partly caused by the inefficiencies of product design. Impurity of the fractions leads to lower recovery yield and thus to lower economic value and higher environmental impact. To enable optimal recovery, the fractions should consist of pure and compatible fragments. Subsequently, this puts demands on the process of disintegration and separation of fragments.

The following example demonstrates the importance of homogenous and compatible fragments for efficiency in the recycling process. Consider a fragment in which a PCBA is connected to aluminium housing with screws and glue. Materials in PCBAs (electronics) can best be recovered in copper smelters, and aluminium housing can best be recovered in aluminium smelters (Reuter & van Schaik, 2015). However, the use of screw and glue connections can prevent the PCBA from completely detaching from the aluminium part (imperfect disintegration) during the disintegration stage. This is likely to cause part of the PCBAs to end up in the aluminium fraction or part of the aluminium housing to end up in the copper fraction, depending on the relative ratios of the materials (imperfect separation). In both cases, this negatively affects the recovery of materials because of mutual incompatibility of aluminium and copper in subsequent recovery processes (imperfect recovery).

Therefore, the way in which materials are connected plays a crucial role in the ability to generate sufficiently homogeneous and compatible fragments during disintegration. This relates to the primary concern to improve recyclability, which is to establish sufficiently homogeneous and compatible material fractions. Even if the materials used are recyclable, they may not be compatible with a particular recovery process and, therefore, will not be recovered if they end up in an inappropriate recovery process. They might even reduce the efficiency of a recovery process.

1.3 Problem statement

According to Eurostat (2018), in 2015, the average WEEE recycling rate in Europe was only 30 wt.-% (3.4 Mt of 11.6 Mt). Consequently, the recovery rate is even lower than this weight percent. Design is seen as pivotal in the creation of products with high recyclability. For this reason, DfR has been researched in the past two decades, resulting in the development of a considerable number of methods and tools. The aim of these methods is to assist designers in assessing the recyclability of their design and to also select adequate product design features that enhance the recyclability of products and, subsequently, enhance the efficiency of the recycling process. However, these methods do not seem to have been very effective; particularly not in the case of electronic products. This is because, despite the considerable number of methods developed thus far and what is claimed in theory, electronic products are still not being optimally disintegrated and separated in actual recycling processes. This results in impurity in fractions and lowers the recovery rate of the recycling process.

1.4 Research objectives and questions

The central observation of the thesis is that despite the existence of DfR methods in the literature, electronic products are still not being optimally disintegrated and separated in actual recycling processes. This may be because:

- a. DfR methods are not effective. In other words, the application of these methods does not lead to the increased recyclability of electronic products.
- b. DfR methods are not applied in practice.

Therefore, the first objective of this thesis is to test the effectiveness of DfR methods. In particular, it will explore whether the existing DfR guidelines – when taken into account explicitly – are effective and lead to adequate disintegration results. The second objective is to investigate current DfR practices based on the experiences of product developers and designers in electronics companies. The aim is to determine whether DfR methods are applied in practice and, if not, to understand the reasons for this based on the perspectives of designers and electronics producers. Therefore, the central research question of this thesis is:

What is the role of design in the effective recycling of electronic products?

To answer the central research question, the following sub-research questions have been formulated:

Current situation and gap analysis

- RQ1. What are the characteristics of existing design for recycling methods that aim to improve the recyclability of electronic products? (Ch. 2)
- RQ2. How do product design features of screens and LED lamps affect the fragmentation results in recycling experiments? (Ch. 3)

Testing the effectiveness of DfR methods

- RQ3. How effective are design for recycling methods in improving the recyclability of electronic products? (Ch. 4)

Exploring current DfR practices and determining the factors that facilitate or hinder the application of DfR methods

- RQ4. What are the current design for recycling practices, based on the experience of product developers and designers in electronic companies? (Ch. 5)
- RQ5. What factors stimulate or hinder the application of design for recycling methods by electronics producers in general? (Ch. 6)

The problem statement of this thesis (see Section 1.3) is based on the findings of Chapter 2 and Chapter 3. Chapter 2 (RQ1) explores the existing DfR methods reported in the literature and their characteristics and reported effectiveness. Chapter 3 (RQ2) investigates the behaviour of electronic products in actual recycling processes. A comparison of findings reveals a clear gap between what is claimed in theory and what emerges in practice. Chapter 4 (RQ3) examines whether this is because DfR methods are not effective. Chapter 5 (RQ4) and Chapter 6 (RQ5) address the question of whether this is because DfR methods are not

applied in practice and discusses the practices of designers, respectively the processes and procedures of companies and governments.

1.5 Research design and scope

The research questions demand both theoretical and empirical analysis of data. The theoretical data was collected through a literature survey, and the empirical data was collected in the GreenElec project through case study research and interviews with product developers and designers. GreenElec was an interdisciplinary project that brought together suppliers, electronics producers, product designers and developers, recyclers and knowledge institutes to improve the recyclability of electronic products. The project was funded by ENIAC JU and took place from 2012 to 2015 (GreenElec, 2012). The project consisted of several studies, ranging from product design optimization, recycling processes, technology optimization and metallurgical recovery calculations to environmental impact assessment, the business rationale of product recyclability and cooperation across the value chain. The work described in this thesis is part of the GreenElec project and explicitly addresses the role of product design in the effective recycling of electronic products. Subsequently RQ1 to RQ5 are explored. Given the applied nature of the research questions, the main body of the thesis consists of empirical research. Table 1.3 provides an overview of the research methods used for each research question.

Table 1.3- Overview of the research methods employed for each of the studies

		Theoretical	Empirical	
		Literature review	Case study research	Interviews
<i>Current situation and gap analysis</i>				
Chapter 2	RQ1			
Chapter 3	RQ2			
<i>Testing the effectiveness of DfR methods</i>				
Chapter 4	RQ3			
<i>Exploring current DfR practices and determining the factors that facilitate or hinder the application of DfR methods</i>				
Chapter 5	RQ4			
Chapter 6	RQ5			

A literature review of the characteristics of existing DfR methods was conducted to answer RQ1. The result of this study is presented in Chapter 2, which provides an overview of 36 existing DfR methods and their characteristics, including: (1) main product design features that are repeatedly addressed and considered most relevant to product recyclability, (2) suitability for use in early stage product design process, (3) suitability for electronics and (4) actual use and effectiveness of DfR methods.

Answering RQ2 and RQ3 required: (1) gathering information on the composition of electronic products, including their parts, materials and connections; (2) conducting recycling experiments; and (3) developing new design solutions to improve product recyclability. Each of these areas required specialized expertise and facilities that the researcher could not master alone and thus required cooperation with other experts. Therefore, the empirical data on each

of these areas was provided by GreenElec participants. Table 1.4 provides an overview of GreenElec participants whose work is included in this thesis, the empirical data provided and which data are used in which chapters.

Table 1.4- Overview of GreenElec participants involved in this thesis, empirical data provided and which data are used in which chapters

Participants	Empirical data provided by GreenElec participants	Data used in
Electronics producers <ul style="list-style-type: none"> - Philips Lighting - TP Vision - Barco 	<p>a) <i>Supplied case study products (incl. redesigned) for recycling experiments</i></p> <ul style="list-style-type: none"> - LED lamps supplied by Philips Lighting - LCD TVs supplied by TP Vision - Medical displays supplied by Barco <p>b) <i>Provided information on product parts, materials and connections (incl. redesigned products)</i></p>	<p><i>Ch. 3 & Ch. 4</i></p> <p><i>Ch. 3 & Ch. 4</i></p>
Recyclers <ul style="list-style-type: none"> - CIT recycling development AB - Stena Technoworld 	<p>c) <i>Conducted recycling experiments on case study products supplied by electronics producers</i></p> <ul style="list-style-type: none"> - Manual disintegration of 3 LCD TVs and 2 medical displays - Mechanical disintegration of 30 LCD modules followed by separation - Mechanical disintegration of 20 LED lamps of various types – small-scale test - Mechanical disintegration of 35,000 LED lamps of various types – large-scale test, followed by separation <p>d) <i>Conducted recycling experiments on redesigned case study products supplied by electronics producers</i></p> <ul style="list-style-type: none"> - Manual disintegration of redesigned displays - Mechanical disintegration of redesigned LED lamps 	<p><i>Ch. 3</i></p> <p><i>Ch. 4</i></p>
Designers and product developers (working for electronics producers) <ul style="list-style-type: none"> - Philips Lighting - TP Vision - Barco 	<p>e) <i>Redesigned the case study products in order to improve their recyclability</i></p> <ul style="list-style-type: none"> - redesigning an MR16 lamp, a medical display and a consumer television 	<p><i>Ch. 4</i></p>
Research organization <ul style="list-style-type: none"> - TNO 	<p>f) <i>Drivers of and barriers to adoption of DfR</i></p>	<p><i>Ch. 6</i></p>

In order to answer RQ2 and RQ3, the existing empirical data collected by GreenElec participants was further analysed (as shown in Table 1.4). This allowed us to investigate various knowledge areas, including case study products, their behaviour during the recycling process and redesigning of case study products, without having to go through the process of data collection ourselves. The research approach in Chapters 3 and 4 is also referred to as case study research, as the researcher was an observer of the work of the producers, designers and recyclers (as described in Table 1.4), documented their work as they carried it out in practice, analysed the findings and drew conclusions aligned with her own research questions.

Chapter 5 explores current DfR practices (RQ4). This was achieved by interviewing product developers and designers from Philips Lighting, Barco and TP Vision who were involved in the GreenElec project. The product developers and designers had been working on the redesigns and, at the time of the interviews, were thus well aware of DfR guidelines and their use. Furthermore, to answer RQ5, the existing body of literature and TNO reports were reviewed (see f. in Table 1.4) to determine the drivers and barriers that producers of electronics perceive as stimulating or hampering the application of DfR methods.

This thesis contributes to the field of design for recycling by specifically investigating the effectiveness and application of DfR methods. The thesis provides an overview of the DfR methods available from a recycling perspective, with a focus on design features important to recycling. Furthermore, it provides a detailed description of case studies to develop a picture of the current status in the recycling of consumer electronic products, demonstrating the design features important to recycling for the case study products. Another contribution of this thesis is the demonstration of the effectiveness of DfR guidelines for improving the recyclability of specific electronic products. Finally, the thesis also examines the limitations of designers and electronics producers in applying DfR methods.

This thesis explicitly addresses the role of product design in the effective recycling of electronic products. The core of this thesis focuses on the design of specific electronic products, current recycling practices and lessons learnt from recycling process with respect to product design. Further this thesis explores drivers and barriers for designers and companies with respect to applying DfR. This implies that some related important topics are outside the direct scope of this thesis. An important driver for improved recyclability is to lower the environmental impact of products. This is the domain of ecodesign. However, the complete ecodesign perspective which includes the entire life cycle of a product from extraction of raw materials to manufacturing, use, disposal, energy and packaging, will only be addressed to a limited extent. Further, the focus on effectivity of recycling assumes that products are collected in the WEEE waste stream. Products that are not officially collected and recycled (complementary recycling, reuse, export and waste bin) are outside the scope of this study. Further, the focus is on material recovery through recycling; other end-of-life strategies such as reuse, repair, refurbishment, remanufacturing, and parts harvesting are also not included.

The scope of this thesis is further limited to Europe. This is because, on a global scale, Europe has been one of the main pioneers in controlling e-waste and encourages electronics producers to enhance the recyclability of their products through product design, as clearly stated in the WEEE, RoHS and Eco-design directives and the Circular Economy action plan (European Commission, 2015; WEEE directive, 2012; RoHS Directive, 2011; Ecodesign Directive, 2009). The EU legislation forces electronics producers to give higher priority to recycling during the

product development process, and also makes them financially and physically responsible for the collection and recycling treatment of electronic products that they bring to the market. This makes Europe an important and interesting region for research in the area of DfR. The conclusions drawn from this thesis may be valid for other countries with recycling infrastructure in place.

1.6 Thesis outline

This thesis has three main parts, as illustrated in Figure 1.2: Part A, current situation and gap analysis; Part B, testing the effectiveness of DfR methods; and Part C, exploring current DfR practices and determining the factors that facilitate or hinder the application of DfR methods.

Part A aims to analyse the current situation of DfR, both in the existing literature and in practice. This enables us to identify the gap between theory and practice and further study the various reasons for the mismatch between the theory and practice of DfR. **Chapter 2** explores the characteristics of existing DfR methods through a literature review. **Chapter 3** investigates how electronic products behave in actual recycling processes.

A comparison of the literature findings of Chapter 2 with the findings of Chapter 3 shows that there is a gap between the aims of DfR methods (Chapter 2) and the results obtained from disintegration tests of electronic products in practice (Chapter 3). The gap between theory and practice may be due to: 1. DfR methods are not effective; in other words, the application of these methods does not lead to increased recyclability of electronic products, or 2. DfR methods are not applied in practice.

Part B tests the effectiveness of DfR methods. The result of this study is presented in **Chapter 4**.

Part C tests whether or not DfR methods are applied in practice and further identifies the factors that stimulate or hinder the application of DfR methods. **Chapter 5** examines this from the perspectives of designers and product developers. **Chapter 6** examines this from the point of view of electronics producers in general, and **Chapter 7** presents conclusions and suggestions for future research.

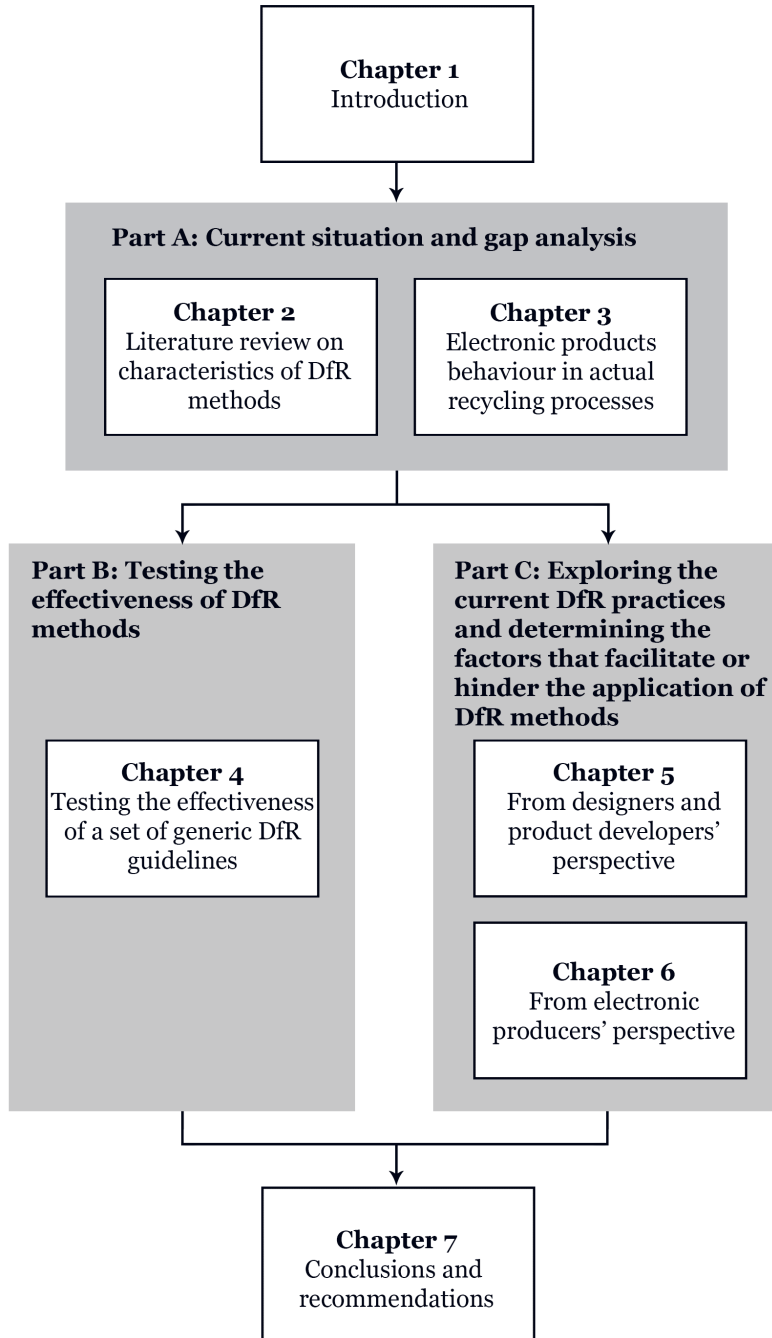
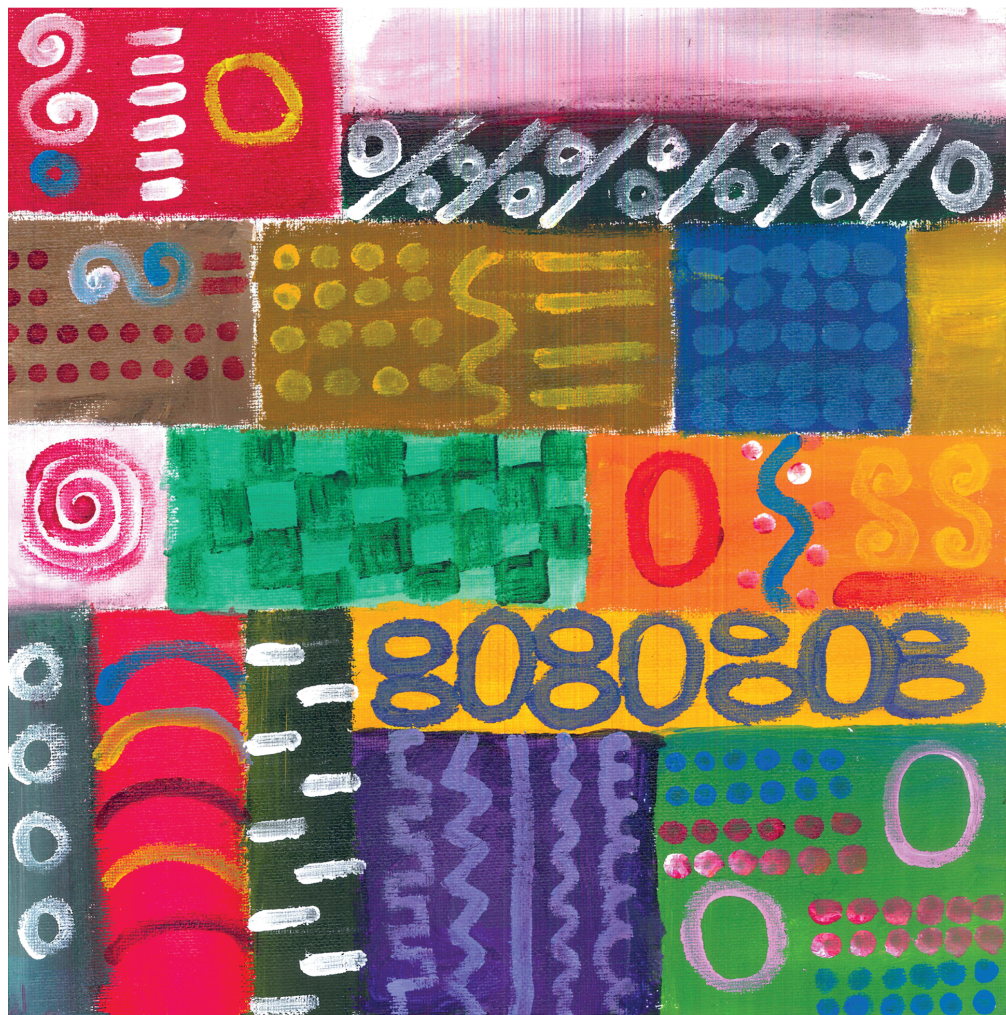


Figure 1.2- Thesis outline

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Painting by Farzaneh Fakhredin

Chapter 2: Literature review on characteristics of design for recycling methods

2.1 Introduction

Improving recycling efficiency through product design can raise the purity of fractions and increase the amount and value of recycled materials. Research has shown that whether a product facilitates or hampers the recycling process greatly depends on design choices and decisions made at early stages of design process (Bovea & Perez-Belis, 2012). Therefore, it is important to identify which product design features are considered most relevant for product recyclability. Communicating the design-relevant requirements of recycling to designers in an effective manner and assisting designers with design for recycling (DfR) related decision making at early design stage is commonly done through DfR methods. To this end, a literature review was done with the aim to examine the characteristics and effectiveness of DfR methods.

RQ1. What are the characteristics of existing design for recycling methods that aim to improve the recyclability of electronic products?

Various DfR methods are developed to improve recyclability of products at various stages of design process. However, in this study our focus is on DfR methods that can assist designers to improve recyclability of electronics at early design stage. Therefore, for the purpose of this review, DfR methods are characterized by their (1) main design aspects that are considered most relevant for product recyclability, (2) suitability for use in early-stage product design process, when vital product design decisions are made (Bovea & Perez-Belis, 2012), (3) suitability for electronics, and (4) effectiveness in actual recyclability of products.

Effectiveness here is defined as the extent to which the application of a DfR method in practice, can really lead to improved recyclability of an electronic product. Recyclability here is defined as the ability to design a product to break down, after manual and/or mechanical disintegration, into fragments that are homogeneous or that consist of compatible materials (Yadav et al., 2018; Sabaghi et al., 2016; Zeng & Li, 2016; Harivardhini & Chakrabarti, 2016; Peters et al., 2012). The effectiveness of a DfR method can for instance be tested by conducting recycling tests on redesigned electronic products.

Designing a new product is a very complex project. The complexity of the design process can raise the level of uncertainty and unpredictable situations. Methods are especially helpful when designers are dealing with these situations. A designer may experience uncertainty when a solution does not come to mind intuitively, sufficient knowledge is lacking, or when a designer feels a lack of confidence in his or her own knowledge or ability. At this point, use of methods can assist designers by bringing structure to their activities and thinking

(Daalhuizen, 2014). Following Daalhuizen (2014), who cites Simon (1996), methods in this thesis are defined as “*means to help designers achieve desired change as efficiently and effectively as possible*” (p. 4). This is a broad definition, and it follows that in this thesis ‘(software) tools’, ‘guidelines’, ‘checklists’, etc, are all considered ‘methods’.

Section 2.2 describes the selection procedure of DfR methods for the purpose of literature review study. Section 2.3 provides a summary of the content of the papers—a concise restatement of what each paper says about the key characteristics of DfR methods including their aim, method, input data, form of presentation, relevant insights and reported effectiveness of the methods. This section sets the background within which arguments can be developed. Section 2.4 discusses key findings and future research needs.

2.2 Research method

A list of key words and key concepts was drawn up to conduct keyword search as summarized in Table 2.1. In order to get as many relevant results as possible, it was important to identify more search terms for each of the key concepts using synonyms, different spellings, singular or plural and similar and related terms. Therefore, thesaurus was consulted to develop a list of synonyms for the main topics.

Table 2.1-combination of various key terms used in literature search engines

Design	Recycling	Method	Designers	Electronic products	Design process
Product design	Recyclability End of life Resource efficiency	Guidelines Tools Approaches Model Methodology	Industrial designers Engineers	Electronics Products Industrial products	Product development process Product innovation process Conceptual design Early design process

The reason for identifying synonyms for main topics is because different authors may mention the same topic differently. The aim was to develop a list of possible ways these topics could appear in literature. To prevent missing other keywords, the key topics (e.g.: design, recycling, method and etc.) were searched using the Google Scholar, then the titles, abstracts and results were scanned and skimmed to look for other possible keywords and further added to Table 2.1.

Boolean operators were used to combine search terms (i.e. “design AND Recycling AND Method”). This led to articles that contain all the three topics. The literature search process was repeated with combinations of all other terms presented in Table 2.1. Further, truncations were used for each word in Table 2.1. For example: recycl* will retrieve recycling, but also terms like: recyclable, recyclability, recycled and recycling. By doing this, search results contained documents including variations of that term. Scopus, ProQuest, Web of Science, JStor, Google Scholar, CRCnetBASE and Narcis were searched for peer reviewed English papers covering the timespan between 1993 and 2018. The most relevant papers were selected based on the following criteria:

- the authors claim that their developed DfR method is aimed at product designers
- method takes into account product features when assessing product recyclability
- method aims to improve recyclability of a product through product design and not through changing recycling techniques or the end of life processes

When assessing relevance, it was made sure that the key authors, key publishers and high cited papers are also included among the selected literature sources. Table 2.2 shows the number of publications assessed in this chapter per reference type. The review of 37 papers showed similar patterns of characteristics across DfR methods. It was found that the same patterns were emerging over and over again in other literature review papers. So, it was decided to stick to 37 papers, as little new information would be gained by adding more references.

Table 2.2- Number of publications per reference type

Reference type	#
Journals	29
Conference papers	8

2.3 Results

This section provides a table with an overview of the identified publications, stating the title of the work, the author's name, the date of publication, the author's thesis and aim of their research, the methods developed and input data required, the form of presentation of the methods, relevant insights and main ideas per paper and the reported practical validation of the DfR methods. Table 2.3 gives details of each study in order of publication year. Examining these characteristics help us to understand the extent to which existing DfR methods are relevant for early design stage, relevant for electronics, effective and address the main design aspects affecting products recyclability.

Table 2.3- Summary table of literature on characteristics of design for recycling methods¹

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Beitz (1993), "Designing for ease of recycling"	"Easy disassembly, use of unitary products or parts, and the selection of recoverable material combinations for non-decomposable products or assemblies."	<ul style="list-style-type: none"> A material compatibility table of aluminium alloy and plastics based on literature study. A table of the features of easily dismountable connections. 	<ul style="list-style-type: none"> Products parts Materials per part Connections 	Heuristic <ul style="list-style-type: none"> Tables 	<ul style="list-style-type: none"> "If functional reasons do not permit use of certain material combinations, the assemblies should be easily dismountable." 	<ul style="list-style-type: none"> "Applied on a dish washing machine and gear box of a hand drill." Without further recycling test.
Chen et al. (1994), "A cost-benefit analysis model of product design for recyclability and its application"	"The development of a cost benefit model that can be used to assess design for recyclability issues."	"A model that primarily looks at the balance between the cost and the benefits of recycling processes."	<ul style="list-style-type: none"> Cost and revenue of recycling processes Environmental factors Detailed product data 	Heuristic <ul style="list-style-type: none"> Flowchart Guidelines Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "The toxicity, compatibility, recyclability and mix of materials determine the cost and benefits of recycling." "Another approach for improving product DfR is to design it for ease of disassembly." 	<ul style="list-style-type: none"> The model is applied on a "dashboard of a popular compact car (model 1985)". Without further recycling test.
Zussman et al. (1994), "Disassembly-oriented assessment methodology to support design for recycling"	"Support product design for the 'end-of-life' phase. It is based on the assessment of feasible options for disassembling a product and applying recycling processes to its components and subassemblies."	<ul style="list-style-type: none"> "All technically feasible disassembly sequences of the product using the AND/OR graphs." "By attaching a decision tree of the feasible recycling options to each node of the AND/OR graph, it is transformed into a 'Recovery Graph'." 	<ul style="list-style-type: none"> Products parts Cost and benefit of end of life processes 	Systematic <ul style="list-style-type: none"> AND/OR graph Recovery graph optimal disassembly sequence graph 	<ul style="list-style-type: none"> "Efficient recycling often requires some amount of disassembly." "Understanding the (uncertainty) regarding future recycling conditions such as the price for raw materials, the refinement of process technologies and the development of dumping fees and regulations are important." 	<ul style="list-style-type: none"> The method is applied on a "washing machine" Without further recycling test.
Kriwet et al. (1995), "Systematic integration of design-for-recycling into product design"	"Supplying the designer with a set of information tools and structured design guidelines for integrating end-of-life aspects into the product design."	"In this approach, the authors look into the product design, production and recycling processes and logistics in order to observe all relevant parameters that influence recycling."	<ul style="list-style-type: none"> Current recycling situation of a product Material composition Product subassembly/co mponent 	Heuristic <ul style="list-style-type: none"> Guidelines 	<ul style="list-style-type: none"> "Besides the environmentally friendly composition of their products, companies have to consider the environmental impact of the processes (production and recycling) and of the logistic support." "The design stage determines 80% of the recycling cost." 	<ul style="list-style-type: none"> The guidelines applied on a "washing machine" Without further recycling test.

¹ Parts of the results reported for DfR methods in Table 2.3 are directly quoted from the literature.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Zhang and Kuo (1997), "A graph-based disassembly sequence planning for EoL product recycling"	"Developing a graph based heuristic approach for the product recycling."	"The planning of disassembly is based on a disassembly tree analysis. A disassembly tree is a group of possible disassembly sequences."	<ul style="list-style-type: none"> Components Connections Subassemblies 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> Product assembly relationship, component-connection assembly relationships, disassembly precedence relationships and number of subassemblies are important to determine disassembly sequence. Finding the feasible disassembly sequence is important. 	<ul style="list-style-type: none"> Applied on a "personal computer". Without further recycling test.
Rosemann et al. (1999), "Design for recycling, recycling data management and optimal end of life planning based on recycling graphs"	"A software system was developed that contains the tools: ReGRED, RecyKon, and DisPlay."	"The methods work based on generation and visualization of an abstract product model and determinate the economically optimal disassembly path and the appropriate recycling strategies for the resulting fractions"	<ul style="list-style-type: none"> Material composition Component Connections Product structure Disassembly time and costs Possible recycling options Recycling benefits 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "Before any recyclability analysis, generation and visualization of an abstract product model which consists of recycling and dismantling relevant data concerning component, connection and the structure of the product is crucial." During the conceptual phase, still no geometrical information is available. therefore, abstract non-geometrical representation of parts and connections in the product structure have to be used to perform analyses on the ease of recycling. 	<ul style="list-style-type: none"> None of these methods are applied in practices.
Knight and Sodhi (2000), "Design for bulk recycling: analysis of materials separation"	"This paper deals with the analysis of materials separation, which determines the least cost or maximum profit level of materials separation."	"The method calculate the cost and profit of material disassembly, shredding and separation."	<ul style="list-style-type: none"> Materials The cost and benefit of disassembly, shredding and separation. 	Systematic <ul style="list-style-type: none"> Charts 	<ul style="list-style-type: none"> "For larger products, some combination of disassembly and bulk recycling will be the most effective." 	<ul style="list-style-type: none"> This approach is applied on a mix of materials, but not applied on other mixtures.
Rose et al. (2000), "A new approach to End of Life Design Advisor (ELDA)"	"The End-of-Life Design Advisor (ELDA) guides product developers to specify appropriate end-of-life strategies. The product end-of-life strategies include Reuse, Service, Remanufacture, Recycle (disassembly first) and Recycle (shred first)."	"ELDA uses technical product characteristics to determine end-of-life strategies."	<ul style="list-style-type: none"> 12 technical product characteristics 	Systematic <ul style="list-style-type: none"> Charts Graphs 	<ul style="list-style-type: none"> "ELDA predicts the end-of-life strategy of products based on technical product characteristics." "This ability to predict strategies enables designers to redesign products based on the end-of-life strategy the product will experience at its end of life." However, the method does not provide any insight on how to do the redesign for different end of life strategies, including recycling. 	<ul style="list-style-type: none"> "The method is applied on a one-time use camera, lead acid batteries, a computer, printers, a computer video projector, a washing machine and vacuum cleaners."

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Hiroshige et al. (2001). "Recyclability evaluation method (REM) and its applications"	"Develop an advanced evaluation that can evaluate a product's ease of recycling, with minimal prototyping and testing of the product at the early design stage."	"The method first conducts a disassembly analysis; the result of disassembly analysis enters a PC software. Then the REM calculation will be conducted automatically which leads to estimated time of disassembly, disassembly and (End of Life) EoL cost and REM score per part."	<ul style="list-style-type: none"> Product and part information Cost of disassembly and EoL treatment 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "In order to make products easier to recycle, it is necessary to take the ease of disassembly into consideration." 	<ul style="list-style-type: none"> Applied on "Hitachi products". Without further recycling test.
Lee et al. (2001), "A multi-objective methodology for evaluating product end-of-life options and disassembly"	"A multi-objective methodology for determining the appropriate end-of-life options for components in a manufactured product is presented."	"A methodology for determining the optimal stage of disassembly of a product is proposed. Showing the impact on the environment and cumulative costs incurred as a product is disassembled."	<ul style="list-style-type: none"> Product parts Time and cost of disassembly Environmental impact of disassembly 	Heuristic <ul style="list-style-type: none"> Disassembly guidelines Disassembly charts (time, cost environmental impact, parts) 	<ul style="list-style-type: none"> "Components of economic value destined for recycling have first to be extracted from the product. Therefore, it is necessary to determine the optimal stage of disassembly." 	<ul style="list-style-type: none"> The methodology is applied on a "coffee maker" and a "television communication pager". No further recycling test.
Ardente et al. (2003). "Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS"	"To develop and to implement a model in a software that minimize the impacts (and costs) of products and facilitate the recycling after product's end-life."	"The model takes into consideration a Multi-Attribute Decision-Making method and allows calculating a "Global Recycling Index" (GRI)"	<ul style="list-style-type: none"> Energy and environmental parameters Economic and technical parameters 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "The software can also employ radar diagrams. This representation allows visualizing and comparing in an easy readable way the performance values of each alternative." 	<ul style="list-style-type: none"> Applied on "electrical lines". No recycling test.
Huisman et al. (2003). "Quotes for environmentally weighted recyclability (QWERTY): concept of describing product recyclability in terms of environmental value"	"The aim of this paper is to develop the concept of quotes for environmentally weighted recyclability (QWERTY) for calculating product recyclability on a real environmental basis (instead of weight basis)."	"To calculate QWERTY scores, first the minimum environmental impact is defined representing a 'best case' end-of-life scenario for the product or product stream under investigation. Second, also a 'worst-case'. Then the relevant actual case."	<ul style="list-style-type: none"> Quantified environmental and economical values of product compositions and end-of-life scenarios 	Systematic <ul style="list-style-type: none"> Charts Graphs 	<ul style="list-style-type: none"> Pay specific attention to toxic and precious materials. "Determine the take-back system strategies that will be most appropriate with existing products and future product design goals." 	<ul style="list-style-type: none"> The method is used on various electronic products including "CRT and LCD TVs, mobile phones and LED lamps". Without further recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Xing et al. (2003), "IREDA: an integrated methodology for product recyclability and end-of-life design"	"This paper introduces a new design approach, Integrated Recyclability and End-of-life Design Algorithm (IREDA), for product recyclability, which is able to implement DfR methodically in design processes."	"Fuzzy sets and graph theory are jointly applied as the basic techniques to formulate the methods for end-of-life strategy planning and structure modularization."	<ul style="list-style-type: none"> Material and connection candidates and Compatibility Material environmental properties "Component end of life intentions Technical characteristics" 	Heuristic <ul style="list-style-type: none"> Guidelines for materials and connections Recyclability Map and its regions 	<ul style="list-style-type: none"> "Product end-of-life strategy planning, structure modularization and material and connection selection improve products recyclability." 	<ul style="list-style-type: none"> The method is applied on an air-conditioning system. Without further testing the recyclability of case study in practice.
Castro et al. (2004), "A thermodynamic approach to the compatibility of materials combinations for recycling"	"Assist designers to choose adequate materials combinations that can be recycled by the existing metallurgic processing routes."	"The method studies the behaviour of a mix of materials in metallurgic reactors."	<ul style="list-style-type: none"> Comminution, separation and metallurgic processes Design of products Product composition 	Heuristic <ul style="list-style-type: none"> THEMA decision tree THEMA matrix Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "Selection of materials combinations that can be recycled by the existing metallurgic processing routes is important." 	<ul style="list-style-type: none"> Applied on a "passenger vehicle" as example. Further, they are used by the authors in other publications and on other case study products. No recycling test.
Castro et al. (2005), "A simulation model of the comminution-liberation-recycling streams relationships between product design and the liberation of materials during recycling"	"A simulation model that describes the relationships between product design and the liberation level attained by shredding."	"The model describes the influence of the type, amount and dimensions of the joints chosen during product design on the liberation level attained after comminution, and further on the contamination levels of the recovered material streams."	<ul style="list-style-type: none"> Joint information such as type, amount and dimensions are needed. Further: analysis of comminution and liberation of the samples were required. 	Heuristic <ul style="list-style-type: none"> Guidelines 	<ul style="list-style-type: none"> "The comminution processes used for recycling are not able to destroy completely all the joints existing between the different materials, resulting in a number of non-liberated material particles. That can enter and pollute other streams" 	<ul style="list-style-type: none"> Applied on a "passenger vehicle". The guidelines drawn from the simulation are used by other researchers. Without further testing the recyclability of case studies in practice.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Herrmann (2005), “Product architect, a new approach for transparency and controlling of the end-of-life performance”	“This paper aims to develop “a DFR software tool that incorporates real recycling market data, market feedback and development experience into a tool.”	“During the assessment, the software uses a special algorithm that simulates the product disassembly. It tries to find the optimal disassembly depth based on optimization criteria selected in the calculation scenario.”	<ul style="list-style-type: none"> • Structure view • Joining techniques • Priorities • Information • Available recycling techniques 	Systematic <ul style="list-style-type: none"> • Software 	<ul style="list-style-type: none"> • Knowing real recycling market data, different regional conditions, requirements, available recycling techniques and infrastructures are important. 	<ul style="list-style-type: none"> • Applied on a “washing machine”. • Validated by other authors in the literature on car seats (Santini,2010). • Without further recycling test.
Johansson and Luthropp (2009), “Material hygiene: improving recycling of WEEE demonstrated on dishwashers”	“The purpose of this paper is to introduce the concept of “material hygiene” and based on that demonstrate a method for grading structural properties in a recycling perspective.”	<ul style="list-style-type: none"> • Products can be categorized based on structural layout of included parts • Disassembly analysis 	<ul style="list-style-type: none"> • Structural layout of Products • disassembly time, equipment, force and information • Weight of products and subassemblies • Layout structure • Number of materials used 	Systematic <ul style="list-style-type: none"> • Dependency tree • Products structural families • Disassembly sequence. 	<ul style="list-style-type: none"> • A simple and visible structure for parts, joints and subassemblies, well-documented, possible to read ocularly or by technical means, promotes recycling. 	<ul style="list-style-type: none"> • The method is applied on “dishwashers”. • The results are based on Swedish recycling conditions. • Without further testing the recyclability of case studies in practice.
Kwak et al. (2009), “Eco-architecture analysis for end-of-life decision making”	“In this paper, a novel concept of eco-architecture is introduced, and the eco-architecture analysis, a design approach supporting the end-of-life decision making process, is proposed.”	“All input information is applied to an integer programming model. As a result, the optimal eco-architecture is identified.”	<ul style="list-style-type: none"> • Product architecture • Connections • Geometrical arrangements 	Heuristic <ul style="list-style-type: none"> • Various eco-architectures • “Guidelines for improving basic eco-architectures” 	<ul style="list-style-type: none"> • “Disassembly analysis to retrieve all the feasible disassembly sequences for a particular component or sub-assembly in the product is important.” 	<ul style="list-style-type: none"> • The method is applied on an “automobile door trim design.” • No recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Favi et al. (2012), "LeanDf: a design for disassembly approach to evaluate the feasibility of different end-of-life scenarios for industrial products"	"The present work describes an approach to support the designer's evaluation of disassemblability by using the 3D CAD model structure and suitable key indices related to product features."	"Software system allows the product model to be analysed and evaluates the disassemblability degree."	<ul style="list-style-type: none"> A 3D solid model (Bill of materials, product structure and components). The structure of the product Cost and environmental impact of materials and recycling processes 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "It is possible to improve recycling by decreasing the disassembly time or cost of disassembly operations." 	<ul style="list-style-type: none"> "The model is applied on the blower system of the cooker hood." Without further recycling test.
Peters et al. (2012), "Prioritizing 'design for recyclability'-guidelines, bridging the gap between recyclers and product developers"	"This paper describes a DFX methodology capable of providing engineers with clear and complete Design for Recyclability guidelines, as well as the possibility to assess a product to obtain an indication of its recyclability performance."	"The performance indicator that measures the degree of recyclability of a product is here defined based on guidelines."	<ul style="list-style-type: none"> Guidelines already available Guidelines collected through expert interviews 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> "A tool developed based on guidelines give designers the ability to assess a concept or product on recyclability using 1. higher level guidelines, or 2. more specific guidelines." 	<ul style="list-style-type: none"> Applied on four small domestic appliances. No further recycling test.
Fukushige et al. (2013), "Quantitative design modification for the recyclability of products"	"Increasing the recyclability of electrical and electronic products. The method estimates the recyclability rate and the disassembly time of a product based on its material composition and end of life scenario."	"The method consists of the following stages: 1. construction of a product model, 2. description of an EoL scenario, 3. estimation of disassembly time, 4. calculation of the RR, 5. sensitivity analysis on the RR and 6. design modification of the product and EoL scenario."	<ul style="list-style-type: none"> The components, their weight, and materials "A structural model of the product, disassembly sequences, shapes of components, connections, disassembly time" 	Systematic <ul style="list-style-type: none"> Excel Graphs Charts Tables 	<ul style="list-style-type: none"> "The construction of a product model to visualize the relationship among the components of a product is crucial using a topological graph, a connectivity graph or a constraint graph." 	<ul style="list-style-type: none"> Applied on a LCD TV based on current recycling scenario in Europe." Without further recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Dostatni et al. (2013), "Application of agent technology for recycling-oriented product assessment"	"The paper aims to describe ideas and implementation of the computer tool for computer-aided and recycling-oriented design."	Agent technology	<ul style="list-style-type: none"> Product structures Types of joints between components Properties of materials Compatibilities of materials Standard and normalized parts Legal requirements regarding the recycling 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> Harmful materials are important and must be identified. It is important to use a permanent joint only when two materials are compatible. 	<ul style="list-style-type: none"> Applied on an "electric kettle" of typical design. There is no follow up study in the literature for further validation or development of the method. Also, no recycling test were conducted.
Umeda et al. (2013), "Generating design alternatives for increasing recyclability of products"	"In this paper, we propose a quantitative method for analysing, and modifying electronic products design to improve the recyclability. In this study, recyclability of a product is quantified as 'recyclability rate' defined as the mass fraction of recyclable materials to the total mass of the product."	"The method consists of the following four steps: 1. The preparation of product model and the description of an EoL scenario, 2. The calculation of the recyclability rate, 3. Impact analysis on the recyclability rate, 4. Generating design alternatives based on the analysis"	<ul style="list-style-type: none"> Bill of materials Geometric model of each component "EoL treatment processes for a product and its components and materials" 	Systematic <ul style="list-style-type: none"> Recyclability index 	<ul style="list-style-type: none"> "Design parameters affecting the entire recyclability rate of a product are the material, mass, and process-type of each component, and the recyclability rates of the components and materials. Among the four types of parameters, the change impact of the mass and recyclability rate are smaller than that of the material and process type in most cases according to our survey." 	<ul style="list-style-type: none"> LCD TV Without further testing the recyclability of case studies in practice.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Sakundarini et al. (2014), "Incorporation of high recyclability material selection in computer aided Design"	"This study is aimed at developing an integrated method of High Recyclability Material Selection that combines recyclability assessment and material selection during product design to improve a product's recyclability in a CAD based environment."	"The use of fuzzy inference system and genetic algorithm is proposed to optimize the multiobjective problem in the selection of recyclable materials."	<ul style="list-style-type: none"> Material type Joining type Material combination Number of parts in sub assembly 	Systematic <ul style="list-style-type: none"> Software 	<ul style="list-style-type: none"> Profit can be quantified but the remaining parameters are imprecise and more suitable to be represented in linguistic form. 	<ul style="list-style-type: none"> This method used on an "automobile part". Without further testing the recyclability of case studies in practice.
Ardenite and Mathieux (2014), "Identification and assessment of product's measures to improve resource efficiency: the case-study of an energy using product"	"The article presents a method, named REAPro (Resource Efficiency Assessment of Products), for the assessment of resource efficiency of products according to: recyclability and recycled content and use of hazardous substances."	"The REAPro method is based on five subsequent steps: selection and characterization of the product, application of the criteria: calculations and assessment, identification of product's «hot spots», identification of potentially relevant, product measures at the 'case-study' level and assessment of policy measures at the 'product group' level."	<ul style="list-style-type: none"> Bill of materials Dismantling information Life cycle impacts, Current and future end of life scenarios Current legislations and policy measures 	Systematic <ul style="list-style-type: none"> Flow chart Tables 	<ul style="list-style-type: none"> "Different requirements enforced via the EU Ecodesign, WEEE, REACH and RoHS Directives must be taken into account." "The prioritization of resources can be performed on the basis of potential environmental benefits related to the potential recycling of the product's parts." "EoL scenario(s) for the selected product group must be defined, representative of the current (or future) EoL treatments in the considered geographical area." Identifying product's parts that contain hazardous substances is important. 	<ul style="list-style-type: none"> The method is applied on a "LCD TV". Without further testing the recyclability of case studies in practice.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Reuter and van Schaik (2015), "Product-centric simulation-based design for recycling: case of led lamp recycling"	"This paper will illustrate how a product-centric simulation approach to recycling is core to DfR & Design for Resource Efficiency."	<ul style="list-style-type: none"> HSC Sim model 8.0 GaBi <p>"Material/element recoveries, losses and recycling rates are calculated for various recycling architectures or product inputs/designs, based on full mass balances and quantities and qualities of (intermediate) recycling flows by applying existing industry tools."</p>	<ul style="list-style-type: none"> Product compositions Connections Metallurgical processes of materials and their environmental impacts 	Heuristic <ul style="list-style-type: none"> Metal Wheel Compatibility matrix Guidelines 	<ul style="list-style-type: none"> The method works best when product design is finished. However, the results are presented in simpler ways for early design stage. 	<ul style="list-style-type: none"> The method is applied on various case study products. The method is also commercialized and can be purchased online. The video tutorials on how to use the method are also available online. Without further testing the recyclability of case studies in practice.
Zeng and Li (2016), "Measuring the recyclability of e-waste: an innovative method and its Implications"	"In this study, we create innovative mathematical models, based on the physical and chemical characteristics of materials contained in e-waste, to measure the recyclability and recycling difficulty of various types of electronics."	"The concentration of all materials in electronics has been substantially evaluated by Shannon's Statistical Entropy function of Information Theory which can measure the loss or gain of information about a system or the variance of a probability distribution."	<ul style="list-style-type: none"> "Physical and chemical characteristics of materials" 	Systematic <ul style="list-style-type: none"> Mathematical models "Systematic map for recyclability of e-waste." 	<ul style="list-style-type: none"> "The recyclability of electronics is in essence dependent upon the types and quantities of its elements and their grades." 	<ul style="list-style-type: none"> Recyclability of various types of electronics measured Without further recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Sabaghi et al. (2016), “Evaluation of products at design phase for an efficient disassembly at end-of-life”	“A hybrid design of experiment (DOE) and TOPSIS method was proposed in order to obtain a unique discriminant disassembly model to calculate the disassemblability index for each two given components.”	“Accessibility, mating face, tools, connections type, quality and variety of connections are the major five parameters that affect disassembly task. In this study, qualitative measures were associated with numerical scales and defined for each parameter using TOPSIS model.”	<ul style="list-style-type: none"> • Accessibility, mating face, • Tools, • Connections type • Quality and variety of connections 	Systematic <ul style="list-style-type: none"> • Mathematical models 	“Products are composed of different components assembled via different type of joints in an organized structure.” AND “The results showed that among the analysed disassembly parameters in the main structure of the aircraft, “Accessibility” and “Quantity and variety of the connections” are the most significant ones which can highly influence the disassembly-task.”	<ul style="list-style-type: none"> • Aircraft • Without further testing the recyclability of case studies in practice.
Smith et al. (2016), “Partial disassembly sequence planning based on cost-benefit analysis”	“This study develops a new partial disassembly sequence planning method. Using life cycle impact assessment tools to perform cost-benefit analyses to find an optimized disassembly stopping point.”	“The method uses constraint matrices and expert rules to create disassembly models and disassembly plans that are functionally, physically, environmentally and economically practical.”	<ul style="list-style-type: none"> • Cost and environmental impacts of disassembly per part • Parts • “Part order, part disassembly directions, number of reorientations, and number of tool changes to find an optimized disassembly plan and an optimized disassembly stopping point.” 	Systematic <ul style="list-style-type: none"> • Graphs and charts 	<ul style="list-style-type: none"> • “Partial disassembly sequence planning can help designers redesign the products, make the parts with high economical (recycling) benefits more accessible, and reduce disassembly cost” 	<ul style="list-style-type: none"> • Driver and scanner Without further recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Movilla et al. (2016). "A method for manual disassembly analysis to support the ecodesign of electronic displays"	"The purpose of this paper is to propose a method for in-depth analysis of dismantling practices of electronic displays in order to obtain useful data for product design."	"The method is composed of three stages: (1) study definition, (2) data construction and (3) data analysis. The first stage allows setting out why, how and where the analysis will be performed. The second stage consists in describing dismantling operations in detail to construct a detailed and meaningful dataset. Finally, product indicators are developed and the best and worst design practices from a dismantling point of view are identified."	<ul style="list-style-type: none"> Materials Connections Accessibility and liberation 	Heuristic "List of the best and worst design practices found on the sample from a dismantling point of view." "Average percentage of dismantling time spent on each component, on each operation and on each tool and product design features that affect the dismantling time"	<ul style="list-style-type: none"> "We have noticed that developed guidelines are mainly based on discussions, interviews or surveys, hence based on subjective perceptions. Other researches produce quantitative data from general analyses of the disassembly processes, i.e., the case of LCD disassembly. However, the data provided do not constitute enough empirical evidence to support the development of specific and measurable design guidelines. This is mainly due to the absence of the application of a systematic method that allows studying in depth the disassembly activities of treatment operators." 	<ul style="list-style-type: none"> 12 flat panel displays Without further testing the recyclability of case studies in practice.
Hariwardhani and Chakrabarti (2016). "A new model for estimating End-of-Life disassembly effort during early stages of product design"	"In this paper, a new model for estimating disassembly effort during early stages of product design is proposed. The model has been developed by integrating two well-known models in the field of product disassembly: Das et al. Disassembly Effort Index (DEI) model and Kroll and Hanft Disassembly Evaluation model."	"The first model is a multi-factor cost and effort model, which is widely used for determining disassembly effort in terms of a DEI score. This score is a representative of the total operating cost incurred in disassembling a product. The second model is commonly used for evaluating ease of disassembly, by assigning task difficulty scores to disassembly tasks."	<ul style="list-style-type: none"> Parts Connections Accessibility 	Systematic <ul style="list-style-type: none"> Disassembly effort index score Evaluating ease of disassembly score 	<ul style="list-style-type: none"> "Many research studies have emphasized the importance of ease of disassembly for a product, especially from the EoL perspective. Ease of disassembly is considered as a significant requirement in order to efficiently carry out recovery processes such as remanufacturing, reuse, recycling, and repair." 	"The proposed model has been demonstrated by an estimation of disassembly effort for a CRT monitor disassembly process using the model and validated by benchmarking the results obtained using the proposed model against results from an existing model for a case study conducted on fifteen computer electronic products." Without further recycling test.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Telenko et al. (2016), "A compilation of design for environment guidelines"	"Based on a broad critical review of DfE literature and best practices, a set of 76 DfE guidelines are compiled and reconciled for use in early stage design of products with minimal environmental impact."	"Compiling the principles, guidelines, and checklists described in the academic literature and industry reports and manuals."	<ul style="list-style-type: none"> Materials and connections 	Heuristic <ul style="list-style-type: none"> Guidelines 	<p>"1. It is difficult to implement some of the guidelines simultaneously. Designers must identify a DfE strategy and implement relevant guidelines. 2. Designers can use guidelines as idea generators. 3. Designers can use the list of guidelines to evaluate concepts. 4. An Expert Knowledge Database can be developed to assist designers to select relevant guidelines based upon desired DfE strategy and design stage."</p>	<ul style="list-style-type: none"> "Various design solutions that follow DfE guidelines." Without further testing the recyclability of case studies in practice.
de Aguiar et al. (2017), "A design tool to diagnose product recyclability during product design phase"	"This paper designed to provide the product's grade of recyclability a graphical diagnosis, aiding the designer in making better design choices. Thus, the designer can diagnose the most critical parts and change the product while still in the design phase, improving the product's recyclability at its end-of-life."	"Proposed five indexes to perform the disassembly analysis and used four indexes to evaluate material recyclability. The proposed indexes are to be used with product's BOM, during the conceptual and embodiment design. To provide a more visual analysis, the fitting level was conceived as a colour-based scale, adjusted to the limits of each index. Darker shades of grey imply worse conditions for product recycling and must be resolved first. After making all modifications, repeat the process from the beginning until the design team is satisfied with the results. The index level should be reduced to the minimum possible value."	<ul style="list-style-type: none"> Bill of materials Connections Recycling infrastructure 	Heuristic <ul style="list-style-type: none"> Visual analysis "Design for Environment suggestion bank to improve the recycling index." 	<p>"The potential for recyclability is connected to two factors: materials recycling and disassembly process. For disassembly process, the number, type and accessibility of fasteners were considered. For material recycling process, recycling infrastructure, material compatibility, presence of hazardous materials and existence of contaminants were considered."</p>	<ul style="list-style-type: none"> "A portable cassette and CD player" Without further testing the recyclability of case studies in practice.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Li et al. (2017), "Evaluation of product recyclability at the product design phase: a time-series forecasting methodology"	"This paper developed a methodology for evaluating the recyclability of the product design by considering both the environmental and economic factors at different stages of the product life cycle."	"The proposed evaluation methodology consists of two main parts namely forecasting module and evaluation module. the forecasting module predicts the price of scrap materials over a period of time. The evaluation module calculates, the manufacturing cost, maintenance cost (cost in usage phase) and cost of recycling operations and environmental impacts of different stages of products life cycle."	<ul style="list-style-type: none"> "It considers various economic and environmental factors of different stages of the product's life cycle." 	Systematic <ul style="list-style-type: none"> Mathematical models 	"In many cases, the recyclability of product is primarily determined at the design stage because about 80% of the economic, environmental and social impacts are determined at the design stage"	<ul style="list-style-type: none"> "A Volkswagen EA888 engine cylinder block" Without further recycling test.
Soo et al. (2017), "The influence of joint technologies on ELV recyclability"	"This paper identifies the types of joining technologies used in the automotive manufacturing industry that hinder the sorting of ELV materials."	"The study is based on an industrial shredding trial of car doors. Observations from the case study showed that steel screws and bolts are increasingly used to combine different material types and are less likely to be perfectly liberated during the shredding process. in Australia."	<ul style="list-style-type: none"> Materials Joints 	Heuristic <ul style="list-style-type: none"> Tables 	"The characteristics of joints that lead to impurities and valuable material losses, such as joint strength, material type, size, diameter, location, and protrusion level, can influence the material liberation in the current sorting practices and thus, lead to ELV waste minimization. Additionally, the liberation of joints is also affected by the density and thickness of materials being joined."	<ul style="list-style-type: none"> End of life vehicles No further recycling test.
Diakun et al. (2018), "Modelling and recycling-oriented assessment of household appliances"	"A software tool facilitating the creation of recycling-oriented models for selected products and calculation of assessment measures for the analysis is presented."	"At the first stage of the analysis, a CAD 3D model of the product is created. Next, the kind of joint (separable, non-separable), type of joint (threaded, glued, welded, etc.) and the components (parts or support) of which a joint is made will be entered. Further, data on materials used in the product (advanced material attributes), which specify toxicity, group materials into categories and define compatibility of categories. Lastly, the main results of the recycling-oriented analysis are presented in a report."	<ul style="list-style-type: none"> Product composition Joints between product components Advanced material attributes Disassembly process Recycling costs Product group 	Systematic <ul style="list-style-type: none"> Software 	Materials, connections and disassembly are three major recycling-oriented aspects of ecodesign	<ul style="list-style-type: none"> Sandwich toaster and hair dryer Without further testing the recyclability of case studies in practice.

Author (year), title	Aim	Method	Input data	Form of presentation	Relevant insights	Reported effectiveness
Yadav et al. (2018), "Development of product recyclability index utilizing design for assembly and disassembly principles"	"This paper explores how designers can use the design for assembly (DFA) parameters to predict the recyclability index of a product."	"Recyclability Index of the product was then determined as the average of product of Recyclability Index of the Material (MR) and Disassembly Rating (DR) of the parts or subassemblies as an extension of the Boothroyd-Dewhurst DEA table. Recyclability of the materials is calculated based on value of materials at three different stages of product life cycle."	<ul style="list-style-type: none"> • Material values • Parts name • Dismantling time per part • "Recyclability of each joint on a scale of 1 (poor) to 3 (good)" 	Systematic <ul style="list-style-type: none"> • Mathematical modelling 	<p>"The recyclability methods can be segmented into two distinct elements recyclability of materials and disassembly rating of parts or joints." AND</p> <p>"The results of the study indicated that the recyclability of the product, as defined by established recyclability metrics, could be predicted through design for assembly measures."</p>	<ul style="list-style-type: none"> • "A fused deposition modelling three-dimensional printer head, a security alarm siren, a stapler, and a three-hole punch." • Without further testing the recyclability of case studies in practice.

Since 1993 till today, the need to assist designers to assess and improve the recyclability of their design choices and further select adequate product design features that facilitate the existing recycling process and minimize the environmental impact and cost of product design and recycling process, led to the development of different kind of DfR methods.

Table 2.3 shows that methods fall into two major categories: heuristic and systematic methods. One major similarity is that they both “aim to guide the cognitive processes of their users by providing prompts for information processing that can assist in learning, decision making, problem solving and reflection” (Daalhuizen, 2014). However, their major difference is in the amount of information processing they require from their users. Heuristic methods require “processing of only certain pieces of information while ignoring the most” (Daalhuizen, 2014). Systematic methods require “processing of as much information as possible” (Daalhuizen, 2014). Another major difference is in the result and process for decision making.

Heuristic methods do not guarantee an optimal result, but they aim to assist designers to find a satisfactory, sufficient and approximate result more directly and in a shorter amount of time. Further, heuristic methods are based on experiential and intuitive processes. Meaning that they allow designers to learn by discovering adequate design choices and decisions themselves and learning directly from their own experiences and intuitions rather than by telling them what adequate choices are (Campana et al., 2017; Fu et al., 2016; Daalhuizen, 2014; Martí & Reinelt, 2011). Daalhuizen (2014) defines a heuristic method as follows: “a heuristic method prompts a designer to focus on particular pieces of information while ignoring most in aiming to reach satisfactory rather than optimal results.” The most dominant heuristic methods are often presented in the form of:

- *Design for recycling guidelines*: these are recommended practices that allow some leeway in their interpretation and use. They are most often given as do's and don'ts statements (de Aguiar et al., 2017; Telenko et al., 2016; Reuter & van Schaik, 2015; Castro et al., 2005; Xing et al., 2003; Lee et al., 2001; Kriwet et al., 1995; Chen et al., 1994) or as a pair of pictures, where one presents the ‘good practice’ and the other presents the ‘poor practice’ (Kwak et al., 2009) or list of best and worse design practices (Movilla et al., 2016). DfR guidelines are derived based on theoretical or empirical research. In theoretical studies, the DfR guidelines are derived based on the aggregation of guidelines specified in academic works and industrial reports (Telenko et al., 2016). In the empirical studies, observations from the actual behaviour of products during recycling treatment process shows the best and worst design practices in terms of product design features hampering or facilitating the recycling process (e.g.: dismantling and shredding) (Movilla et al., 2016). This further lead to development of guidelines. DfR guidelines address a range of different design aspects including materials, connections and product structure (see Table 2.4). Figure 2.1 is an example of design for recycling guidelines as used in (Kwak et al., 2009).

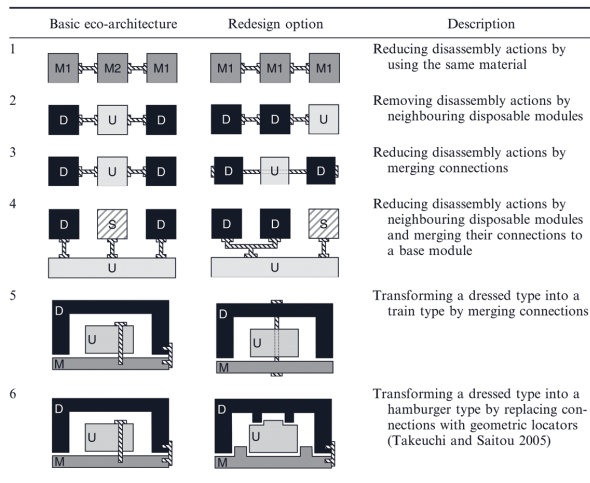


Figure 2.1-Examples of design guidelines as used in (Kwak et al., 2009)

- *Table of connections*: contain a list of connection techniques (e.g.: welding, brazing, soldering, adhesive bonding, clicking, press fit, mechanical fastening and etc.). Various connections are evaluated and rated according to the degree of disintegration behaviour during a manual or mechanical disintegration test (Soo et al., 2017; Beitz, 1993). Connection tables can indicate which connections are perfectly disintegrated or are less likely to be perfectly disintegrated during manual or mechanical disintegration. Rankings are generally presented based on a colouring system of green, orange and red or based on a rating scale of good, average and bad. Green/good means the connection is highly disintegrable during manual or mechanical disintegration, orange/average means medium disintegrable, and red/bad means low disintegrable (Reuter et al., 2013; Beitz, 1993). In some cases the authors provide a descriptive explanation of disintegration behaviour of connections (Soo et al., 2017). Connection tables help designers to select connections that facilitate the disintegration process. Figure 2.2 is an example of Table of Connections as used in (Beitz, 1993).

		Material connection					Frictional connection					Positive connection				
		principle of connection		plastic/metal adhesive bonding		welding	magnetic connection	Velcro fastener	bolt/nut	spring connection	snap joint	bent-lever connection	quarter-turn fastener	press-turn fastener	press-press fastener	band with lock
carrying capacity	tensile strength	●	●	●	●	●	●	●	●	●	●	●	○	○	○	●
	Transversal strength	●	●	○	○	●	●	●	●	●	●	○	●	●	●	○
	Fatigue strength	○	●	○	○	●	●	●	●	○	●	●	○	○	○	●
	Joining expenditure	●	○	●	○	●	●	●	●	○	●	●	○	○	●	○
joining detaching behaviour	Detaching expenditure	●	○	●	○	●	●	●	●	○	●	●	○	○	●	○
	Destruction expenditure	●	○	●	●	●	●	●	●	●	○	○	○	○	○	●
Recycling		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

● = good ● = average ○ = bad

Figure 2.2- Example of Table of Connections as used in (Beitz, 1993)

- Material compatibility matrixes:** aim to illustrate how to select feasible combinations of materials for recycling (material recovery stage). The compatibility matrixes indicate which material combinations are acceptable and which combinations must be avoided in various material recovery streams. The compatibility of materials is illustrated based on Harvey balls or colouring system. Harvey balls are circle shaped ideograms where full black circle means the two materials are compatible, half black circle means compatible within limits, quadrant black circle means compatible in small quantities and empty circle means non-compatible (Beitz, 1993). In colour-based rating systems, green means compatible (acceptable combination). Red means incompatible (avoid mixing) unless the connection between the materials can break easily. Orange means uncertain and problems in material recovery can occur (Reuter & van Schaik, 2015; Castro et al., 2004). Examples of material compatibility matrixes are presented in (Reuter & van Schaik, 2015; Castro et al., 2004; Beitz, 1993). Figure 2.3 is an example of a Material Compatibility table as used in Castro et al. (2004).

Input streams	Industrial streams (metals)							
	Aluminum (cast)	Aluminum (wrought)	Copper	Lead	Magnesium	Pt-family alloys	Stainless steels	Steel + Cast iron
Aluminum (cast)								
Aluminum (wrought)								
Copper alloys								
Lead alloys								
Magnesium alloys								
Pt-family alloys								
Stainless steels								
Steel + Cast Iron								
Zinc alloys								
Glass								
Synt.Elastomers								
Natural Fibers								
Natural Rubber								
Porcelain								
Thermosets								
Thermoplastics								

0 - MUST separate, avoid mixing

1 - SHOULD separate, problems can occur

2 - DON'T separate, good combination

Figure 2.3-Exmple of Material Compatibility Table as used in Castro et al. (2004)

Table 2.4 summarize the heuristic methods that guide DfR decision-making in the early design stage. The heuristic methods are organized according to three design decisions that are considered most relevant for product recyclability including: selection of materials, selection of connections, accessibility and product structure. The heuristic methods include a set of 36 DfR guidelines, material compatibility matrixes and connection tables compiles from the reviewed literature on DfR methods.

Table 2.4-Heuristic methods that guide DfR decision-making in early design stages

Design decisions related to DfR	Examples of design guidelines	Specific methods
Selection of materials	<ul style="list-style-type: none"> Minimize the variety of materials used Avoid toxic and harmful materials (hazardous substances) Minimize number of materials used Use highly recyclable materials Design with recycled materials Use mono- colour for recyclable plastics Use/combine compatible materials Choose the materials that are compatible with the product recycling and material recovery process Avoid secondary finishes (galvanizing, laminates, coating, plating, paintings) on metals Do not mold in metals inserts into plastic bodies Use markings to identify the type of plastics used in components Label products/parts based on recovery and compatibility Inform the materials used in all products parts 	<ul style="list-style-type: none"> Guidelines for material selection (de Aguiar et al., 2017; Telenko et al., 2016; Xing et al., 2003; Kriwet et al., 1995; Chen et al., 1994) Compatibility matrix of Al alloys (Beitz, 1993) Compatibility matrix of plastics (Beitz, 1993) THEMA decision tree (Castro et al., 2004) THEMA matrix (compatibility matrix of metals, glass and plastic) (Castro et al., 2004) Metal wheel (Reuter & van Schaik, 2015) Best and worst design practices based on in depth disassembly analysis (Movilla et al., 2016)
Selection of connections	<ul style="list-style-type: none"> Minimize variety and number of connections Use same size and type of connections Use standard connections Use easily disintegrable connections Use snap fit connection for plastic parts Reduce the amount of connections used, in terms of connections mass Prefer physical connections over chemical connections Keep the orientation of connections consistent (horizontal or vertical) Choose a connection that is physically and chemically compatible with the two materials/parts to be combined Use irreversible connections (welding, riveting, brazing) when two or more materials are compatible. Use connections that can be easily disintegrated (when two materials are incompatible) Make sure connections are visible and easily accessible Use connections that can be disintegrated with regular dismantling tools Use connections that do not require frequent changes of tools Use snap fits instead of screws when possible 	<ul style="list-style-type: none"> Guidelines for connection selection (de Aguiar et al., 2017; Castro et al., 2005; Xing et al., 2003; Kriwet et al., 1995) Features of easily dismountable connections (Beitz, 1993) Table of connections and their liberation behaviour (Reuter et al., 2013) Disassembly guidelines (Lee et al., 2001; Kriwet et al., 1995; Chen et al., 1994) Best and worst design practices based on in depth disassembly analysis (Movilla et al., 2016) Descriptive explanation of various joint types and their disintegration behaviour during mechanical disintegration (shredder) (Soo et al., 2017)
Accessibility and product structure	<ul style="list-style-type: none"> Make scarce/valuable/harmful materials/parts easily accessible Cluster parts with similar or compatible materials together that can be easily removed “Transforming a dressed type into a train type by merging connections” (Kwak et al., 2009) “Transforming a dressed type into a hamburger type by replacing connections with geometric locators” (Kwak et al., 2009) Minimize number of subassemblies Configure a product with physical connections, geometrical arrangements and modular features of components, parts and subassemblies that facilitates the disintegration process. In case of manual disintegration, the design must be able to decrease dismantling time and cost and in case of mechanical disintegration the design must be able to breakdown into homogenous and compatible fragments Develop a dismantling guide for the product Avoid long disassembly paths 	<ul style="list-style-type: none"> Four types of basic product structure (Kwak et al., 2009) Guidelines for improving product structure (de Aguiar et al., 2017; Kwak et al., 2009) Disassembly sequence for five common product structures (Johansson & Luttrupp, 2009) Dependency tree visualizing connections between parts (Johansson & Luttrupp, 2009) Disassembly guidelines (Lee et al., 2001; Kriwet et al., 1995; Chen et al., 1994) Best and worst design practices based on in depth disassembly analysis (Movilla et al., 2016)

As opposed to heuristic methods, systematic methods seek to achieve optimal results through deliberative processes. Systematic methods are usually based on mathematical relationships combining a systematic, detailed vision over the whole product design and recycling process. Daalhuizen (2014) defines a systematic method as follows: “a systematic method prompts a designer to include as much information as possible in aiming to reach optimal rather than satisfactory results.” The systematic methods are mainly presented in the form of computer-based software addressing the following main topics: disassembly oriented assessment, eco-efficiency and calculating recyclability rate.

Disassembly oriented assessment methods: End of life products are sometimes disassembled to allow removal of hazardous and high-valuable parts/materials. This can lead to a higher recovery rate of materials (Sabaghi et al., 2016; Smith et al., 2016; Movilla et al., 2016). However, disassembly is not always economically feasible. Therefore, the majority of disassembly methods reviewed use disassembly sequence planning methods to find the optimal disassembly path and the degree to which a product can be disassembled (also known as “optimized disassembly stopping point” or “optimal stage of disassembly”).

Smith et al. (2016), Lee et al. (2001), Herrmann et al. (2005) use life cycle assessment methods and economic value of disassembly to conduct a cost-benefit analysis to find the extent to which a product must be disassembled. The analysis of cost-benefit shows the optimized disassembly stopping point. The result of their studies is presented in the form of disassembly charts illustrating the environmental impact and costs associated with each disassembly step. Designers can use these disassembly charts for product redesign. For example, designers can identify parts/components with high economical value and/or high environmental impact and make them easily accessible by changing their position in the product structure. Further, designers can reduce the dismantling time by changing connections or reducing the number connections (Lee et al., 2001).

Beside cost-benefit analysis, some authors introduced graph-based approach to find the optimal disassembly path and the extent to which a product must be disassembled. In this approach authors generate a graph representation of product structural models using AND/OR graphs, disassembly tree, dependency tree or precedence matrix to illustrate all possible disassembly plans/sequences of product and to visualize all connections between components. Further, they evaluate various disassembly paths, identify the optimal disassembly path and disassembly termination based on mathematical models. The graphs contain information regarding the product architecture, connections used, time, force, equipment and easiness to understand per connection. Further, the graphs contain information regarding the disassembly time and its associated cost per disassembly path. The best disassembly path for components would minimize the disassembly time and cost. These graphs can assist designers in selection connections and design of product structure to decrease disassembly time and cost. Examples of these methods are presented in Zussman et al. (1994), Zhang and Kuo (1997), Rosemann et al. (1999), Hiroshige et al. (2001), Lee et al. (2001), (Herrmann et al., 2005), Johansson and Luttrupp (2009), Favi et al. (2012) and Fukushima et al. (2013).

Besides disassembly sequence planning methods, some disassembly methods use multi criteria decision making techniques to calculate the disassembly index (“the level of difficulty associated to a disassembly task” (Sabaghi et al., 2016)). In their study, Sabaghi et al. (2016) identified five parameters that affect products disassembly including accessibility, tools,

ating face, quantities and variety of connections, and connections types. Each disassembly task was evaluated based on these five parameters. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method were used to calculate the disassemblability index. The TOPSIS method involves the following steps: 1. prepare a decision matrix including the five parameters and disassembly tasks. The five parameters are used to evaluate the disassembly tasks, 2. normalization of decision matrix, 3. find out the ideal positive and negative solutions, 4. calculation of the distance from the positive or negative solutions, and 5. the disassemblability index value. The disassemblability index value is between zero and one. The closer this value to one the easier is the disassembly task. The final assessment is presented in a chart that shows the disassemblability index per disassembly task. Using this chart, designers can identify which disassembly tasks require more effort and adapt the design features accordingly.

To estimate the disassembly effort, Harivardhini and Chakrabarti (2016) developed a new model that integrates two well-known disassembly models by Das et al. (2000) and Kroll and Hanft (1998). In their studies, Das et al. (2000) identified six parameters that affect products disassembly including time, fixture, access, tools, force, instruct and hazards. Similarly, Kroll and Hanft (1998) identified four parameters that affect products disassembly including positioning, accessibility, force and base time. Each disassembly task was evaluated based on these ten factors and allocated a Disassembly Effort Index (DEI) (also referred to as disassembly difficulty rate). The DEI score can help designers to identify which disassembly task requires the highest disassembly effort. By changing the physical configuration of products (accessibility and positioning), base time, force and etc. designers can enhance product design for disassembly and reduce the total dismantling time.

Only one method allows in-depth analysis of disassembly process to find out product design features that facilitate or hamper disassembly process based on empirical studies. In their studies, Movilla et al. (2016) argued that majority of disassembly methods are very general and theoretical and lack empirical evidence. Therefore, in their studies they disassembled 12 flat panel displays (FPD), as they are considerably growing in the e-waste stream. The result of their disassembly analysis led to a list of product design features that facilitate or hamper the disassembly process. The time required to manually remove the components was a direct indicator to assess the ease of manual disassembly. Successful product features were those that reduce the dismantling time. Unsuccessful product features were those that increased the dismantling time.

Beside disassembly-oriented assessment methods, there are other types of systematic methods that not only focus on disassembly but on the entire stages of e-waste recycling process. These methods are known as eco-efficiency methods and methods for calculating the recyclability rate.

Eco-efficiency methods: the recycling process is composed of several activities. Each activity is associated with its costs, benefits and environmental impacts. Changing product design features can affect the cost and environmental impact of recycling process. Combining the costs and environmental impact of recycling processes in an eco-efficiency model can help designers to compare the economic and environmental behaviour of various design scenarios during the recycling process. By changing the product design features designers can observe how the cost and environmental impact of recycling process changes. For example, preventing the use of toxic materials in product design reduces the environmental impact and also the cost of manual disintegration. These tools can assist designers to select product

design features that reduce cost and environmental impacts and increase the revenue of recycling. Examples of these tools are cost-benefit models by (Knight & Sodhi, 2000; Chen et al., 1994), ENDLESS (“eco-sustainable energy and environmental strategies in design for recycling”) by (Ardente et al., 2003), QWERTY/EE (“Quotes for environmentally weighted recyclability and eco-efficiency of the end of life electronic products”) by (Huisman et al., 2003), a time-series forecasting methodology by (Li et al., 2017).

Methods for calculating recyclability rate: some methods focus on calculating the recyclability rate. To do so, these methods follow a number of steps: First, a product model is generated which includes information on Bill of Materials and other parameters such as material combinations, material separation, selection of connections that can increase recyclability of materials. Second, the recyclability rate is calculated based on mathematical models and computational algorithms. For example Peters et al. (2012) measured the recyclability rate of electronic products based on quantifying and weighting a set of design guidelines. Ardente and Mathieux (2014) assessed products recyclability based on agent technology. Sakundarini et al. (2014) used fuzzy interface system and generic algorithms, and Zeng and Li (2016) used entropy function to calculate the recyclability rate. Thirdly, the assessment of recyclability led to design changes to increase products recyclability rate. Other examples that calculate the recyclability rate of products are presented in (Diakun et al., 2018; Ardente & Mathieux, 2014; Umeda et al., 2013; van Schaik & Reuter, 2004; Huisman, 2003).

Heuristic methods are more useful at early design stages than systematic methods. Heuristic methods help give direction to the design process, as soon as first design concepts have been created (Bovea & Perez-Belis, 2012). Systematic methods need a lot of technical, environmental and economic data about the product and recycling process. This makes them less efficient and more time consuming. This also makes them to be more applicable at late design stages when more detailed and embodied data about a product is formed. Often at this stage a product is frozen and changes are no longer possible. Therefore, the systematic methods are mostly used for product redesign and improvement. Systematic methods however, are important because by critically analyzing their results (in particular when a method has been applied many times, allowing for a meta analysis), patterns can be detected that can lead to the development of heuristic methods. In this way, heuristic and systematic methods are linked, with heuristic methods dependent on the results of systematic methods. Referring to Table 2.3, the majority of reviewed papers focused on development of systematic methods. Out of 37 DfR methods reviewed, 24 are systematic methods and 13 are heuristic methods.

2.4 Discussion and conclusion

This chapter aimed to answer the following questions:

RQ1. What are the characteristics of existing design for recycling methods that aim to improve the recyclability of electronic products?

In answer to this question, the analysis of the methods underlying data shows that a number of product design features are repeatedly addressed in the literature which are considered to be important to improve products recyclability including selection of materials, selection of connections and product structure. Disassembly and recycling knowledge regarding these design aspects can assist designers to improve the recyclability of products. Obviously to some extent this knowledge is already available in the current literature (see Table 2.4). However, in majority of reviewed papers disassembly and recycling knowledge regarding these aspects are derived based on subjective perceptions, simulations, idealized recycling processes and are largely based on theoretical considerations and mathematical models regarding disassembly and recycling process and lack enough empirical evidence. Therefore, there is a need for more empirical studies that examine the disintegration behaviour of electronics under actual recycling conditions to collect more empirical data.

From the literature review, it also became clear that majority of DfR methods developed are systematic and not suitable for early stages of design process. Consequently, development and application of DfR heuristic methods addressing early design stage must receive more attention. Providing recycling information at early design stage could guide designers to think of and select materials, connections and product structure that enhance products recyclability when changes are still possible.

The discussed DfR methods are mainly applied on vehicles and electronics. For electronics, the case studies are mainly large equipment (washing machines), and screens (LCD TVs, CRT TVs). However, the DfR methods have hardly been applied for other categories of electronics including lamps, small IT and telecommunication equipment, temperature exchange equipment and small equipment. Practical cases can teach us valuable lessons about how DfR issues have been dealt with in practice. However, in particular, there is a need for more situated and detailed case studies and examples. Lessons learned from other (electronic) products may be wider applicable to other cases, but this always has to be checked, as what works well for one design may be inappropriate for another design that seems superficially similar.

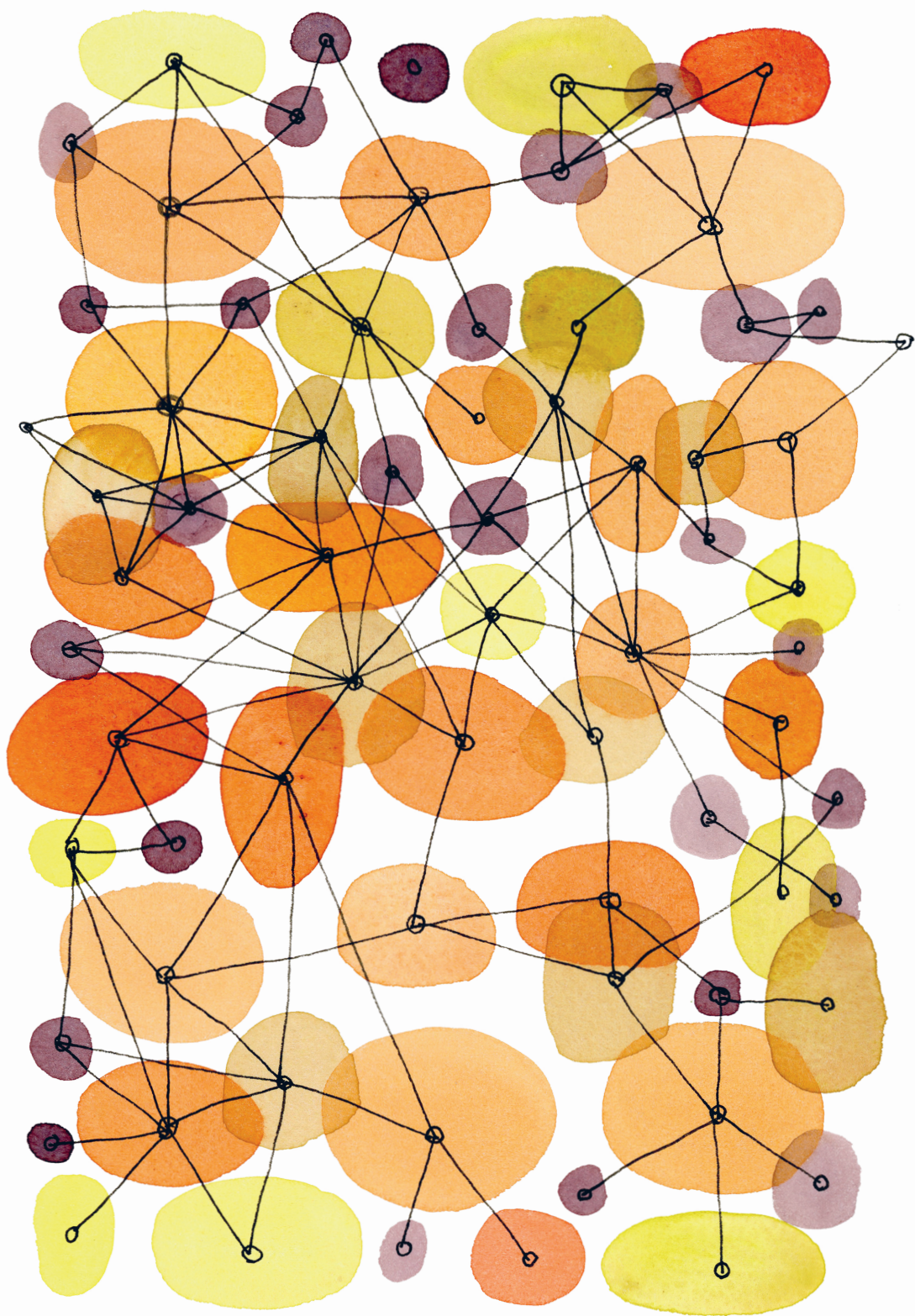
Furthermore, the literature review shows that most of the academic work is theoretical in nature and the actual use and effectiveness of DfR methods has hardly been tested in practice. In most cases, the methods are developed and applied on case studies in theory without further testing the recyclability of case studies in practice, to discover the degree to which the current methods lead to successful and desired results. From the existing theoretical case studies, it is still unclear if DfR methods are applied at all in practice or to what extent product recyclability is improved when designers take into account the existing DfR methods. For future research, there is a need to test the actual use and the effectiveness of DfR methods in practice.

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Painting by Louise van Terheijden

Chapter 3: Identifying product design features that affect disintegration of electronic products during recycling

3.1 Introduction

Recycling of products aims for the recovery of the constituting materials. The ability to separate the materials depends on the disintegration of the product and the subsequent sorting of the materials. Design choices regarding selection of materials, selection of connections and product structure are considered important (Chapter 2). However, most of the work on design for recycling (DfR) is theoretical in nature and considers idealized processes. Insight in the results of actual recycling processes is required to evaluate the findings of the theoretical studies and to assess the extent to which DfR methods are applied in practice. This chapter will therefore investigate how electronic products behave in actual recycling processes and identify product design features that affect disintegration of electronics from a practical point of view.

The e-waste stream is classified by the EU into six different categories as follows (since August 2018, after a transition period from 2012 to 2018 in which 10 categories were distinguished): small equipment, large equipment, screens & monitors, lamps, small IT and telecommunication equipment and temperature exchange equipment (WEEE directive, 2012). Special attention must be given to screens and small IT and telecommunication equipment since these two categories contain the highest amount of precious metals in comparison to other e-waste categories (70-90%) (Golev et al., 2016). Further, special attention must be given to small equipment which have the highest rate in e-waste stream (16mt out of 44.7mt of e-waste generated in 2016) with significant amount of copper, iron and tin (Balde et al., 2017; Golev et al., 2016). Further, temperature exchange equipment must also receive attention as they contain significant amount of aluminum (39.4%) (Golev et al., 2016).

The current research was carried out as part of the GreenElec project (GreenElec, 2012). An objective of GreenElec was to closely link innovations in the design of electronic products to recycling, sorting technologies and materials recovery. The large variety of electronic equipment makes it very hard to establish a representative set of products with respect to their recyclability. To establish attention to both different classes of electronics as well as different markets, the project dealt with 3 different types of products: LED lamps, consumer televisions and professional displays.

LED lamps (designed by Philips Lighting) are considered representative for small scale inexpensive electronics. LED lamps are not yet part of the waste stream as they just started penetrating the lighting market. However, from an electrical perspective LED lamps can be compared to household electronics with regard to the size of the product and the complexity of the electronics. The current collected fraction for small household appliances and lighting products is only about 26%: a relatively large fraction ends up in ordinary waste (Balde et al., 2015). Given the lower value of recovered materials, dismantling is unlikely to be viable. Lamps are therefore most likely mechanically disintegrated to enabling separation of materials.

Consumer televisions (designed by TP Vision) are considered representative for high-end larger household electronics. The current fraction of collected WEEE flat screen monitors and televisions is about 40% (Balde et al., 2015). When recycling a LCD TV today, the fraction of non-ferrous metals that is non-mixed is less than 10%. Dismantling of LCD TVs is not economically viable currently (too costly and time consuming), thus not done on a large scale.

Professional display systems (designed by Barco) exhibit a functionality that is largely comparable to that of the consumer televisions. However, in the safety critical professional product manufacturing space reliability is critical, which results in a built that is more rigorous than that of consumer television. At end-of-life these displays usually end up in the same waste stream as consumer televisions. Amounts are not monitored.

By maintaining a broad scope and generalizing in terms of design aspects, it is anticipated that these three product categories can be considered representative for similar products from other suppliers as well as for electronics in the same e-waste categories. Although the carrier products clearly do not cover the entire field of electronic products, their specific variations in type of electronics and customers addressed serves as an worthwhile starting point for investigating the recyclability of a broad range of electronic products.

Here the focus is on displays and LED lamps which fall under the third and fourth e-waste categories. Therefore, the central question of this chapter is:

RQ2. How do product design features of screens and LED lamps affect the fragmentation results in recycling experiments?

To answer this question, the results obtained from the recycling of electronic products within the framework of the GreenElec project were used. This project focused on improving the recyclability of electronic products and consisted of research studies ranging from product design optimization, recycling processes and technologies optimization to metallurgical recovery calculations and environmental impact assessment. In this chapter, the results of small and large-scale recycling experiments are used to study the design features that affect the recyclability of electronic products with a specific focus on the recycling process of LED lamps and displays, as examples of low-end and high-end electronic products. Low-end electronics LED lamps are typically mechanically disintegrated, using methods like shredding. Displays contain high-end electronics, which makes (partial) manual disintegration more attractive.

The focus will be on the composition of fragments that result from the disintegration process. These fragments should ideally consist of pure materials or materials that are compatible in a

single recovery process. Otherwise, the final yield of the recycling processes will be limited, as materials will end in a recycling process from which they cannot be recovered (see subsection 1.2.4 in Chapter 1).

The recycling process as carried out for case study products within the context of GreenElec project is described in Section 3.2. The mechanical recycling processes are common for current recycling of the large majority of electronic products if they are correctly collected (Zhang & Xu, 2016) (otherwise they might end up in incineration or landfill). Although new technologies are being developed, introduction of such technologies in actual recycling is very slow (S.Sjölen, personal communication, December 11, 2014). We therefore focused on the current recycling techniques as these can be expected to predominate in electronics recycling for the coming decade. Although manual sorting is rather uncommon (at least in Western Europe), is interesting from an environmental perspective due to the potentially higher quality of separation and therefore is considered by some recyclers (S. Sjölin, personal communication, December 11, 2014). Section 3.3 describes the results of manual disintegration of displays. The results are discussed in terms of design features. Section 3.4 describes the results of mechanical disintegration of LCD modules obtained after (partial) manual disintegration of displays. Further this section describes the mechanical disintegration of LED lamps. Results of mechanical disintegration tests as well as subsequent sorting results are discussed and related to the design of the product.

3.2 Research method

Products were obtained from Philips (LED lamps), TP Vision and Barco (displays). The recycler in the project, Stena, also selected displays from their usual waste display operations. The lamps were manually sorted in different fractions dependent on their built, in order to be able to connect recycling results to the design of the products. Displays were separated in cold-cathode fluorescent lamp (CCFL) illuminated displays and light-emitting diode (LED) illuminated screens, as CCFL needs a dedicated recycling path due to their mercury content. After sorting disintegration takes place, this can be either manually and/or mechanically. The resulting fragments are sorted based on their composition. These fragments are subsequently processed to retrieve materials.

Combined manual and mechanical disintegration was carried out for the displays. This is required to separate the mercury containing lamps in the case of CCFL displays. It is also considered economically interesting for products containing relatively valuable electronics. The process sequence is depicted in Figure 3.1.

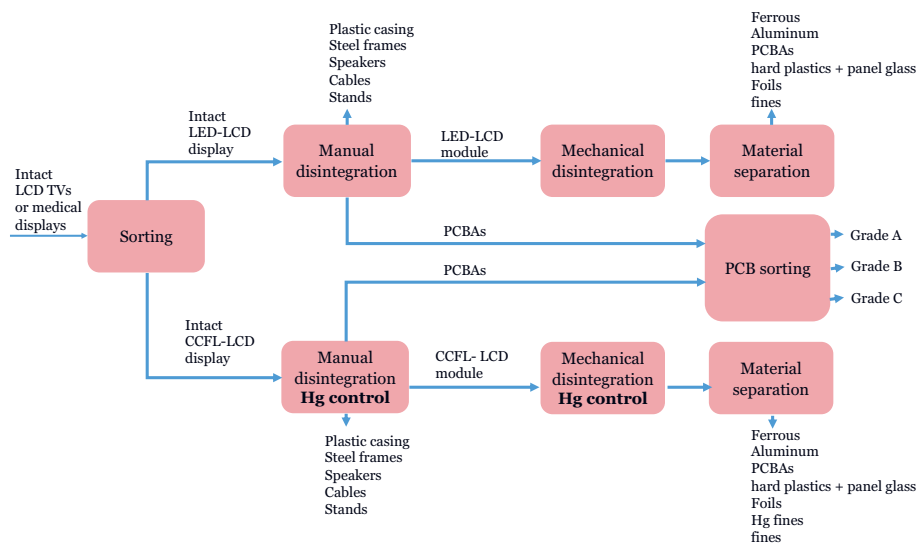


Figure 3.1-Recycling process of displays. Figure provided by Johan Felix, CIT Recycling Development AB.

As shown in Figure 3.1, the first step of the display recycling process was sorting, where the LED LCD displays were separated from CCFL LCD displays. CCFL-LCD display has fluorescent tubes containing mercury as backlight; and LED-LCD display has LED as backlight. The mercury containing CCFL-LCD displays were treated in a dedicated line to avoid contamination of other products with mercury.

The second step was manual disintegration (dismantling). In this step, the stand(s), plastic casing, frames and cables around the LCD modules were removed with a focus on recovering the PCBAs. Here the focus was on the LED-LCD displays, as these are currently in production and therefore more relevant to design.

For this study, five LED LCD displays were dismantled: three LED LCD TV displays provided by TP Vision and two LED professional medical displays provided by Barco. The three LCD models were Philips 42PFL7705, 32PFL7605 and 47PFL6907. The two professional displays subjected to manual dismantling were CCFD-2320 and MDNG-5121. Although the number of displays manually dismantled is too small to allow for statistical significance, the data obtained as well as the observations made while monitoring the dismantling process, are considered insightful from a design perspective. As the emphasis is on the observation of the effect of design features on dismantling and the displays are directly compared and also contain a large variety of commonly encountered design features, this is considered a useful way to compare the effect of various design features.

The dismantling sessions were conducted at Stena in December 2013 by an experienced operator. Ideally, this type of measurement is done with several operators with varying level of experience. Unfortunately, due to time constraints this was not possible. However, as the focus is on the observations during the disassembly process and on comparing displays with different design features, working with a single experienced operator is considered sufficiently insightful: differences in dismantling time could be directly linked to design variations. The

dismantling was conducted mainly using a power tool with different screw bits to remove the screws fixing the stands, the covers and shields. Click connectors, flex-foils and taped wires were removed by hand. Cables were removed by diagonal pliers. Further, LED strips along the cover edges were removed using a knife. Small PCBs with low weight and value which were also hard to disassemble remained on the LCD module. The PCBAs obtained from dismantling were then manually sorted into different PCBA grades (low-end electronics, respectively high-end electronics that contain noble metals). During the dismantling sessions, the dismantling steps were recorded by taking videos and photos. By observing the disassembly process and determining the time needed for removal of specific parts the required effort was established.

In addition to actual dismantling time of displays, we also looked into the dismantling time as calculated by the ease of disassembly of products (eDIM) method (Peeters et al., 2018). eDIM aims to assess the ease of disassembly of electronic products. eDIM is composed of a database with all the disassembly operations and their average dismantling time. Once the disassembly sequence of a display is known, the eDIM database can be checked to find the list of operations and their associated time including disassembly time for different types of connections, tool changes, etc. With this information the average disassembly time of a display can be estimated. The application of eDIM method to five display case studies presented in this chapter has been used for comparison with the data that are derived from actual disassembly tests.

The third step studied was mechanical disintegration (shredding). The shredding was carried out in 2013 by Stena at a dedicated LCD recycling site with safe mercury control. This step was carried out with a batch of 30 CCFL-LCD displays (517 kg) from various brands that represent the current major current waste stream of displays. Seven material fractions were obtained from shredding and material separation of CCFL-LCD modules using conventional methods: ferrous, aluminium, PCBAs, hard plastics + panel glass, foils, Hg fines (because of CCFL backlight) and fines. The next step was material separation where the fragments obtained from mechanical disintegration were further sorted into different fractions.

Section 3.3 presents the result of LED-LCD displays manual disintegration. Subsection 3.4.1 presents the results obtained from shredding of CCFL-LCD modules. The results are discussed in terms of design features that hamper or facilitate the manual/mechanical disintegration process.

Whereas the displays which are subjected to a combined manual-mechanical disintegration, LED lamps (low-end electronics) were taken apart with mechanical disintegration techniques as manual disassembly is economically not considered viable for this type of products. Figure 3.2 shows the LED lamps recycling process sequence. The LED lamps can be distinguished in spot lights and bulbs, which basically differ in geometry and built. In the first step, the spot LED lamps were separated from bulb LED lamps. Further, each type of lamp (spots or bulbs) was subjected to mechanical disintegration. The fragments obtained from mechanical disintegration were subsequently further sorted into various fractions.

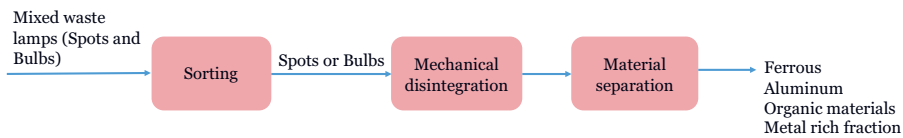


Figure 3.2-Recycling process of LED lamps. Figure provided by Johan Felix, CIT Recycling Development AB.

To determine the behaviour of LED lamps in mechanical disintegration, two types of experiments were conducted: small-scale tests with 5 to 20 selected LED lamps, and large-scale test with respectively bulbs and spot lights of mixed types. Details of the LED lamps are given in section 3.4.

These experiments were conducted between October and December 2013 by Stena and CIT on LED lamps supplied by Philips Lighting as part of the GreenElec project. The mechanical disintegration equipment used for the small-scale disintegration test were a crush auger, a high-speed disperser and a roller mill. Figure 3.3a shows the crush auger equipment and its major parts. The crush auger technique uses a spiral auger (see Figure 3.3b) within a cylindrical housing in the form of a tube where the disintegration of products happens. As the e-waste enters the cylindrical housing through the hopper the rotating auger disintegrates the products and further moves the disintegrated parts along the wall of the tube towards the collection pan.

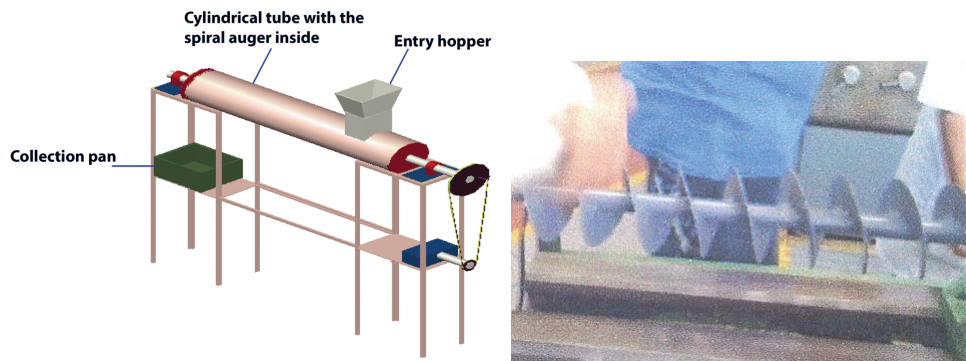


Figure 3.3- a: crush auger, b: spiral auger (Ekwuea & Seepersad-Singhb, 2011)

Figure 3.4 shows the high-speed disperser equipment. The main parts of the equipment are rotor and stator. The rotor is placed inside the stator (a cylindrical housing) and spins at a high speed. The rotor and stator both have blades. When the products enter the high-speed disperser, because of the high rotational speed of the rotor, the products collide with rotor and stator blades and break into small fragments.

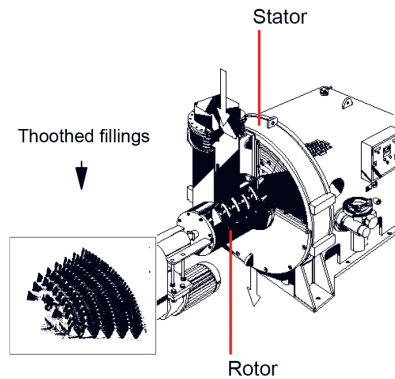


Figure 3.4-high-speed disperser (Kumar et al., 2007)

Figure 3.5a shows the roller mill equipment. The roller mill technique crushes the products by passing them between rotating rollers (Figure 3.5b). The distance between the rollers, rolls surface (blades) and the speed of the rollers affect the disintegration results. For all three techniques, standard settings were used to disintegrate the LED lamps, except for the roller mill in which the gap distance between the roles and rotational speed was varied to optimize the disintegration of LED lamps.



Figure 3.5- a: roller mill equipment, b: rotating rollers. Images provided by Johan Felix, CIT Recycling Development AB.

The mechanical disintegration equipment used for the large-scale disintegration test was a granulator. A granulator employs a number of knives with sharp blades that spin at a high speed (see Figure 3.6). The LED lamps disintegrate by colliding with the spinning knives and stationary bed knives. Close to the cutting action there is a grid with a mesh of either a 40 mm or 20 mm that determines the size of the output fragments. The resulting fragments were subsequently sorted into four fractions: 1. ferrous material, 2. aluminium, 3. low-density polymer-rich fraction, and 4. high-density polymer-rich fraction, using respectively magnet, eddy current and wind sieve separation techniques.

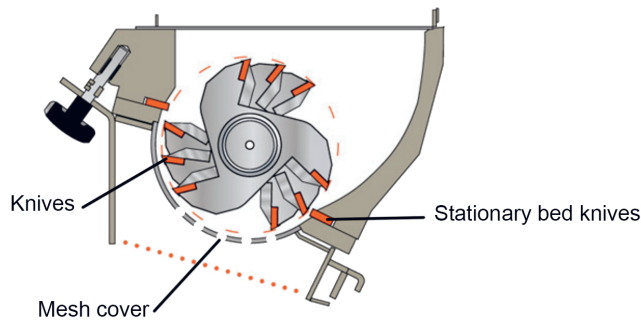


Figure 3.6-Granulator (Conair, 2017)

Subsection 3.4.2 reports the results obtained from the small-scale disintegration tests of LED lamps. Subsection 3.4.3 reports the results obtained from the large-scale disintegration tests of LED lamps. The results are discussed in terms of design features that hamper or facilitate the mechanical disintegration process.

3.3 Manual disintegration of LED-LCD displays

High-end electronics contain valuable materials like copper and noble metals in larger amounts than low-end electronics (Chancerel et al., 2009; Cui & Zhang, 2008; Hagelucken, 2006). This might make partial manual disintegration attractive, as this is an effective way to avoid that these materials end up in waste fractions from which they cannot be recovered. In the case of manual disintegration, prime interest is in the extent to which product features facilitate or hamper the removal of parts. A successful product feature must be able to reduce the dismantling time (Movilla et al., 2016; Ardenete et al., 2014). The time required to manually remove the PCBAs or other key components is a direct indicator for the ease of manual disassembly.

Figure 3.7 shows the time needed for the separation of the back casing and subsequent PCBAs from the three Philips LCD TVs. The horizontal axis shows the number of parts (cover and PCBAs) removed. In Figure 3.7, “back cover” refers to the plastic casing of LCD TVs which must be removed first in order to be able to access the PCBAs. The vertical axis shows the cumulative dismantling time of parts in seconds. In total, dismantling the back casing and subsequent PCBAs took 196 seconds for 42PFL7705, 252 seconds for 32PFL7605 and 168 seconds for 47PFL6907. Differences in dismantling time between case studies can be explained based on the differences in their design features. Therefore, in the following, the disassembly steps for each case study, the time associated with disassembly steps and their relation to product design features are described.

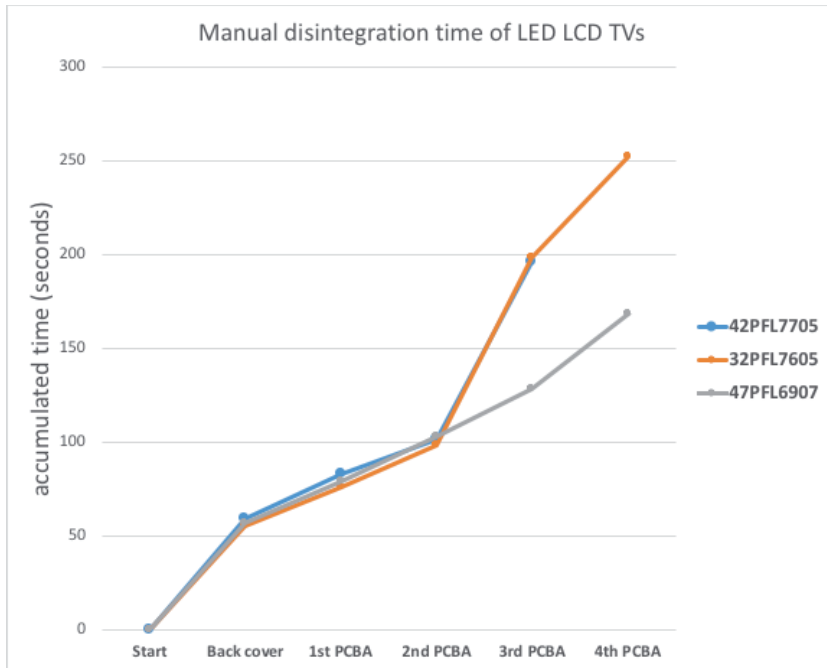


Figure 3.7- Time for dismantling PCBAs from LED LCD TVs

In the case of 42PFL7705 removal of the casing took 59 s in total. Part of this time (29 s) was needed to remove 12 screws, which were all of the same type. After removing the screws, it took another 30 s to remove the casing by hand, as it was not intuitively obvious for the operator how the casing should be opened even after loosening the screws. The first two PCBAs (1st PCBA and 2nd PCBA) were subsequently removed in 24 and 18 s. respectively. The 1st PCBA was fixed with only 5 screws and the 2nd PCBA with 6 screws of the same type, which makes them relatively easy to disassemble. The first two PCBAs were also attached to the rest of the TV by click connectors, which could be easily removed by hand. The 3rd PCBA took 95 secs to remove. This was due to a several reasons. First, the screw bits had to be changed as the screws used to fix the 3rd PCBA were not the same as other screws used. The operator had to change the screw bits twice in order to find the right one. Second, a metal shield and covers that were fixed with 8 screw connections in total had to be removed first, before getting access to the 3rd PCBA. Even after removal of shield and covers, the 3rd PCBA was not easily accessible and required a knife to be removed. However, separation of 3rd PCBA was facilitated by the use of click connectors instead of soldering. Table 3.1 summarizes the disassembly steps of 42PFL7705 LED LCD TV, disassembly time per step and the number and type of connections removed per step. Table 3.2 provides step by step images of the disassembly of 42PFL7705 LED LCD TV. Referring to eDIM method tool positioning and removing a screw is assumed to take 5.76s, tool positioning and removing click connections are assumed to take 2.16s and changing tools is assumed to take 1.44s. Table 3.1 also shows the total dismantling time of 42PFL7705 based on eDIM method. The disassembly time difference between our experiment and eDIM was small in this case.

Table 3.1-Disassembly profile of 42PFL7705 LED LCD TV

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove casing screws	29	12 screws	69.12	Power tool
	2. Remove back cover	30			Hand
1 st PCBA	3. Change tool	3		1.44	
	4. Remove 1 st PCBA	9	5 screws	28.8	Power tool
2 nd PCBA	5. Remove click connectors	12	6 click connectors	12.96	Hand
	6. Remove 2 nd PCBA	14	6 screws	34.56	Power tool
3 rd PCBA	7. Remove click connectors	4	3 click connectors	6.48	Hand
	8. Change power tool's screw bits	33			
	9. Remove metal shield	8	4 screws	5.76	Power tool
	10. Remove front cover	33	4 screws	5.76	Power tool
	11. Change tool	3		1.44	
	12. Remove front cover	8			Knife
	13. Remove 3 rd PCBA	10			Knife
		196s		202.32	

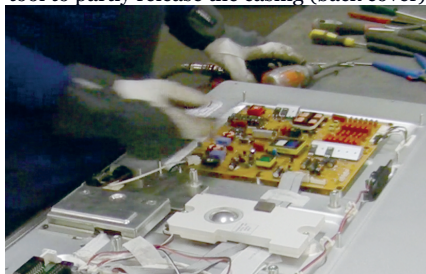
Table 3.2- Disassembly steps of 42PFL7705 LED LCD TV. Images provided by Johan Felix, CIT Recycling Development AB.



1. twelve screws are removed with power tool to partly release the casing (back cover)



2. after that, the back cover was completely removed by hand



3. after removing the back cover by hand, operator picked up the power tool in order to unscrew the PCBAs

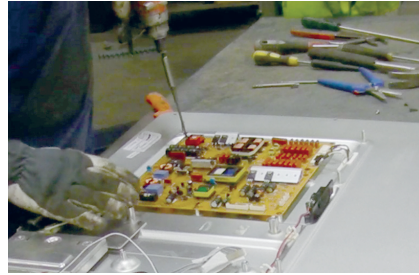


4. five screws are removed with power tool to partly release the 1st PCBA

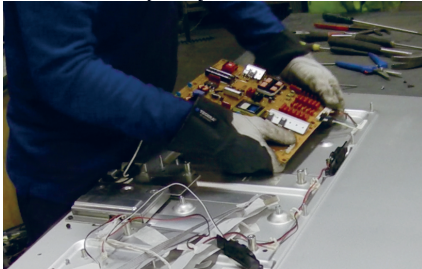
Table 3.2- Disassembly steps of 42PFL7705 LED LCD TV (continued)



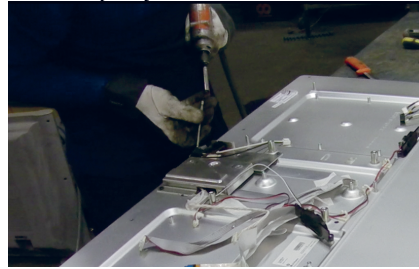
5. next, six click connectors are removed by hand to completely release the 1st PCBA



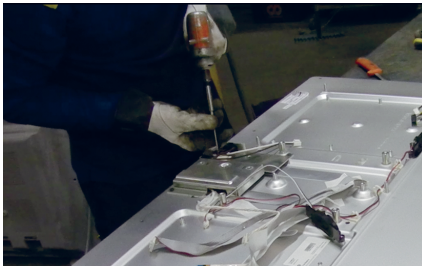
6. six screws are removed with power tool to partly release the 2nd PCBA



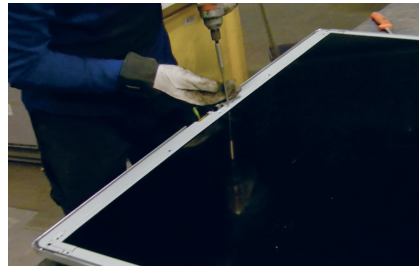
7. after that, three click connectors are removed by hand to completely release the 2nd PCBA



8. then power tool's screw bit needs to be changed since the screws of the metal shield were not the same as the screws of the 1st and 2nd PCBA



9. a metal shield was fixed with four screws had to be removed first, before getting access to the 3rd PCBA



10. further, cover that was fixed with four screws had to be removed first, before getting access to the 3rd PCBA

Table 3.2- Disassembly steps of 42PFL7705 LED LCD TV (continued)



11. then a tool need to be changed since complete removal of the front cover was not possible even after removal of screws



12. The front cover was removed with a knife



13. the 3rd PCBA was not easily accessible and required a knife to be removed

Dismantling of the 32PFL7605 followed a similar pattern, and it took almost the same amount of dismantling time to remove the back cover, 1st, 2nd and 3rd PCBAs, although the number of PCBAs, connections and accessibility showed some variation. Removal of the casing took 55 s in total. A large amount of this time was needed to remove 18 screws, which were all of the same type. In case of 42PFL7705 model, the total number of screws used to fix the back cover was only 12, but there significant time was needed for removing the case after screw detachment. This is the reason why in both cases dismantling the back cover took almost the same amount of time. After removal of the casing of 32PFL7605 the first two PCBAs were subsequently removed in 21 and 22 s. The 1st PCBA was fixed with 4 screws and the 2nd PCBA with 6 screws. Similar to previous model, because of good accessibility and a limited number of screws the first two PCBAs were relatively easy to remove. However, similar to previous model, the 3rd PCBA was more difficult to remove and took longer (100 sec). This was mainly because at this step the position and visibility of the PCBAs was not intuitively clear to the operator. It took a while for the operator to understand where the 3rd and 4th PCBAs are located and how to proceed. Other design features that affected the dismantling time of the 3rd PCBA were the metal shield which was fixed with 4 screws, and 4 screws used to fix the 3rd PCBA to the back of LCD module. Finally, it took 54 seconds to remove the 4th PCBA with knife, as it was mounted along the edges of the LCD module and not easily accessible. Table 3.3 summarizes the disassembly steps of 32PFL7605 LED LCD TV, disassembly time per step and number and type of connections removed per step. The disassembly time difference between our experiment and eDIM was also small in this case.

Table 3.3- Disassembly profile of 32PFL7605 LED LCD TV

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove cable	2			Diagonal pliers
	2. Change tool	3		1.44	
	3. Remove casing screws	50	18 screws	103.68	Power tool
1 st PCBA	4. Remove 1 st PCBA	11	4 screws	23.04	Power tool
	5. Remove click connectors	10	5 click connectors	10.8	Hand
2 nd PCBA	6. Remove 2 nd PCBA	14	6 screws	34.56	Power tool
	7. Remove click connectors	8	6 click connectors	12.96	Hand
3 rd PCBA	8. Remove metal shield	21	4 screws	23.04	Power tool
	9. Remove 3 rd PCBA	79	4 screws	23.04	Power tool
4 th PCBA	10. Change tool	7		1.44	
	11. Remove 4 th PCBA	47			Knife
		252		234	

In the case of 47PFL6907 removal of the casing took 57 s in total. A large part of this time (46 sec) was needed to remove 16 screws, which were all of the same type. The first two PCBAs (1st PCBA and 2nd PCBA) were subsequently removed in 22 and 24 s. Both PCBAs were fixed with only 5 screws each, which were all the same type. A low number of screws made the PCBAs easily detachable. The 3rd PCBA was removed in 25 s. This time was needed to change the power tool screw bits (7 s), remove metal shields which were fixed with 4 screws of the same type (10 s), change tool (3 s) and 5 s to remove the 3rd PCBA with a knife. The 4th PCBAs was removed in 40 s. 20 s of this time was need to remove the metal shield which was fixed with 5 screws, 12 s to remove the 4th PCBA which was hold in place with 6 screws and 8 seconds to remove the 3 click connectors and flexi foils by hand. The dismantling time of the back cover and the first two PCBAs were very similar to the previous models. However, it took less time to dismantle the 3rd and 4th PCBAs compare to the other two cases. This is mainly because in this model the position and visibility of the 3rd and 4th PCBAs was intuitively clear to the operator, and the 3rd and 4th PCBAs were both mounted on the back side of the LCD module, which made them easily accessible. Table 3.4 summarizes the disassembly steps of 47PFL6907 LED LCD TV, disassembly time per step and number and type of connections removed per step.

In general, the disassembly time difference between our experiments and eDIM was small in most of the cases. However, in case of 47PFL6907 LED LCD TV the differences were notable. The differences might be attributed to several factors:

- Different tools carry out the same job with different efficiency. For instance, using a power tool (used in actual experiment) to unscrew the screws is likely to be faster than a manual screw driver (as assumed in eDIM). Multiplying this time difference to several screws could cause a significant difference in total;
- The disassembly time mentioned in eDIM databases are based on average disassembly time of forty different notebooks which might be different comparing to disassembly time of specific TVs and medical displays.

- c. In our experiment, we focused on destructive dismantling of displays, while the eDIM method focuses on reversible disassembly of displays. Of course, destructively or reversibly dismantling can also affect the dismantling time.

Table 3.4-Disassembly profile of 47PFL6907 LED LCD TV

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove casing screws	46	16 screws	92.16	Power tool
	2. Change tool	2		1.44	
	3. Remove cable	2	1 zip ties		Diagonal pliers
	4. Change tool	2		1.44	
	5. Remove back cover	5			Knife
1 st PCBA	6. Change tool	3		1.44	
	7. Remove 1 st PCBA	12	5 screws	28.8	Power tool
	8. Remove click connectors	7	4 click connectors	8.64	Hand
2 nd PCBA	9. Remove 2 nd PCBA	15	5 screws	28.8	Power tool
	10. Remove click connectors	9	3 click connectors	6.48	Hand
3 rd PCBA	11. Change power tool's screw bits	7			
	12. Remove metal shield	10	4 screws	23.04	Power tool
	13. Change tool	3		1.44	
	14. Remove 3 rd PCBA	5			Knife
4 th PCBA	15. Remove metal shield	20	5 screws	28.8	Power tool
	16. Remove 4 th PCBA	12	6 screws	34.56	Power tool
	17. Remove click connectors	8	3 click connectors and flexi foils	6.48	Hand
		168		264.96	

Similar to the LCD TVs, two medical displays were subjected to manual disintegration. Figure 3.8 shows the dismantling time for the major PCBAs of the two Barco medical displays: CCFD-2320 and MDNG-5121. The horizontal axis shows the number of parts (cover and PCBAs) removed and the vertical axis shows the cumulative dismantling time of the PCBAs. In total, dismantling the back casing and subsequent PCBAs took 361 seconds for MDNG-5121, and 487 seconds for CCFD-2320. It is evident that dismantling the PCBAs from the professional displays took significantly longer compared to the LCD TVs. This is mainly because of differences in product design features and time needed per step. Therefore, in the following, the disassembly steps for both medical displays, the time associated with the disassembly steps and their relation to product design features are described.

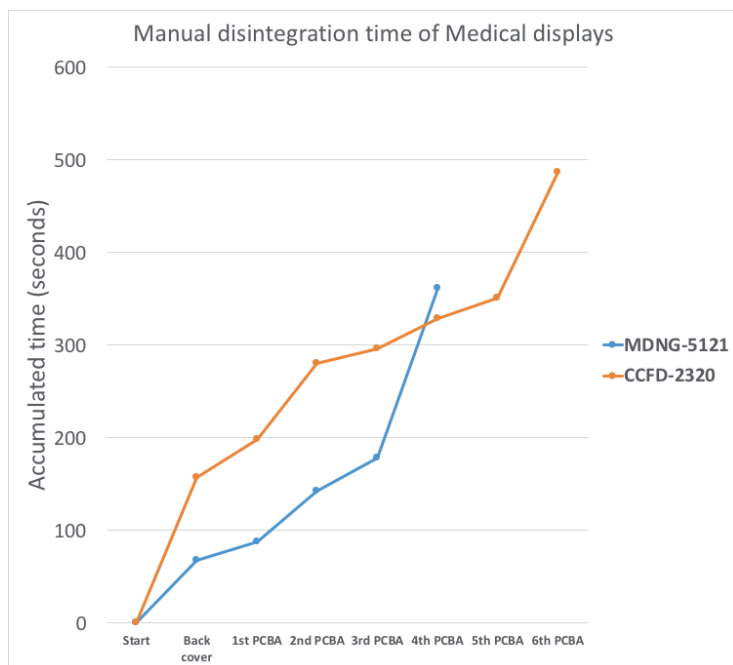


Figure 3.8- Time for dismantling PCBAs from professional displays

In the case of MDNG-5121 removal of the casing took 68 s in total. 15 s of this time was needed to remove 4 screws of the back cover, which were all of the same type. 20 s was needed to change the screw bits since the screws of PCB bracket were not the same as the screws of the back cover. Finally, 33 s was needed to remove 12 screws of the PCB bracket. After removing the PCB bracket, it took 20 s to remove the 1st PCBA. This time was needed to remove 8 screws of the same type, and also removing the click connectors. However, the dismantling of the 2nd PCBA took longer (54 s in total). 34 s of this time was needed to remove of the LCD bracket, which was on top of the 2nd PCBA and fixed with 6 screws of the same type. The other 20 s was needed to remove click connectors and 6 screws of the same type that fixed the 2nd PCBA on the back side of the LCD module. The brackets are used for electromagnetic compatibility (EMC) to prevent radiation. However, they clearly limited the speed of disassembly and thus the ease of accessibility of PCBAs. It took 36 s to remove the 3rd PCBA. The major part of this time was needed to remove 10 screws of the same type, 4 of which were used to fix the metal shield, and 6 to fix the 3rd PCBA on the backside of the LCD module. Finally, it took 183 s to remove the last PCBA. This is because the 4th PCBA was placed along the edges of the LCD module and therefore not easily accessible. The operator needed to unfold the aluminium plates around the LCD module, remove 18 screws and change tools 14 times in order to be able to get access to the 4th PCBA. Table 3.5 summarizes the disassembly steps of MDNG-5121 medical display, disassembly time per step and number and type of connections removed per step. Table 3.6 provides step-by-step images of disassembly of MDNG-5121 medical display. The disassembly time difference between our experiment and eDIM was again small in this case.

Table 3.5-Disassembly profile of MDNG-5121 Medical display

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove screws	15	4 screws	23.04	Power tool
	2. Change power tool's screw bits	20		1.44	
	3. Remove the PCB bracket	33	12 screws	69.12	Power tool
1 st PCBA	4. Remove 1 st PCBA	17	8 screws	46.08	Power tool
	5. Remove click connectors	3			Hand
2 nd PCBA	6. Remove LCD bracket	34	6 screws Cut wires	34.56	Power tool Diagonal pliers
	7. Remove 2 nd PCBA	14	6 screws	34.56	Power tool
	8. Remove click connectors	6			Hand
3 rd PCBA	9. Remove the metal shield	15	4 screws	23.04	
	10. Remove the 3 rd PCBA	18	6 screws	34.56	
	11. Remove click connectors	3			
4 th PCBA	12. Change tool	10		1.44	
	13. Unfold the aluminium plates around the LCD module	11			Knife
	14. Change tool	1		1.44	
	15. Remove screws	14	4 screws	23.04	Power tool
	16. Change tool	1		1.44	
	17. Remove 4 th PCBA (one side)	25			Knife
	18. Change tool	1		1.44	
	19. Remove screw	2	1 screw	5.76	Power tool
	20. Remove 4 th PCBA with hand	6			Hand
	21. Change tool	11		1.44	
	22. Unfold the aluminium plates around the LCD module	6			Knife
	23. Change tool	2		1.44	
	24. Remove screws	8	3 screws	17.28	Power tool
	25. Change tool	1		1.44	
	26. Unfold the aluminium plates around the LCD module	4			Knife
	27. Change tool	1		1.44	
	28. Remove screws	9	3 screws	17.28	Power tool
	29. Change tool	5		1.44	
	30. Remove 4 th PCBA	5			Knife
	31. Change tool	10		1.44	
	32. Remove screws	14	4 screws	23.04	Power tool
	33. Change tool	2		1.44	
	34. Unfold the aluminium plates around the LCD module	8			Knife
	35. Change tool	1		1.44	
	36. Remove screws	12	3 screws	17.28	Power tool
	37. Change tool	2		1.44	
	38.				
	39.				
	40. Remove 4 th PCBA	11			Knife
		361		388.8	

Table 3.6-Disassembly steps of MDNG-5121 Medical display. Images provided by Johan Felix, CIT Recycling Development AB.



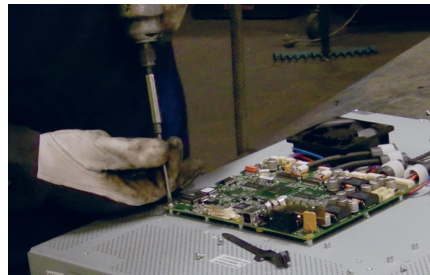
1. four screws are disconnected with power tool in order to remove the back cover



2. then power tool's screw bit needs to be changed since the screws of the back cover are not the same as the screws of the PCB bracket



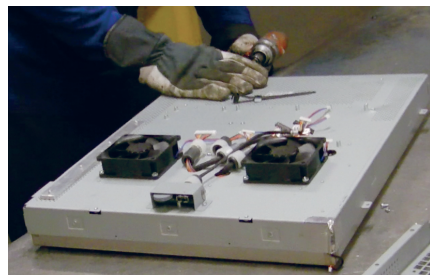
3. twelve screws are removed with power tool to release the PCB bracket



4. eight screws are removed with power tool to partly release the 1st PCBA

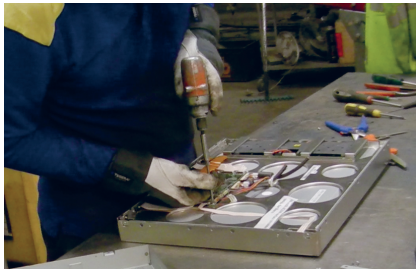


5. click connectors are removed by hand to completely release the 1st PCBA

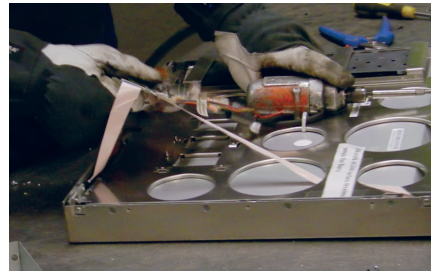


6. six screws are removed with power tool to release the LCD bracket

Table 3.6-Disassembly steps of MDNG-5121 Medical display (continued)



7. six screws are removed with power tool to partly release the 2nd PCBA



8. then, click connectors are removed by hand to completely release the 2nd PCBA



9. four screws are removed with power tool to remove the metal shield that covers the 3rd PCBA



10. six screws are removed with power tool to partly release the 3rd PCBA

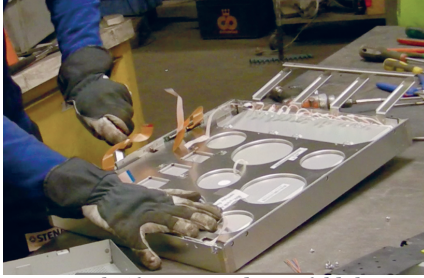


11. then, click connectors are removed by hand to completely release the 3rd PCBA



12. then a tool needs to be changed since the 4th PCBA was along the edges of the LCD module and not easily accessible

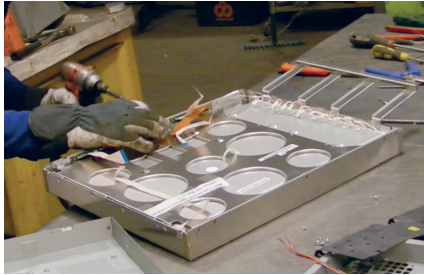
Table 3.6-Disassembly steps of MDNG-5121 Medical display (continued)



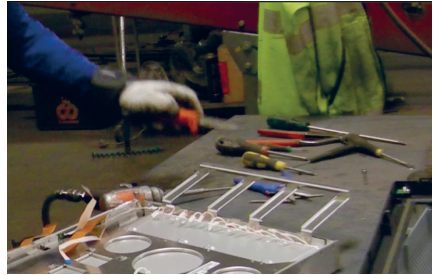
13. a knife were used to unfold the aluminium plates around the LCD module



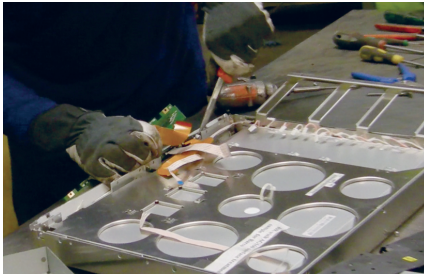
14. then a tool needs to be changed since the 4th PCBA was also screwed to the LCD module



15. in total, eighteen screws are removed with power tool to partly release the 4th PCBA



16. then a tool needs to be changed since complete removal of the 4th PCBA was not possible even after removal of screws



17. the 4th PCBA was completely removed with a knife (one side)

In case of CCFD-2320, dismantling of the back cover took 46 s. This time was mainly needed to remove 11 screws of different types. Use of different type of screws required the operator to change the screw bits 2 times. Each time the change of the screw bits took 3 s. Removal of the PCB bracket took 111 s in total. This was primarily needed to remove 31 screws of different types. To remove the screws, the operator again had to change the screw bits two times. The first time it took 8 s and the second time 9 s. It took 41 s to remove the 1st PCBA. 11 s was required to change the screw bits and 30 s of this time was needed to remove 10 screws and click connectors.

Removing the 2nd PCBA took two times more than the 1st PCBA (82 s in total). 18 s of this time was needed for the operator to understand how to proceed with disassembly operation. 4 s was required to change the screw bits. 34 s was needed to remove the LCD bracket which was fixed with 5 screws of same type. Without removing the LCD bracket, it was not possible to access the 2nd PCBA. Again, to remove the 2nd PCBA there was a need to change the screw bit, which took 10 s. Lastly, it took 16 s to remove 4 screw connections and click connectors, which fixed the 2nd PCBA at the back side of the LCD module.

The 3rd PCBA was removed in 16 s. The 3rd PCBA was fixed with only 4 screws of the same type which made it relatively easy to disassemble. The 4th PCBA took 33 s. 4 s of this time was needed to change the screw bits. 17 s to remove the metal shield which was fixed with 5 screws and 12 s of this time was needed to remove 2 screw connections and click connectors that fixed the 4th PCBA on the back side of the LCD module.

The 5th PCBA was removed in 22 s. The 5th PCBA was fixed with only 2 screws of the same type, which made it relatively easy to disassemble. Finally, it took 136 s to remove the last PCBA. This is because the 6th PCBA was placed along the edges of the LCD module and therefore not easily accessible. The operator needed to unfold the aluminium plates around the LCD module, remove 9 screws and change tools 9 times in order to be able to get access to the 6th PCBA.

Table 3.7 summarizes the disassembly steps of CCFD-2320 medical display, disassembly time per step and number and type of connections removed per step. In this model, the dismantling time of the back casing and first three PCBAs took almost two times more than the previous model. This can be explained mainly because of the time needed to remove different type of screws, change screw bits and remove PCB and LCD brackets. Further, this model had two more PCBAs in compare with previous model, which were easily accessible. Similar to the first model, the last PCBA of this model took a long time, as in both cases the PCBAs were mounted along the edges of the LCD module and were not only accessible after unfolding aluminium plates. The disassembly time difference between our experiment and eDIM was again small in this case.

Table 3.7-Disassembly profile of CCFD-2320 Medical display

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove screws	11	6 screws	34.56	Power tool
	2. Change screw bits	3			
	3. Remove screws	24	4 screws	23.04	Power tool
	4. Change screw bits	3			
	5. Remove screws	5	1 screw	5.76	Power tool
Removal of PCB bracket	6. Change screw bits	8			
	7. Remove screws	78	25 screws	144	Power tool
	8. Change screw bits	9			
	9. Remove screws	16	6 screws	34.56	Power tool
1 st PCBA	10. Change screw bits	11			
	11. Remove screws of 1 st PCBA and click connectors	30	10 screws	57.6	Power tool
2 nd PCBA	12. Understanding how to proceed	18			
	13. Change screw bits	4			
	14. Remove LCD bracket	34	5 screws	28.8	Power tool
	15. Change screw bits	10			
	16. Remove screws of the 2 nd PCBA	6	4 screws	23.04	Power tool
	17. Remove click connectors of the 2 nd PCBA	10			
	18. Remove screws of the 3 rd PCBA	7	4 screws	23.04	Power tool
3 rd PCBA	19. Remove click connectors of 3 rd PCBA	9			
	20. Change screw bits	4			
4 th PCBA	21. Remove metal shield	17	5 screws	28.8	Power tool
	22. Remove screws of 4 th PCBA	8	2 screws	11.52	Power tool
	23. Remove click connectors of 4 th PCBA	4			
	24. Remove screws of 5 th PCBA	22	2 screws	11.52	Power tool
5 th PCBA	25. How to proceed	19			
	26. Change tool	1			
6 th PCBA	27. Unfold the aluminium plates around the LCD module	15			Knife
	28. Change tool	1			
	29. Remove screws	5	2 screws	11.52	Power tool
	30. Change tool	2			
	31. Unfold the aluminium plates around the LCD module	30			Knife
	32. Change tool	1			
	33. Remove screws	6	2 screws	11.52	Power tool
	34. Change tool	1			
	35. Remove 6 th PCBA	9			Knife
	36. Change tool	5			
	37. Remove screws	7	3 screws	17.28	Power tool
	38. Change tool	1			
	39. Unfold the aluminium plates around the LCD module	13			Knife
	40. Change tool	1			
	41. Remove screws	5	2 screws	11.52	Power tool
	42. Change tool	1			
	43. Remove 6 th PCBA	13			Knife
		487		502.56	

During the manual disintegration (dismantling) of the LED LCD TVs and medical displays, it was observed that the higher amount of time it takes to manually disintegrate the back cover and PCBAs can be related to:

- Use of a high number of screws
- Use of different types of screws with different dimensions, requiring to change the screw bits.
- Position and visibility of screws
- Covers to shield PCBAs that are fixed with screws, lowering the accessibility of PCBAs.
- Position, visibility and accessibility of PCBAs. As PCBAs are normally fixed to various frames in a display, and their accessibility requires dismantling of some intermediate parts first such as covers, brackets, shields.

It should be noted that full manual disintegration is not economically attractive because of the high dismantling cost relative to the value that is generated in the recycling process. However, shredding based treatment of the entire display will likely lead to losses of materials (Ardente et al., 2014). The actual process for products containing high value electronics in practice therefore will often be a combination of manual disassembly of PCBAs that can be removed relatively rapidly and mechanical disintegration of the remaining part of the display.

3.4 Mechanical disintegration of LCD screens and LED lamps

The aim of this section is to study the disintegration behaviour of CCFL-LCD module and LED lamps by observing the fragmentation under various mechanical disintegration conditions to analyse how product design features affect mechanical disintegration. Subsection 3.4.1 reports on the results obtained from mechanical disintegration of CCFL-LCD modules. Subsection 3.4.2 reports the results obtained from small-scale disintegration test of LED lamps. Subsection 3.4.3 reports the results obtained from large-scale disintegration test of LED lamps.

3.4.1 Mechanical disintegration of CCFL-LCD modules obtained after partial dismantling – large scale test

The use of LEDs as backlight only started recently and LED-LCDs are still not abundant in the waste stream. Therefore, CCFL-LCD modules, which have fluorescent tubes containing mercury as backlight were considered for mechanical disintegration test. These are available in high volumes and their recycling treatment is well-established.

A large-scale mechanical disintegration experiment was conducted where 30 units of CCFL LCD TVs (517 kg) of different brands were subjected to partial manual disintegration (as shown in Figure 3.1). The first disintegration step was manual disintegration with the aim of removing the casings, frames, metal shields, speakers, cables, stands and as many PCBAs as possible in a short amount of time (about 3-4 PCBAs). PCBAs along the edges of LCD module removed with a knife. However, small PCBAs with low value/weight and hard to manually remove remained on the LCD module, and further sent to the mechanical disintegration. The second step was mechanical disintegration of the entire LCD modules containing CCFL tubes. At this step, about 270 kg of CCFL-LCD modules were shredded. The mechanical disintegration took place at a separate LCD recycling line with safe mercury control.

CCFL-LCD modules are composed of front and back plates which are connected with screws. Further, within the CCFL-LCD module, the LCD screen, plastic frame and foils lay on top of each other with no connection between them and the light guide and reflector are kept in place with a click connection. In addition, the CCFL tubes are kept in place with rubbers and plastic click connections.

Following the shredding process, the resulting fragments were separated in a number of different fractions. Ferrous, foils, Hg fines and fines fractions were rather clean with no fragments that contain PCBA parts. However, PCBA fragments were found in three other fractions namely aluminium, PCBAs and hard plastics + panel glass (see Figure 3.9). The majority of PCBAs fragments ends up in the PCBAs fraction, whereas a lower amount of PCBA fragments is found in the aluminium fraction and in the hard plastics + panel glass fraction. The reason why the PCBA fragments end up in the aluminium and plastic fractions is not due to the PCBAs still being attached to aluminium or plastic parts after mechanical disintegration, rather it is because of the separation quality after the sorting technologies.

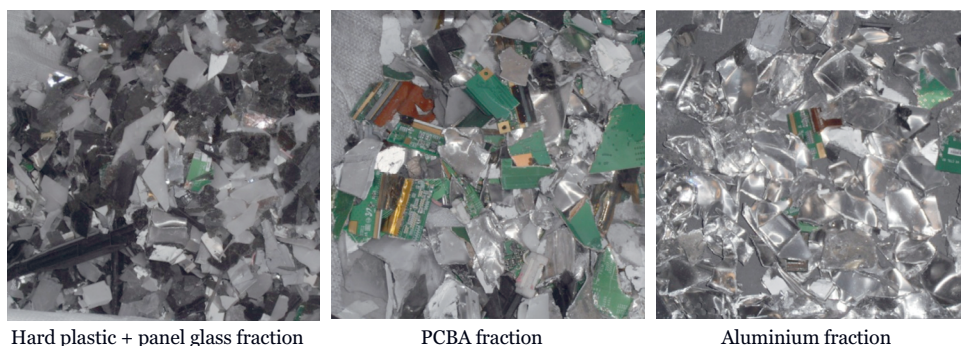


Figure 3.9- Sample of fractions. Images provided by Johan Felix, CIT Recycling Development AB.

It is clear that the mechanical disintegration is able to disintegrate the CCFL-LCD modules into relatively clean and pure fragments, and the existing design features within the LCD modules do not strongly hamper the mechanical disintegration. The front and back plates of the CCFL-LCD modules are bonded with screw connections. This connection is strong enough to hold the CCFL-LCD modules shells (front and back plates) together but breaks down under recycling conditions. Further, the absence of connections and the use of click connections inside a LCD module are considered to play an important role in obtaining relatively pure fragments in mechanical disintegration of CCFL LCD modules, as dissimilar parts are not strongly joined.

3.4.2 Mechanical disintegration of LED lamps - small scale tests

For small scale disintegration test, sets of 5 to 20 LED lamps of a single type were disintegrated in a single test, employing the disintegration techniques mentioned in Section 3.2. The types of LED lamps subjected to these tests exhibited different features in terms of size, thickness and shape. Also, the connections between the parts were different for various types of lamps. Figure 3.10 shows an overview of the LED lamps used.



Figure 3.10- LED lamps geometrical differences. Image provided by Thomas Marinelli, Phillips Lighting.

Basically, two different types of lamps can be distinguished: the larger bulbs and the smaller spot lights. The LED bulbs are pear-shaped and typically larger in size than the spots. The main constructive element of these lamps is a robust and relatively thick aluminium heat spreader that also acts as housing. These lamps are further composed of a polycarbonate (PC) or silicone dome, that is used to collimate the light. The electronics consist of a PCBA containing the LEDs and a PCBA with the driver electronics that also converts the power from power net AC to DC. The LED PCBA is connected to the heat spreader with a thermal pad to assure good heat conductivity from PCBA to heat spreader. The end cap of a bulb usually consists of a glass filled polybutylene terephthalate (PBT) base and an aluminium or steel socket. The largest part of the electronics is located within the heat spreader. The base is filled with rubbery potting compound fixing the driver PCBA in the base. Figure 3.11 shows an exploded view of the typical built of such LED bulb lamps.

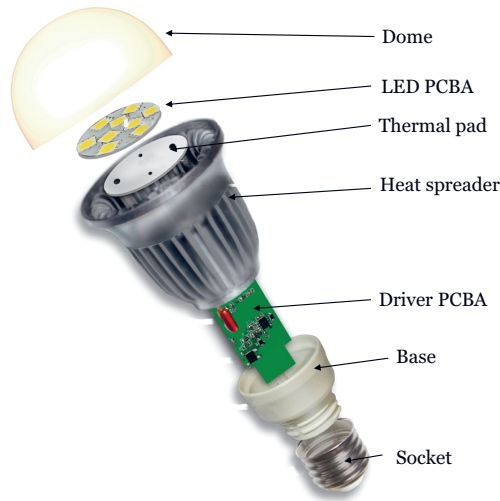


Figure 3.11- Exploded view of a bulb LED lamp (EETimes, 2013)

The LED spot lights are funnel shaped and are typically smaller in size (with the exception of some older types). Again, the main constructive element is the aluminium heat spreader. Both a LED PCBA and a driver PCBA are used. As these lamps are typically operated at lower powers, the heat spreader can be smaller than in the case of the LED bulbs. These lamps further are typically composed of a PBT ring screw, PC lens or collimator, thermal pad, PBT base, and copper connector pins. The electronics are largely located within the base of these lamps. The base is full of rubbery potting compound that mainly serves to improve heat conduction from the electronics to the housing. Figure 3.12 shows an exploded view of the typical built of such LED spot lamps.

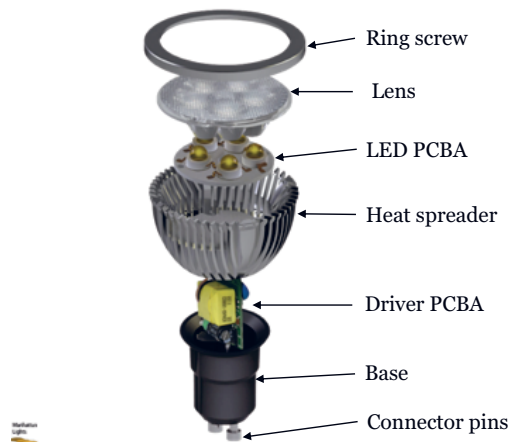


Figure 3.12- Exploded view of a spot LED lamp (Manhattanlights, 2013)

After the disintegration tests using the three different techniques, the resulting fragments were evaluated by visual inspection. Further, the lamps before disintegration and fragments after disintegration were weighed to check if any material was lost during the disintegration process. None of the techniques caused significant material losses.

First, results for disintegration of single lamp types in small scale tests with the different disintegration techniques will be discussed. Figure 3.13 shows some LED lamps after application of the crush auger technique. With this technique, the lamps remained almost intact and fragment separation was not possible without further disintegration of lamps. This is mainly because the LED lamps have a relatively thick housing of aluminium and the applied forces are insufficient to break down the housing.



Figure 3.13-Example of LED lamps after a crush auger. Images provided by Johan Felix, CIT Recycling Development AB.

With the high speed dispergator the lamps with smaller size were disintegrated into finely crushed and powdered materials. This is less favourable as separation becomes increasingly difficult when fragments are too small. In case of larger lamps, the base jammed between the rotating wheel and cylinder wall and had to be removed manually. Furthermore, the base was compressed in such a way that it encapsulated pieces of the driver PCBA and potting inside. The results of the small-scale high speed dispergator test thus were unsatisfactory for both spot and bulb LED lamps.

Using the roller mill technique, the heat spreader/housing of the lamps was crushed and further fragmentation became possible. The roller mill technique led to disintegration of the LED lamps in fragments that were suitable for subsequent sorting steps as shown in Figure 3.14. However, as can be seen, after disintegration of the die-casted aluminium housing some parts still remain connected to form heterogeneous fragments. Figure 3.14a shows PCBA fragments encapsulated in the potting materials. Note that potting is not intended as a connection as such, but by its form-filing nature joins the parts together. Figure 3.14b, shows that the driver PCBA remained connected to the base because of the solder connection, also the LED PCBA remained connected to the housing because of glue and screw connections. Similarly, Figure 3.14c shows that the LED PCBA remained connected to the heat spreader because of screw and glue connections.

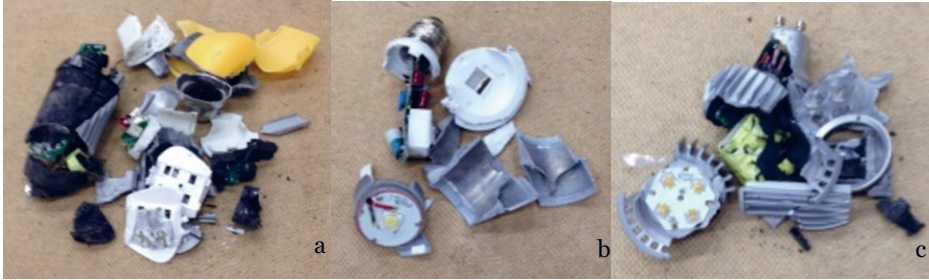


Figure 14-Example of LED lamps after a roller mill. Images provided by Johan Felix, CIT Recycling Development AB.

Figure 3.15 shows an example of a bulb LED lamp after roller milling. In this example, the heat spreader does not act as housing, but is an insert made of thin aluminium alloy surrounded by a PBT housing. The analysis of the disintegration shows that the plastic housing breaks down, while the compliant deep-drawn thin aluminium heat spreader does not break down but deforms. This shows that in addition to connections, the use of ductile materials in geometrical shapes that are likely to plastically deform during mechanical disintegration, may result in the enclosure or clamping of other materials or parts.

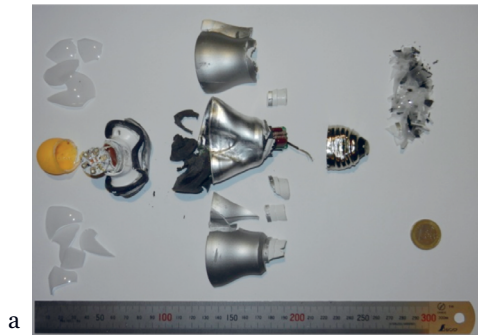
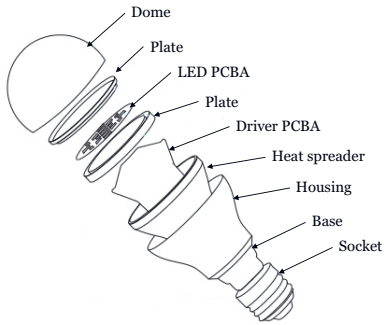


Figure 3.15- a: exploded view of a LED lamp consisting of heat spreader and housing. Image provided by Philips Lighting, b: an example of a LED bulb consisting of heat spreader and housing after roller mill. Image provided by Johan Felix, CIT Recycling Development AB.

Analysis of the fragments shows that because of the way in which parts are connected, fragments might consist of multiple materials. Rubber potting, solder, screws and glue connections are difficult to break down at the level of the connection. Also, ductile material might capture other parts upon deformation.

Roller milling was also applied on a batch of 20 spot lights. Similar to the results obtained from disintegration of a single LED lamp at a time, the simultaneous disintegration of 20 small sized LED lamps also showed that use of rubber potting, glue and screw connections hamper the mechanical disintegration of LED lamps into homogenous fragments. The parts made of polymers (ring screw, lens, base) break down and can be separated and recovered. The robust aluminium housing only partially breaks down and the PCBAs are to a large extent not detached but remain connected to the housing because of screw and glue connections. Further, PCBAs often cling to rubber potting or other parts because of rubber potting (see Figure 3.16).

Fragments composed of heterogeneous and incompatible materials can hamper recovery of materials. For example, materials in PCBAs (electronics) can best be recovered in copper smelters, and aluminium housing can best recovered in aluminium smelter (Reuter & van Schaik, 2015). However, the use of screw and glue connections prevented the PCBA to become detached from the housing. This is likely to cause the PCBAs to end up in the aluminium fraction or the aluminium housing to end up in copper fraction, dependent on the relative ratios of the materials. In both cases this negatively affects the recovery of materials because of mutual incompatibility of aluminium and copper in subsequent recovery processes. Aluminium and copper are incompatible because they cannot be both recovered from the same smelting process. Metals that are not compatible with a particular smelting process are dissolved in the major metal or are lost in the slag material. Non-compatible materials can also adversely affect the recovery rate of other materials.



Figure 3.16- Spot lights fragments. Image provided by Johan Felix, CIT Recycling Development AB.



The results of these small-scale tests show that in a roller mill in which disintegration is optimized, the fragments are still heterogeneous and contain incompatible materials. Analysis of the fragments led to the identification of a number of product design features which hamper the disintegration of LED lamps:

- Use of connection techniques which result in relatively strong joints that prevent separation of incompatible materials/parts from each other, like screws, solder, and glue.
- Use of filler materials, like potting, that mechanically interlock different materials and parts.
- Use of ductile materials in geometrical shapes that are likely to plastically deform during disintegration, resulting in the enclosure or clamping of other materials/parts (for instance: deep drawn, thin walled aluminium housing).

3.4.3 Mechanical disintegration of LED lamps - large scale test

A large-scale disintegration test was conducted by Stena and CIT on LED lamps supplied by Philips Lighting as part of the GreenElec project between October and December 2013. In the large-scale disintegration tests, about 35000 LED lamps of various type (a sea container load) were disintegrated using a large-scale granulator, the fragments were subsequently sorted by magnets and sieve. The mixed batch of LED lamps was first manually sorted into a batch of bulbs with a weight of 2284 kg and a batch of spot lights weighing 1315 kg. The type, image and number of spot lights and bulbs subjected to the large-scale disintegration tests are listed in Table 3.8.

Table 3.8- Description of batches going into large-scale disintegration test. Image of the lamps provided by Phillips Lighting.

Type	Image	Amount (pieces)	Remark
Bulb		11590	<ul style="list-style-type: none"> • Pear-shaped • Lamp dimension: 110 x 60 mm • The heat spreader does not act as housing, but is an insert made of thin aluminium alloy surrounded by a PBT housing • Composed of a polycarbonate (PC) dome, plastic plate, LED PCBA, aluminium plate, driver PCBA, aluminium heat spreader, plastic housing, plastic base and aluminium or steel socket (see the exploded view in Figure 3.15) • The largest part of the electronics is located within the heat spreader.
Spots		23200	<ul style="list-style-type: none"> • Funnel shaped • Lamps dimensions: <ul style="list-style-type: none"> - Top: 50 x 46 mm - Middle: 51 x 51 mm - Bottom: 80 x 50 mm • Robust and thick aluminium heat spreader • Smaller heat spreader than bulb lamps • Composed of a PBT ring screw, PC lens or collimator, LED PCBA, thermal pad, aluminium heat spreader, driver PCBA, PBT base, and copper connector pins. The electronics are largely located within the heat spreader and base of these lamps

The batches were treated separately. For each batch, the mechanical disintegration of the LED lamps was conducted in two subsequent runs, as depicted in Figure 3.17. In Run-1 the LED lamps entered a granulator with a 40 mm mesh grid.

The resulting fragments were subsequently sorted into four fractions: 1. ferrous material, 2. aluminium, 3. low-density polymer-rich fraction, and 4. high-density polymer-rich fraction, using respectively magnet, eddy current and wind sieve separation techniques. The disintegration of the lamps in Run-1 resulted in successful separation of ferrous and aluminium fragments, but the separation of the remaining polymer-rich fragments into a low-density and a high-density fraction was not sufficient as the composition of both fractions was highly heterogeneous, both fractions containing significant amount of PCBA fragments.

Therefore, a second disintegration run on these fractions was carried out to improve the materials separation of the low-density and high-density fractions. The low-density and high-density polymer-rich fractions were mixed and further disintegrated in the granulator with a 20-mm mesh grid, followed by a wet table separator. This was done for the bulb batch as well as for the spot light batch. In both cases, this led to a fraction rich in copper wire, PCBA fragments and electronic components (metal rich fraction) as well as a fraction rich in organic materials (mainly mixed plastics and potting). Below, the composition of the fragments will be discussed in more detail and a relation to the design of the lamps will be made.

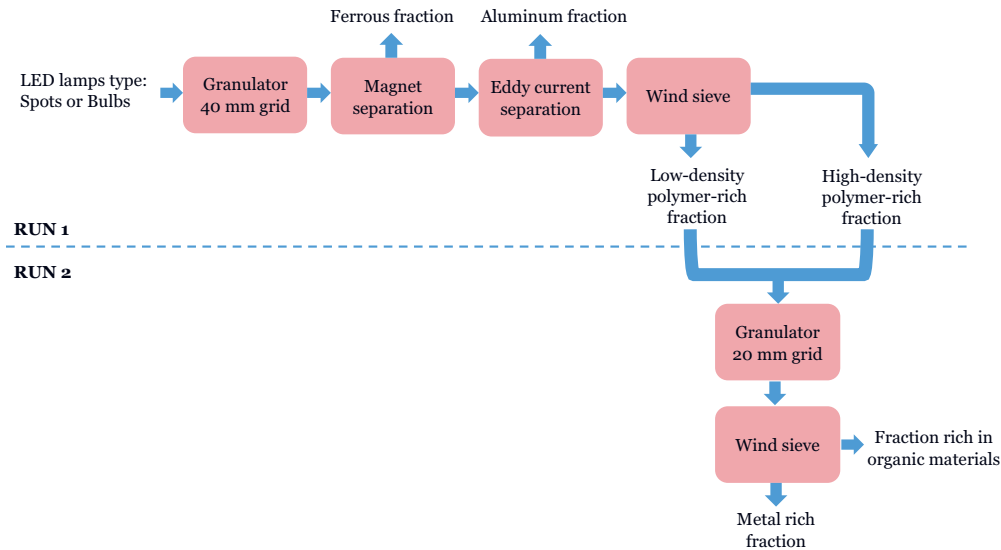


Figure 3.17- Disintegration and sorting processes of large batches of LED lamps and resulting fractions. Figure provided by Johan Felix, CIT Recycling Development AB.

Figures 3.18 and 3.19 show the spot and bulb LED lamps after application of the granulator technique with 40mm grid. As is evident from the figures some fragments consist of a single material (pure PCBA fragments, pure aluminium fragments, pure plastic fragments). Other fragments still consist of two or more materials, implying that impurities will be added to the fractions in which these fragments will end up. The parts made of polymer (e.g. dome, ring screw, lens and base) easily break-down and can be separated.

For spot LED lamps, the die-casted thick aluminium heat spreaders appeared to break in the granulator. The LED PCBA and driver PCBA often remained connected to the heat spreader because of glue and screw connections. Besides screws and glues, the rubbery potting inside the lamps, which is used for heat conductivity, coincidentally joins PCBAs, connector pins, heat spreader and base together like an adhesive bond (see Figure 3.18).

For bulb LED lamps, the PBT housing often does not break down. In those cases, the thin aluminium heat spreader, potting materials and driver PCBA remain encapsulated inside the housing and further separation will not be possible. Further, the driver PCBAs frequently remained connected to the sockets because of the solder connection. In some cases where the housing broke down the rubbery potting still joined PCBAs, housing and/or wires together (see Figure 3.19).



Figure 3.18-Close up of granulated spots. Image provided by Johan Felix, CIT Recycling Development AB.



Figure 3.19- Close up of granulated bulbs. Image provided by Johan Felix, CIT Recycling Development AB.

Figures 3.20 and 3.21 show the aluminium fraction after eddy current separation for spots and bulbs. For both spots and bulbs, this fraction was mainly composed of aluminium parts. However, as shown in these figures the aluminium fraction also consists of plastic parts, PCBAs and potting materials. In case of spots, this was mainly attributed to connection through potting materials. In case of the bulbs, the aluminium parts remained connected to non-aluminium parts during disintegration. For example, the aluminium plate sometimes remained connected to the PBT housing because of the glue connection (see Figure 3.15 for an exploded view of the lamp). Further, some LED PCBAs remained connected to the aluminium heat spreader because of screw connections. In other cases, the aluminium heat spreader was encapsulated by the PBT housing and was not disintegrated. Due to soldering of the socket to the driver PCBA separation of these parts was difficult. Further, in many cases aluminium sockets remained attached to the plastic bases.



Figure 3.20-Aluminium fraction after eddy current separation for spots LED lamps. Image provided by Johan Felix, CIT Recycling Development AB.



Figure 3.21-Aluminium fraction after eddy current separation for bulb LED lamps. Image provided by Johan Felix, CIT Recycling Development AB.

Figure 3.22 shows the high-density fraction after wind sieve separation in Run-1 of spots and bulbs. This is the fraction where the PCBAs are ideally expected to end up. However, in both cases, this fraction consists of a lot of potting materials as well. This is because in both cases the PCBA parts are partly encapsulated by the rubber potting materials, which makes the rubber potting materials end up in the high-density fraction.



Figure 3.22-High-density fraction after wind sieve separation for LED bulbs in Run-1. Left: spots, right: bulbs. Images provided by Johan Felix, CIT Recycling Development AB.

Figure 3.23 shows the associated low-density fraction after wind sieve separation in Run-1 of spots and bulbs, which is expected to be mainly composed of plastic parts which are lens and base in case of spots and dome, plastic plate, housing and base in case of bulbs. However, there are still quite a number of PCBAs in the low-density fraction. This is attributed to the fact that the PCBAs were still attached to other (relatively large) plastic parts.



Figure 3.23-Low-density fraction after wind sieve separation for LED bulbs in Run1. Left: spots, right: bulbs. Images provided by Johan Felix, CIT Recycling Development AB.

Since the outcome of the wind sieve separation in Run 1 resulted in unsuccessful separation of polymers and PCBAs, a second disintegration run on these fractions was carried out to reduce the size of particles. For each type of lamp, the low-density and high-density fractions were mixed and subjected to granulation with 20mm mesh grid. The fragments obtained from the granulator were further sorted using wind sieve separation technique. This improved the homogeneity of the fragments and led to a fraction rich in copper wire and PCBA fragments and electronic components (material rich fraction) as shown in Figure 3.24.



Figure 3.24-Metal-rich high-density fraction obtained from Run 2. Image provided by Johan Felix, CIT Recycling Development AB.

Analysis of the fragments present in the different fractions show that a number of design features complicate mechanical disintegration of LED lamps into homogenous fragments, notably:

- Use of ductile materials in geometrical shapes that are likely to plastically deform during disintegration, results in the enclosure or clamping of other materials/parts (for instance: deep drawn, thin walled aluminium housing).
- Use of filler materials that mechanically interlock different materials and parts.
- Use of connection techniques that may hamper disintegration: glue, solder, screws.

Stacked parts with similar geometrical shapes could form a hard and inflexible configuration which is hard to disintegrate (under some disintegration techniques) and results in the enclosure of other materials/parts (e.g.: enshrouded/stacked aluminium heat spreader with PBT housing).

3.5 Discussion and conclusion

In this chapter, manual disassembly of LED-LCD displays and mechanical disintegration of CCFL-LCD modules and LED lamps was investigated to answer the following research question:

RQ2. How do product design features of screens and LED lamps affect the fragmentation results in recycling experiments?

The results obtained from manual disintegration tests show that especially the high number and different types of connections, intermediate parts (including: covers, shields and brackets) and the necessity to change tools limit the speed of disassembly and thus the ease of accessibility of components that are both regarding materials and value worthwhile to recover. Clearly, the products studied have not been designed in such a way that the key components can be dismantled in a short amount of time, which is a necessity for economically viable recycling.

The observations regarding fragmentation in the large-scale mechanical disintegration tests are similar to the results obtained by evaluating the disintegration and fragmentation of single units or small-batches in a roller mill. This strengthens our findings regarding disintegration and in addition demonstrates that small-scale results can be used to obtain meaningful information on the recyclability of lamps. The advantage of the larger scale processes is that detailed information on the behaviour of the fragments in subsequent sorting processes can be obtained.

The results obtained from mechanical disintegration tests showed that the products studied to a large extent broke down in heterogeneous fragments that did not enable optimal separation of materials for subsequent recovery processes. Studying the composition and structure of the fragments led to the identification of a number of key design features that hamper the breakdown of products into homogeneous fragments upon shredding. These design aspects relate to:

- materials
- connections
- product structure

These design aspects are critical for manual and mechanical disintegration of products and are as expected based on the design aspects mentioned in Chapter 2. A short summary of the main literature findings regarding these aspects is as follows:

- For selection of materials it is recommended to avoid mixing incompatible materials (incompatible materials are mix of materials that cannot be recovered in the same smelting process and must be separated. Otherwise at least one of the materials will be lost or negatively affect the recovery of other materials), minimize the variety and number of materials used, avoid using toxic and harmful materials or label the toxic materials/parts and make sure they can be easily removed, design with highly recyclable or recycled materials and etc. (de Aguiar et al., 2017; Telenko et al., 2016; Movilla et al., 2016; Reuter & van Schaik, 2015;

Castro et al., 2004; Xing et al., 2003; Kriwet et al., 1995; Chen et al., 1994; Beitz, 1993).

- Connections address in what ways materials/parts are put together in a product. To improve products recyclability, it is important to select connections that can be easily disintegrated during manual and mechanical disintegration such as snap fit and click connections (the ability to disintegrate). On the other hand, connections like adhesive bonding, soldering, brazing and welding that cannot be easily disintegrated must be avoided especially when used between incompatible materials. Improving recyclability of products can also be achieved by minimizing the variety, number, size and type of connections, using standard connections, using connections that can be disintegrated with conventional and standard disassembly and shredding facilities and do not require frequent changes of tools or adjustment of equipment, enhancing the visibility and accessibility of connections and etc. (de Aguiar et al., 2017; Soo et al., 2017; Movilla et al., 2016; Reuter et al., 2013; Castro et al., 2005; Xing et al., 2003; Lee et al., 2001; Kriwet et al., 1995; Chen et al., 1994; Beitz, 1993).
- Product structure deals with the arrangement and position of materials, parts and subassemblies in a product and the connections between them, and the possibilities to design a product such that scarce, valuable or harmful materials and parts can be easily accessible during disintegration process in a short amount of time. This can be achieved by changing materials/parts position in the product structure, reducing or removing (intermediate) parts, clustering similar/compatible materials/parts together, minimizing number of subassemblies, minimizing or removing connections, or transforming product structure (train, star, hamburger, dress, shell, twin, rod) (de Aguiar et al., 2017; Movilla et al., 2016; Johansson & Luttrupp, 2009; Kwak et al., 2009; Lee et al., 2001; Kriwet et al., 1995; Chen et al., 1994).

A more extensive overview of material compatibility and connections on recyclability will be presented in the next chapter

A comparison of literature findings with our empirical findings in this chapter shows that both theory and practice agree that materials, connections and product structure are critical to improve product recyclability and address the same issues and recommendations regarding these design aspects. However, the actual recycling results obtained on both low-end and high-end electronic consumer products evidently indicate a gap between what DfR methods aim for, and the results obtained from disintegration tests of electronic products in practice. This implies that DfR methods are either not applied or not effective.

3.6 References

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Chapter 4: Effectiveness of design for recycling methods in improving the recyclability of electronic products

4.1 Introduction

Recycling of electronics is complicated due to the large number of different materials present. The recycling practices show that electronics are still not optimally disintegrated and separated in actual recycling processes, in spite of many years of studies regarding design for recycling (DfR).

Product design plays a crucial role to facilitate the disintegration process during end-of-life treatment such that materials can be recovered with a high yield (Metzger, 2003; Bellmann & Khare, 2000). Chapter 3 investigated the effect of product design on actual disintegration of electronics during the recycling process. A number of LCD TVs and medical displays were subjected to manual disintegration. LED lamps, spots as well as bulbs were subjected to mechanical disintegration. The resulting fragments were analysed and directly linked to product design aspects that affected respectively the manual and mechanical disintegration process.

In Chapter 3, it was observed that, in addition to recyclability of the materials as such, the way in which materials are connected plays a crucial role in the ability to generate sufficiently homogeneous fragments during disintegration. This relates to the primary concern to improve recyclability, which is to establish material fractions that can be treated simultaneously in further recovery processes: even if the materials used are recyclable, they may not be compatible to a particular recovery process and therefore will not be recovered if ending up in the wrong sorting fraction. They might even reduce the efficiency of another recovery process.

The observations regarding recyclability in Chapter 3 are in agreement with the DfR guidelines as mentioned in literature and reported in Chapter 2. However, the observations on disintegration of electronic products show that the resulting fragments are far from homogeneous. This raises questions with respect to the actual use and the effectiveness of DfR guidelines. Drawing conclusions regarding use and effectiveness is not possible based on reported results, as most of the academic work on DfR is theoretical in nature and specific product categories are usually not investigated. Further, use of particular guidelines is often implicit and is therefore hard to investigate.

By investigating explicitly the DfR of specific electronic products, i.e. LED lamps and displays, this chapter focuses on the effectiveness of DfR for electronics and addresses the following research question:

RQ3. How effective are design for recycling methods in improving the recyclability of electronic products?

This has been studied by redesigning products, while explicitly taking into account a set of DfR guidelines. These guidelines were developed in the framework of the GreenElec project. Subsequently, designers at Philips Lighting, Barco and TP Vision were asked to redesign respectively LED lamps, TVs and medical displays using these specific DfR guidelines. The redesigned products were subsequently disintegrated and sorted into fractions for further recovery processing by recyclers (Stena and CIT). The results were compared to other electronic products with similar functionality in which these explicit guidelines were not taken into account in order to evaluate the effectiveness of the design guidelines.

The guidelines that were applied, were derived from the results of the recycling experiments as described in Chapter 3. Based on insights obtained from the actual disintegration results of case study products, a set of generic design guidelines was proposed with a specific focus on materials, connections and electronic PCBAs. The latter implies that connections to other non-electronic parts should be broken down during the disintegration stage of the recycling process. The first two aspects, i.e. materials and connections, can also be directly recognized from the guidelines based on literature as discussed in Chapter 2. The additional point related to electronics is due to the relatively high environmental impact and the economic value of the materials in electronic components. This requires a specific effort with respect to these materials (Hadi et al., 2015; Ghosh et al., 2015; Canal Marques et al., 2013; Wang & Gaustad, 2012; Huang et al., 2009). Fortunately, dedicated technologies for recycling of electronics exist: electronics can be considered as a homogeneous fraction from recycling perspective, i.e. a large fraction of the materials in electronics is compatible in a single recycling process (Reuter & van Schaik, 2015), implying that preferably they are sorted into a fraction containing only electronic parts.

Section 4.2 describes the guidelines and the way in which they were applied by designers at the case study companies. This section also describes the way in which the recyclability of the redesigned products was tested in small scale disintegration tests. Section 4.3 reports on the application of the DfR guidelines to displays with the aim to achieve improved manual disintegration. In this section, also the resulting recyclability of the redesigned displays is discussed. Section 4.4 reports on the application of the DfR guidelines to LED lamps for improved mechanical disintegration and discusses the recyclability of the redesigned LED lamps. Section 4.5 provides a discussion on effectiveness of DfR guidelines in obtaining better disintegration results and discusses the results from a broader environmental and economic perspective.

4.2 Research method

LED lamps, TVs and medical displays were redesigned in order to improve their recyclability. Designers in Philips Lighting, Barco and TP Vision received the explicit assignment to improve the recyclability of these products, based on the following simple and generic recyclability guidelines that specifically focus on materials, connections and electronic PCBAs (Balkenende et al., 2014; Aerts et al., 2014):

- (1) Use recyclable materials
- (2) Use connections that facilitate break down in homogeneous fragments
- (3) Ensure that electronic parts are released as separate fragments

This particular set of design guidelines was provided to designers in Philips Lighting, Barco and TP Vision to be explicitly taken into account when redesigning a MR16 lamp, a medical display and a consumer television, respectively.


























The designers implemented these guidelines in their normal design process as additional requirements. The DfR guidelines had to be taken into account from the earliest design stages on. In the case of the lamps a complete redesign was allowed. The work on the medical display and television had a redesign character, implying that choices regarding new materials and (internal) build of these products were more limited. During the design process the generic guidelines translated into specific and more extended design decisions for redesigning the case study products.

All designers involved (at Philips Lighting, TP Vision and Barco) were skilled product designers. They were experienced in the design of their respective product, knowing at detailed level the 'standard' product requirements. They operated in a multidisciplinary design team as is usual for design assignments in those companies and collaborated in those teams with mechanical engineers, electrical engineers and (in the case of the LED lamps) physicists specialised in optics and thermal transport. These projects were led by designers who followed the development process as is common within their companies. These development processes are more extensively described and discussed in Chapter 5. In addition to the DfR guidelines they took the usual design requirements into account to develop a product that is technologically fully within spec (including product performance) and that is interesting to manufacture from an economic perspective.

The designers were introduced into design for recyclability by explaining to them the essential guidelines as depicted in Figure 4.1. In addition to the guidelines a table with material compatibility for metals and plastics was provided (shown in Figure 4.2) and a table with ease of disassembly and shredding of connections (Figure 4.3). It was emphasized that the guidelines and tables were intended as inspirational sources, not to prescribe solutions.

materials	<ul style="list-style-type: none"> • Only use materials that can be recycled • Limit the number of different materials • Use pure materials
connections	<ul style="list-style-type: none"> • Avoid fixed connections • Break-down (by shredding/disassembly) to <ul style="list-style-type: none"> ○ Pieces with uniform composition ○ Pieces of relatively large size (>1 cm)
electronics	<ul style="list-style-type: none"> • Get PCB out in one piece (→ smelting) • Enable easy/fast detection of materials

Figure 4.1-Design for Recycling guidelines as used in the Green Elec project

Contaminant Dominant	Steel	Copper	Aluminum	Polymers	PCB/PV
Steel					
Copper					
Aluminum					
Polymers					
PCB/PV					















 Incompatible
 Uncertain
 Compatible

Figure 4.2- Material Compatibility Table

Connections	Recyclability	
	Manual Dismantling	Mechanical disintegration
Clicking		
Pressing / Press fit / Shrink fit		
Mechanical fastening		
Cold Forming techniques		
Staking		
Adhesive bonding		
Soldering		
Brazing		
Welding		
Molded connection		



 Good
 Average
 Bad

Figure 4.3-Table of Connections

To evaluate the effectiveness of the DfR guidelines, the redesigns were manufactured in small quantities (20-100 pieces for the lamps, prototypes for the displays) and subsequently subjected to similar disintegration treatments as described in Chapter 3 for small numbers of products: manual disintegration and separation for the displays and mechanical disintegration and automated separation for the LED lamps using roller mill technique.

Mechanical disintegration of redesigned LED lamps was carried out by CIT and Stena as described in Chapter 3. After mechanical disintegration of LED lamps, the composition of resulting fragments was evaluated by visual inspection to check to which extent application of DfR guidelines led to fragments consisting of homogenous or compatible materials on the one hand and incompatible mixtures of materials on the other. By doing this, the effectivity of the application of DfR guidelines was assessed by establishing the degree of disintegration of the case study products.

During manual disintegration of displays, the time required to manually remove the PCBAs of the redesigned displays was compared with the original designs (described in Chapter 3, Section 3.3) to check if adaptations of the product design features based on the DfR guidelines reduced the dismantling time of the redesigned displays and improved their accessibility. The medical display dismantled had the brand code MDCC-4230, also identified as Coronis Fusion 4MP DL. This medical display had a LED backlight. At Barco dismantling was carried out by the project leader of the redesigned display who was familiar with the built of the display, but had no specific dismantling experience. The LCD TV dismantled at TP Vision was a LED LCD television with the product code Philips 48PFS8109. Also, at TP Vision dismantling was performed by a mechanical engineer who was involved in the redesign of the LED LCD TV, but with limited disassembly experience. In contrast to the display dismantling described in Chapter 3, dismantling of the redesigned displays could not be carried out by an experienced operator at Stena. This makes direct comparison of the data on dismantling times as obtained in Chapter 3 difficult. However, with emphasis on the dismantling observations and as the focus is primarily on identifying the effect of particular design features within the displays, the results are insightful.

In addition to actual dismantling time of displays, we also looked into the dismantling time as calculated by the ease of disassembly of products (eDIM) method (Peeters et al., 2018). The application of eDIM method to two redesigned display case studies presented in this chapter has been used for comparison with the data that are derived from actual disassembly tests.

4.3 Displays: application of design for recycling and evaluation of manual disintegration

This section reports on the application of DfR to displays for improving manual disintegration. Subsection 4.3.1 reports on LED LCD TVs and subsection 4.3.2 reports on medical displays. In this section, also the resulting recyclability of the redesigned displays is discussed.

4.3.1 Redesigned LED LCD TV

For the redesign of LED LCD TV, the focus was on

- reducing the number of screws,
- using the same type of screws with same dimensions,
- improve the accessibility of PCBAs.

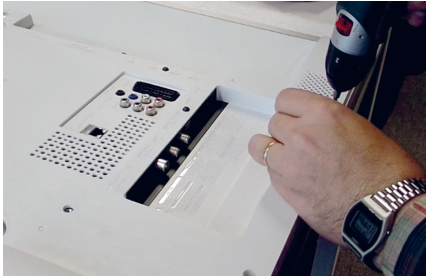
In the developed prototype, the number of screws for fixing the back cover was reduced from 16 to 11 screws. Further, only a single type of screws was used for the entire LED LCD TV to avoid the necessity to exchange bits of the power tool for removing screws. Finally, the LED LCD TV's internal design was modified to make the nature and order of the subsequent disassembly steps self-explanatory in order to improve the accessibility of parts and the speed of disassembly.

The redesigned television prototype was evaluated in terms of feasibility for manual dismantling. This was carried out during a company visit in November 2014. The handling as well as the time required to manually remove the PCBAs of the redesigned LED LCD TV was recorded. The dismantling was carried out by a mechanical engineer who had been involved in the redesign of the LED LCD TV. He had only limited disassembly experience. Table 4.1 summarizes the disassembly steps of the redesigned prototype, the disassembly time per step and number and type of connections removed per step. Table 4.2 provides step by step images of the disassembly of redesigned LED LCD TV. Similar to Chapter 3, the eDIM method (Peeters et al., 2018) is applied on the redesigned displays presented in this chapter for comparison with the actually obtained data that are derived from disassembly tests. In chapter 3 a number of aspects that might explain the difference between eDIM and actual disassembly has already been mentioned. Here we observed that the most important factor was the disassembly assumed per screw, which amounts to 5.76 s in eDIM, whereas in practice this was less than 3 s. This can be attributed to the difference between using a manual screw driver (eDIM) or a power tool.

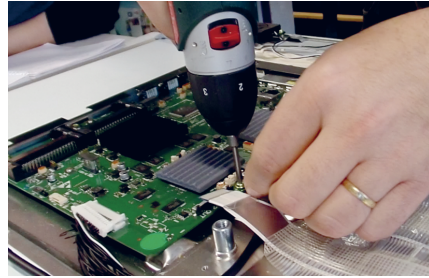
Table 4.1-Disassembly profile of the redesigned LED LCD TV (model: 48PFS8109)

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove casing screws	29	11 screws	63.36	Power tool
1 st PCBA	2. Remove 1 st PCBA	14	6 screws	34.56	Power tool
	3. Remove click connectors	10	8 click connectors		Hand
2 nd PCBA	4. Remove 2 nd PCBA	9	5 screws	28.8	Power tool
	5. Remove click connectors	4	2 click connectors		Hand
3 rd PCBA	6. Remove metal shield	14	6 screws	34.56	Power tool
	7. Remove cover	3	1 screw	5.76	Power tool
	8. Remove click connectors	8	4 click connectors		Hand
		91		197.28	

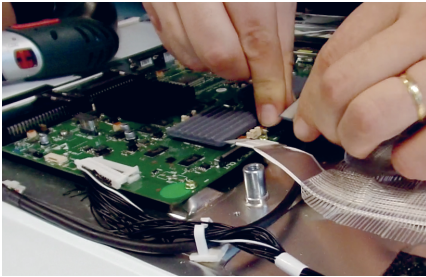
Table 4.2-Disassembly steps of the redesigned LED LCD TV (model: 48PFS8109)



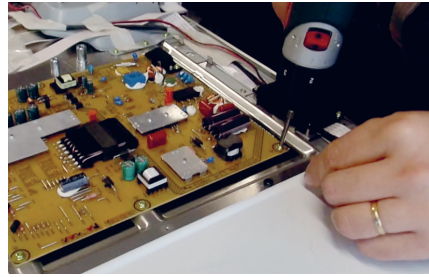
1. eleven screws are disconnected with power tool in order to remove the casing (back cover)



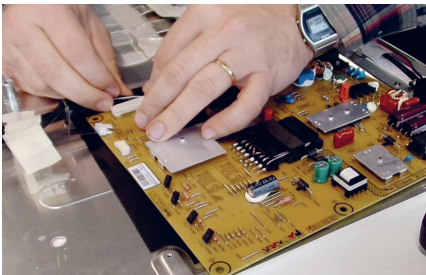
2. six screws are removed with power tool to partly release the 1st PCBA



3. next, eight click connectors are removed by hand to completely release the 1st PCBA



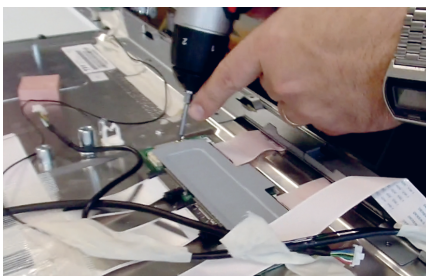
4. five screws are removed with power tool to partly release the 2nd PCBA



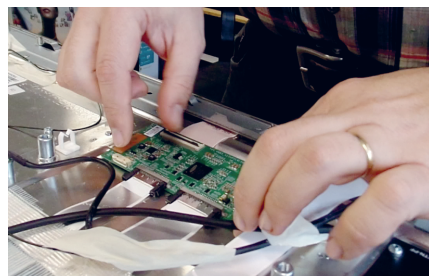
5. after that, two click connectors are removed by hand to completely release the 2nd PCBA



6. six screws are removed with power tool to remove the metal shield that covers the 3rd PCBA



7. then, one screw is removed with power tool to remove the cover of the 3rd PCBA



8. finally, four click connectors are removed by hand to completely release the 3rd PCBA

Figure 4.4 compares the dismantling time of the PCBAs from the three original LED LCD TVs with the new design. The horizontal axis shows the number of parts (cover and PCBAs) removed. The vertical axis shows the cumulative dismantling time of parts in seconds. Manual disintegration test on the redesigned LED LCD TVs (48PFS8109) showed that manual disintegration down to LCD module level was completed in 90-120 seconds compared to the original designs which took 168-252 seconds. In more detail, the reduced number of back cover screws reduced the dismantling time of the back cover from 57 seconds to 29 seconds. Whereas in previous designs, changing the screw bits could take up to 33 seconds, in the new design this is completely eliminated, as all the screws of the back cover, PCBAs and metal shields could be removed with a single screw bit. Further, in the new design the position and visibility of all PCBA was intuitively clear. This is in contrast with the previous designs, in which the PCBAs were mounted along the edges of the LCD module and shielded with covers. This severely hampered accessibility in the previous design, while it also required changing the tools from power tool to knife a number of times, which in best case takes up to 10 seconds. The shorter total timeframe is especially striking as dismantling was now carried out by an engineer unexperienced in disassembly, whereas the reference displays were dismantled by an experienced recycler.

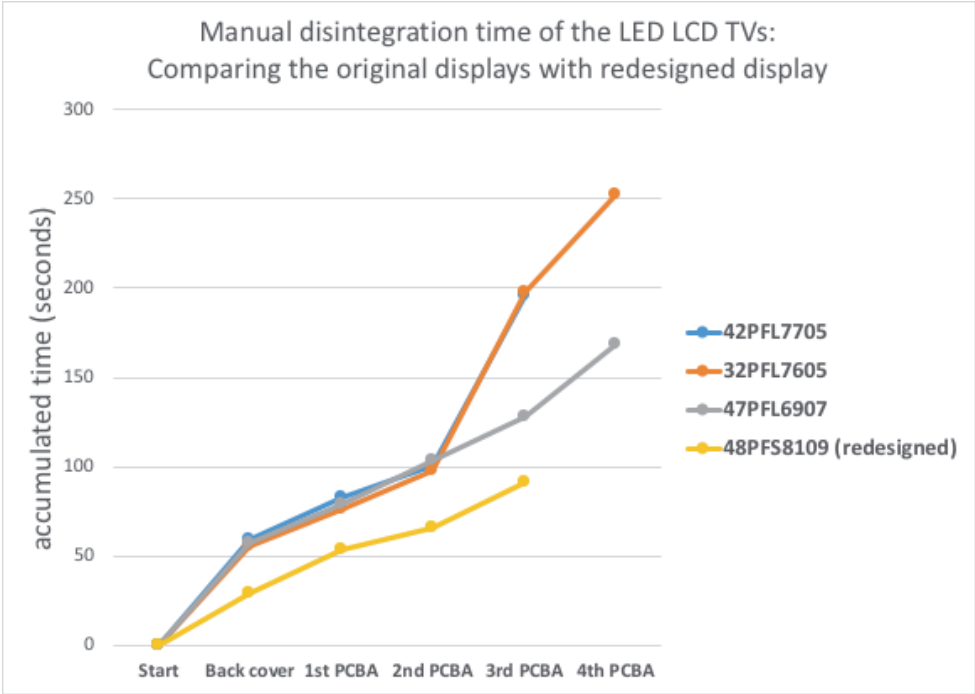


Figure 4.4-Dismantling time of PCBAs from original and redesigned LED LCD TVs

Summarizing, in Chapter 3 (Section 3.3), it was observed that manual disintegration of the back cover and subsequent PCBAs from the Philips LED LCD TVs took 168 to 252 seconds. The amount of time it took to manually disintegrate the back covers was related to the use of high number of screws. This number has been reduced in the new design. Further, a relatively large effort was then needed to dismantle the back cover and the 3rd and 4th PCBAs. This was related to the use of different type of screws and the position of these PCBAs: in some cases,

the position and visibility of these PCBAs was not intuitively clear to the operator, and it took a while for the operator to understand how to proceed. Further, these PCBAs were generally deeply embedded in the displays and their accessibility required dismantling of some intermediate parts first, such as covers, brackets and shields. Also, the lack of accessibility required frequent changing of the tools, which also affected the total dismantling time. By adapting the design such that visibility and accessibility were improved and the order of dismantling became more obvious, the speed of removal of the inner PCBAs was considerably improved. This clearly shows that the adaptations of the product design features based on the DfR guidelines enables a reduction of the dismantling time. Further, as the weight and value of the PCBAs of the redesigned TV were similar as for the original TVs, this enhances the profitability of partial manual disintegration of LCD TVs for recyclers.

4.3.2 Redesigned medical displays

For the redesign, designers in Barco focused on

- reducing the number of screws,
- reducing the types of screws used,
- improving the accessibility of connectors,
- avoiding the need to switch between tools during manual disassembly.

In addition to the requirements for improving recyclability, the number of PCBAs in the display was reduced due to a simultaneous electronic redesign. From a disassembly perspective, the principal advantage of reducing the number of PCBAs is that in the new design some previously interconnected PCBAs are merged into one single PCBA, which might facilitate accessibility. Other direct advantages are a reduced number of connections (screws) required to fix the PCBAs and the presence of fewer wire bonds and interconnects.

In medical displays, the PCBAs are placed in metal boxes known as PCB brackets and LCD brackets. The brackets are used to assure electromagnetic compatibility (EMC), i.e. to avoid unintentional exposure to electromagnetic energy. By reducing the number of PCBAs, the size of metal brackets can also be decreased. As a result, the size of plastic covers around the metal brackets also reduces in size. In another word, the number and size of PCBAs governs the size and configuration of brackets, which in turn affects the size of plastic covers and the general product architectural design. The reduction in the number of PCBAs thus creates opportunities for a significant redesign of the existing product, in which not only connections can be revisited, but also allowing for a more thorough reconstruction of the display. However, as a limitation to the redesign, the designers in Barco had to adapt the plastic covers of an old design for direct reuse in the redesigned display. As a consequence of this retrofitting, in the redesign of these parts of the display the DfR guidelines could not be followed and were even opposed.

During a company visit in October 2014, the redesigned medical display was evaluated in terms of feasibility for manual disintegration of PCBAs together with the project leader of the redesigned display from Barco. Manual dismantling was performed by the project leader for the redesigned display whose expertise was in electrical engineering with limited disassembly experience. Table 4.3 summarizes the disassembly steps of the new design, disassembly time per step and number and type of connections removed per step. Table 4.4 provides step-by-step images of disassembly of redesigned medical display. The disassembly time difference between our experiments and eDIM was again considerable.

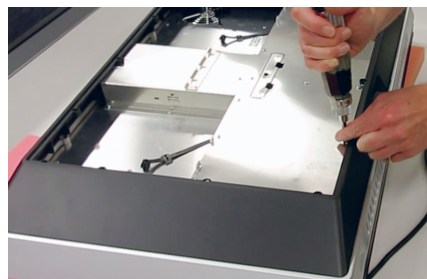
Table 4.3-Disassembly profile of the redesigned medical display (model: MDCC-4230)

Disassembly targets	Disassembly steps: type of actions and changes in tools	Time (seconds)	Number and type of connections	eDIM method	Tools
Removal of casing	1. Remove back cover down	9	2 screws	11.52	Power tool
	2. Removal of back bezel	17	4 screws	23.04	Power tool
	3. Removal of mid bezel	48	12 screws	69.12	Power tool
	4. Removal of front bezel	37	12 screws	69.12	Power tool
	5. Change tool	3			
	6. Removal of front bezel	29	6 screws	34.56	Screwdriver
	7. Remove click connectors	14	2 click connectors	4.32	Hand
	8. Remove PCB bracket	107	30 screws	172.8	Power tool
1 st PCBA	9. Remove click connectors	13	10 click connectors	21.6	Hand
	10. Remove screws	30	10 screws	57.6	Power tool
	11. Change tool	12			
	12. Remove screws	11	4 screws	23.04	Screwdriver
2 nd PCBA	13. Remove LCD bracket	33	8 screws	46.08	Power tool
	14. Remove 2 nd PCBA	13	4 screws	23.04	Power tool
	15. Remove click connectors	5	4 click connectors	8.64	Hand
3 rd PCBA	16. Remove metal shield	10	4 screws	23.04	Power tool
	17. Remove screws	3	2 screws	11.52	Power tool
	18. Remove click connectors	8	4 click connectors	8.64	Hand
		402		610.56	

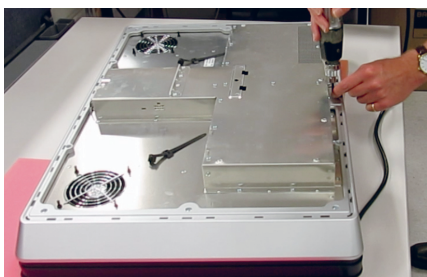
Table 4.4-Disassembly steps of the redesigned medical display (model: MDCC-4230)



1. two screws are disconnected with power tool in order to remove the back cover down



2. four screws are disconnected with power tool in order to remove the back bezel



3. twelve screws are disconnected with power tool in order to remove the mid bezel

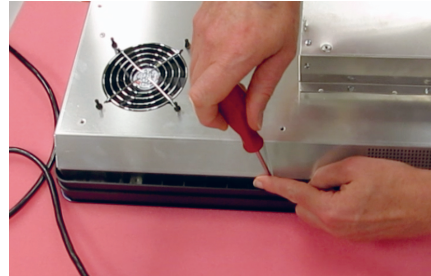


4. twelve screws are removed with power tool to partly release the front bezel

**Table 4.4 -Disassembly steps of the redesigned medical display (model: MDCC-4230)
(continued)**



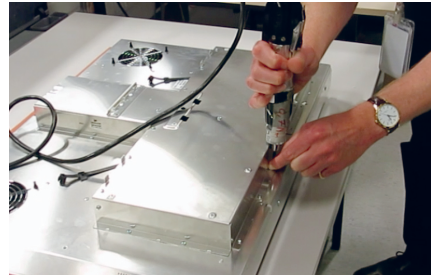
5. then a tool needs to be changed since the screws of front bezel were not all the same type



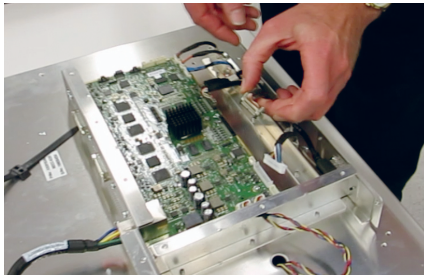
6. finally another six screws are removed with screw driver to completely release the front bezel



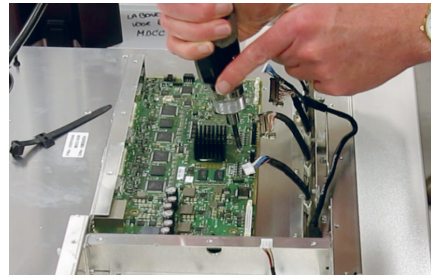
7. two click connectors are removed by hand



8. thirty screws are removed with power tool to release the PCB bracket



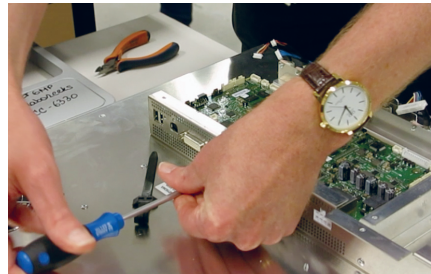
9. ten click connectors are removed by hand to partly release the 1st PCBA



10. after that, ten screws are removed with power tool to partly release the 1st PCBA

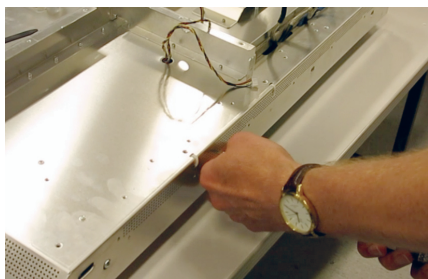


11. then a tool needs to be changed since the screws used to fix the 1st PCBA were not all the same type

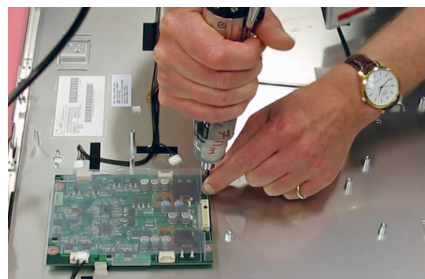


12. finally another four screws are removed with screw driver to completely release the 1st PCBA

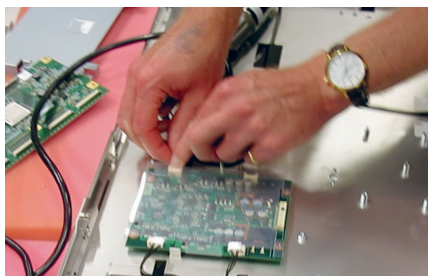
Table 4.4 -Disassembly steps of the redesigned medical display (model: MDCC-4230) (continued)



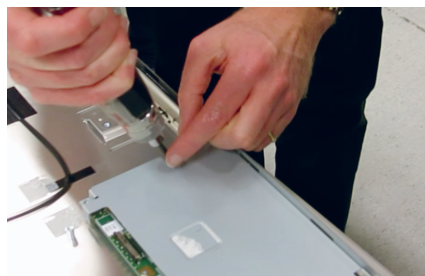
13. eight screws are removed with power tool to release the LCD bracket



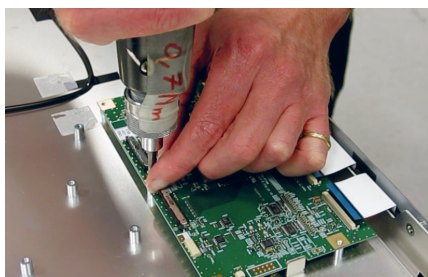
14. four screws are removed with power tool to partly release the 2nd PCBA



15. then, four click connectors are removed by hand to completely release the 2nd PCBA



16. four screws are removed with power tool to remove the metal shield that covers the 3rd PCBA



17. two screws are removed with power tool to partially release the 3rd PCBA



18. four click connectors are removed by hand to completely release the 3rd PCBA

In Chapter 3 (Section 3.3), it was observed that manual disintegration of the medical displays took 361 to 487 seconds. The time it took to manually disintegrate the displays down to the LCD module were related to a number of factors, including high number of screws, use of brackets and shields, use of different type of screws, and position (visibility and accessibility) of PCBAs, which required frequent changes of the tools. Medical displays also use a relatively high number of PCBAs, which increases the complexity of manual disintegration. Especially the latter aspect was addressed in the redesigned medical display, However, as the original bezels and brackets had to be used, the redesign was sub-optimal in this respect.

Figure 4.5 compares the dismantling time of the PCBAs from the two original medical displays with the new design. The horizontal axis shows the number of parts (back cover and PCBAs) removed. The vertical axis shows the cumulative dismantling time of parts in seconds. Manual disintegration test on redesigned medical display (MDCC-4230) showed that manual

disintegration was completed in 402 seconds compared to original designs which took 361-487 seconds. Clearly, dismantling of the redesign did not take less time than dismantling of the original products. A first aspect that needs to be addressed here is that dismantling conditions are not directly comparable. A highly experienced dismantler at Stena, who took a destructive approach while dismantling the displays, dismantled the MDNG-5121 and CCFD-2320. At Barco dismantling was carried out by the project leader of the redesigned display who was familiar with the built of the display but had no specific dismantling experience. Also, dismantling was carried out in a reversible way. This implies that timings cannot directly be compared and the duration required by the project leader at Barco is likely to exceed that of the recycling technician at Stena.

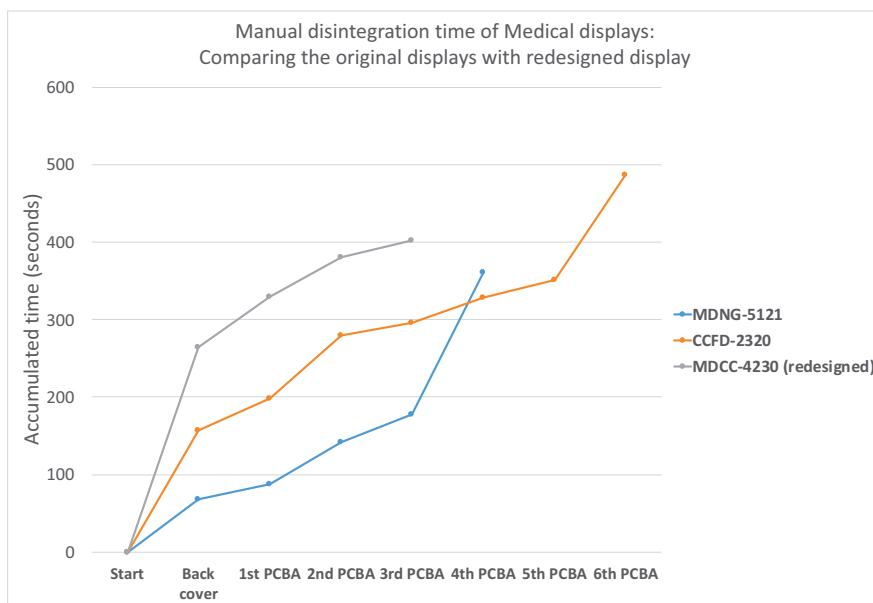


Figure 4.5-Dismantling time of PCBAs from original and redesigned medical displays

As is evident from the figure, especially manual disintegration of the back cover of the redesigned display at Barco took almost double the time needed for the older displays taken apart by Stena. Although experience and non-destructive way of working of the project leader at Barco are likely to have played a role, this is to a large extent explained by the fact that designers in Barco had to re-use the plastic covers of an old design to the redesigned display (front bezel, mid bezel and back bezel, see Table 4.4, images 2, 3 and 4).

In original designs, it was observed that manual disintegration of the back covers and PCB brackets took 68 to 157 seconds. This amount of time was needed to remove 16-42 screws of which 4-11 screws were used to fix the back cover and 12-31 screws were used to fix the PCB bracket. In the new design, manual disintegration of the back cover and PCB bracket took 264 seconds. This time was needed to remove 66 screws of which 2 were used to fix the back cover, 34 screws to fix the front, mid and back bezels adapted from an old design and 30 screws to fix the PCB bracket. In all cases about 4 s per screw was needed. Due to the use of the bezels from an old design the number of screws actually increased, as is to be expected leading to a proportional increase in dismantling time.

Further, in the original design the size of PCB brackets was determined by the size of the first PCBA. The size of the plastic back cover around the metal brackets only required 4 to 11 screws. However, in the redesigned displays designers could not reduce the size of the PCB bracket to the size of the first PCBA, because the size of the plastic covers (bezels) was copied from the old design. This in turn determined the size of LCD and PCBA brackets. The large size of the adapted plastic covers (bezels) necessitated to design large brackets. Therefore, the size and configuration of brackets used to cover the PCBAs became larger than necessary (see Table 4.4, images 8 and 9). This also implied that the number of screws required to fix the brackets was relatively large. Designers in Barco pointed out that reducing the size of plastic covers and reducing the size of metal brackets to the size of PCBs would have reduced the dismantling time as then a smaller number of screws would be needed, roughly between 16 to 42 screws.

After the removal of the back cover, the dismantling speed of the PCBAs is similar for the redesign and the original displays (i.e. similar slopes in Figure 4.5). Given the higher number of screws in the redesigned display, this is an indication that the use of the bezels from an old design indeed reduced the speed of disassembly. In spite of this, the total dismantling time was similar to that of MDNG-5121 and shorter than for CCFD-2320 due to the reduced number of PCBAs on the one hand and the avoidance of difficult accessibility of the connectors to release the last PCBA. The latter is especially evident from the much steeper slope observed for the final PCBA boards in Figure 4.5.

The disappointing result of redesigning the Barco display in terms of ease of manual dismantling can to a large extent be attributed to additional boundary conditions in the redesign process. On the one hand, the reduced number of PCBAs lead to an intrinsic advantage, whereas on the other hand the requirement to reuse existing plastic covers (bezels) severely reduced the opportunities for improvement. This actually led to a number of design choices that were the opposite from the directions in the DfR guidelines. The evaluation is further hampered by different disintegration procedures, i.e. by an experienced operator and destructively at Stena, compared to an inexperienced operator and working in a reversible way at Barco. Taking all these aspects into account, the effects of the design interventions on the design process follow the expectations based on the design guidelines, some contributing to better recyclability, while others hamper easy dismantling. Considering the further improvements based on the DfR guidelines that Barco will be able to incorporate when a subsequent redesign also addresses the plastic covers (bezels) and brackets, it is concluded that also in this case recyclability will be improved when following the DfR guidelines.

In Chapter 3 (Section 3.3), it was observed that manual disintegration of the LCD TVs took 168 to 252 seconds. This number has been reduced in the new design to 91 seconds. Further, it was observed that manual disintegration of the medical displays took 361 to 487 seconds. This number has not been significantly reduced in the new design due to the use of the bezels from an old design the number of screws actually increased, as is to be expected leading to a proportional increase in dismantling time. The same results are achieved using the eDIM method. As shown in Table 4.5, the dismantling of LCD TVs can take 202.32 to 264.96 seconds using the eDIM method. This number has been reduced in the new design to 197 seconds. In case of medical displays. The dismantling can take 388.8 to 502.56 seconds using eDIM method. This number has been increased in the new design to 610.56 seconds. This was expected as the bezels and brackets were adapted from an old design which increased the number of screws and therefore the dismantling time.

Table 4.5-Comparing the actual dismantling time of displays with eDIM method

	LCD TVs				Medical displays		
	Original design		Redesign		Original design		Redesign
Dismantling time of displays based on our experiment (in seconds)	196	252	168	91	361	487	402
Dismantling time of displays based on eDIM method (in seconds)	202.32	234	264.96	197	388.8	502.56	610.56

4.4 LED lamps: application of design for recycling and evaluation of mechanical disintegration

In contrast to the displays discussed in the previous section, lamps are disintegrated by shredding. This implies that the guidelines should aim at improving the fragmentation during the shredding process. The DfR guidelines were applied to the redesign of the MR16 LED spot light. This implies that form factor (i.e. outer envelope shape), electronic functionality and light output are largely fixed by the standards for these spot lights (Treurniet, 2014). Within these boundary conditions, the designers where free to vary with materials and connections. To explore different directions guided by the DfR guidelines, redesigns have been made with different focus, i.e. with a focus on

- improving breakdown of the connections in the existing MR16 LED lamp design,
- on using recyclable materials,
- on the elimination of connections.

In this way, while working on a product with prescribed functionality, different opportunities for DfR were explored and evaluated.

4.4.1 Fracture lines

Focusing on the existing MR16 LED lamp, the major bottleneck in achieving the desired fragmentation was the connection between the heat spreader and both the driver PCBA and the LED PCBA. As shown in Chapter 3 (Section 3.4), when original LED spot lamps are subjected to mechanical disintegration, the parts made of polymers (ring screw, lens, base) break down and can be separated. However, the robust die-casted aluminium housing only partially breaks down and the PCBAs are to a large extent not detached but remain connected to the housing because of multiple screw connections.

In this attempt to a minimal redesign the focus was on the screw connections that prevent the PCBA to release from the heat spreader during shredding. The screw connections are applied to guarantee a highly reliable strong connection between PCBA and heat spreader, because local heat generation is performance limiting when the temperature of the electronics increases too much. Unfortunately, the strength of the screws and the strong bonding that is achieved make break-down during shredding unlikely. A number of solutions was considered to weaken this bond, e.g. the use of different screw materials, weakening of the screw itself or use of memory shape materials (which would deform at the temperatures achieved in a shredder). Finally, as a solution that was tested in practice, it was proposed to apply fracture lines to the heat spreader that pass through the screw holes. The fracture lines are intended to facilitate the disintegration of the robust aluminium housing, while simultaneously guiding fracturing of the housing along the screw holes, which would lead to release of the screw connections.

Fracture lines can easily be defined in a mould like the one used for die casting the housing. However, in this specific case, for testing purposes, existing housings were used and the fracture lines were applied using laser ablation. Figure 4.6a shows a redesigned lamp. The result of a small-scale shredding test on LED spot lights with fracture lines using roller mill technique (as explained in 3.4.2) is shown in Figure 4.6b. As can be clearly seen in this figure, the housing indeed breaks down along the fracture lines, resulting in homogeneous fragments of aluminium heat spreader and PCBAs separately. In sorting this is expected to lead to homogeneous fractions and high recovery yield of materials. This redesign strategy largely improved the recyclability of LED lamps without significant changes in the product design, the production process or extra cost.

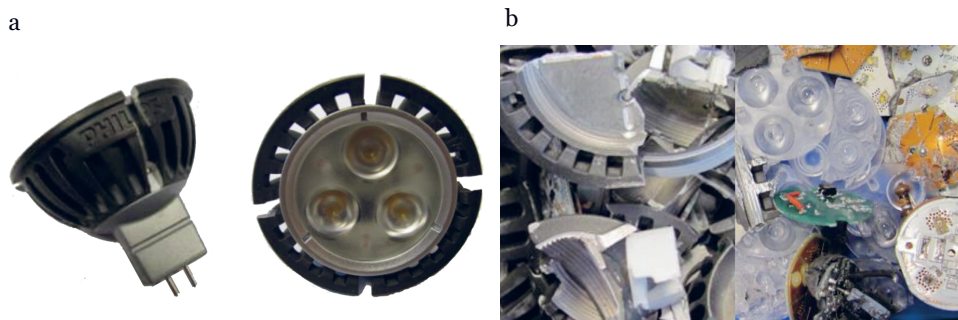


Figure 4.6-a: LED spot lamp with fracture lines. Image provided by Philips Lighting., b: fragments resulting from shredding of LED spot lamps with fracture lines applied to the heat spreader. Image provided by Johan Felix, CIT Recycling Development AB.

4.4.2 Stacked design without inner connections

Focusing on the permanent connection that hampers the fragmentation during shredding, also a completely different strategy was pursued. As the bottleneck in recycling is the presence of the screw connections, an obvious strategy is to simply remove the screws from the design and more in general to minimize the number of fixed connections. However, as the screws guarantee the essential contact area between PCBA and heat spreader, such a strategy will only be acceptable if alternative measures are taken to establish a good thermal contact.

The direction that was elaborated was to remove all internal connections. The lamp is entirely made by stacking parts. The parts are firmly pressed to each other by applying a clamp ring at the top of the housing. This design meant that the housing should consist of a single part, whereas usually the bottom part of the housing is made of an isolator to avoid problems with the electrical connections, while the top part is made of a corrugated metal to assure a relatively large area for heat dissipation to ambient. Also, the internal heat spreader to which the PCBs are attached could no longer be integrated with the housing, as that would prevent insertion of the driver electronics. On the other hand, this means that the shape of the housing becomes less complicated and follows the shape of the outer envelope prescribed by the standard. It was further decided to make the housing and most of the other parts from aluminium to limit the number of materials to a single good recyclable material, while simultaneously reducing the total amount of aluminium used. This could be achieved because the stacking process allowed for less complicated structures, which allowed the parts to be made by deep drawing instead of die-casting. Deep drawing leads to a reduction of the amount

of aluminium used as thinner wall structures could be made. Interestingly this also leads to a considerably lower manufacturing cost (about 50%) for the mechanical parts of this lamp.

Figure 4.7 shows an exploded view of the redesign. The new design will be referred to as stacked MR16. The final design consists of the following parts: silicone sleeve, aluminium ring (heat spreader top), polycarbonate lens (which acts as light collimator), LED printed circuit board (LED PCB), two aluminium inlays that act as heat spreaders, driver PCB, polybutylene terephthalate support for the driver PCB (driver clamp that also isolates the connector pins from the housing), Ni-coated copper connector pins and aluminium housing. The sleeve was used instead of coating the aluminium housing and serves to increase the emissivity of the surface for infrared radiation, thus improving the thermal performance. The aluminium parts replace parts made of polymers to make sure that material can be recycled and also to reduce the diversity of materials.

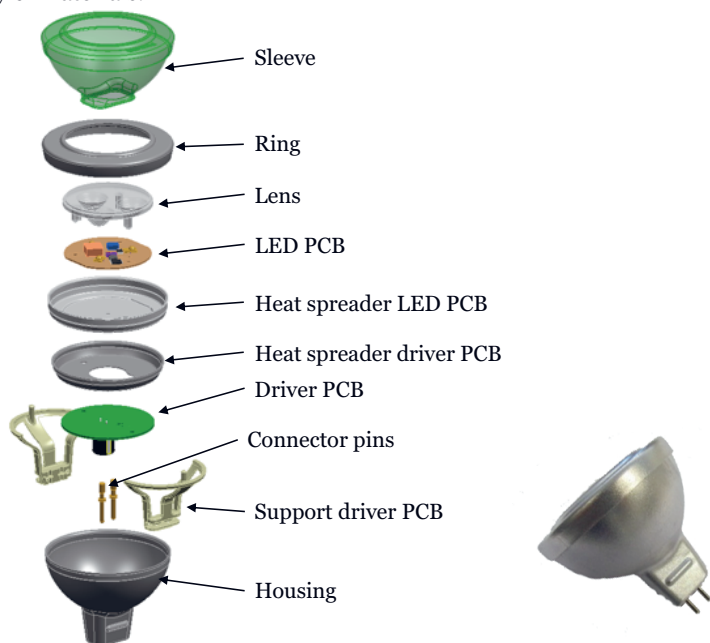


Figure 4.7-Exploded view of redesigned standard spot lamp: stacked design. Image provided by Philips Lighting.

A small-scale shredding test with 20 lamps using roller mill technique showed that the deep drawn aluminium housing deforms during disintegration. This results in the enclosure or clamping of electronics and other parts (Figure 4.8a). This can be directly attributed to the use of a thin compliant material that is able to fold around the other parts when subjected to the forces in the roller mill equipment.

As this folding effect was anticipated, potting was applied to redesigned lamps to increase the stiffness of the construction. Potting implies that an electronic assembly is filled with a compound to improve e.g. thermal conductivity, moisture sensitivity or sock resistance. Potting material is regularly used in lamps, including MR16 LED lamps. Here two alternatives were tested, both in sets of 20 lamps: silicone potting as already applied to similar lamps and

sand potting. Silicone potting has the advantage that it is a common potting material with established processing during manufacturing. Also, the adhesion of silicones to electronics is weak, implying that the material can be easily removed from the electronics and will not contaminate the electronics waste stream. However, a disadvantage is its relatively high environmental impact. With sand as potting material the lamp is filled with fine-grained sand, which doesn't adhere at all and has a low environmental impact. However, the processing is less common, although applied in some factories. For recyclers the amount of sand is small and the sand becomes part of the dust that is anyhow generated during the shredding process. This was not considered disturbing (J. Felix, personal communication, December 11, 2014). The essential element from a design perspective here was to demonstrate that stiffness can be an important parameter regarding the recycling result.

A small-scale shredder test using roller mill technique on the stacked lamps with potting resulted for both types of potting in very good separation of all parts. Due to the easy breakdown of the single outer connection and the absence of internal connections all parts were released without adhering to other parts, implying that sorting quality will be largely improved. Fig 9b shows this for the PCBAs, which are almost perfectly separated.



Figure 4.8- a: fragments obtained from shredding of staked LED spot lamps, b: PCB fragments after shredding when potting is added. Images provided by Johan Felix, CIT Recycling Development AB.

4.4.3 Brittle housing

In the original design as well as in both redesigns already discussed, the housing combined the structural stability to the product with heat spreading functionality. In an alternative approach, this combined functionality of housing and heat spreader was reconsidered. In this redesign, the housing is a glass envelope, identical to that of the original MR16 halogen spotlights. Heat spreading is taken care of by a deep-drawn aluminium insert. A ring at the top again takes care of connecting all internal parts by applying pressure. This lamp will be referred to as glass MR16.

Figure 4.9 shows an exploded view of the redesign with glass envelope. The lamp consists of the following main parts: polycarbonate lens, driver PCBA and LED PCBA, thermal pad, two heat spreaders, housing and connector pins. This design is very similar to the previous design strategy (see 4.3.2) where all parts are simply stacked and pressed together by a directly accessible ring at the top of the lamp. Furthermore, the housing is made of glass. This implies

that now a brittle material is used as housing, thus eliminating the risk of folding. As glass is an insulator also the need for a plastic part to isolate the connector pins from the housing is eliminated. In addition, glass has a substantially lower environmental impact than metals and plastics in manufacturing.

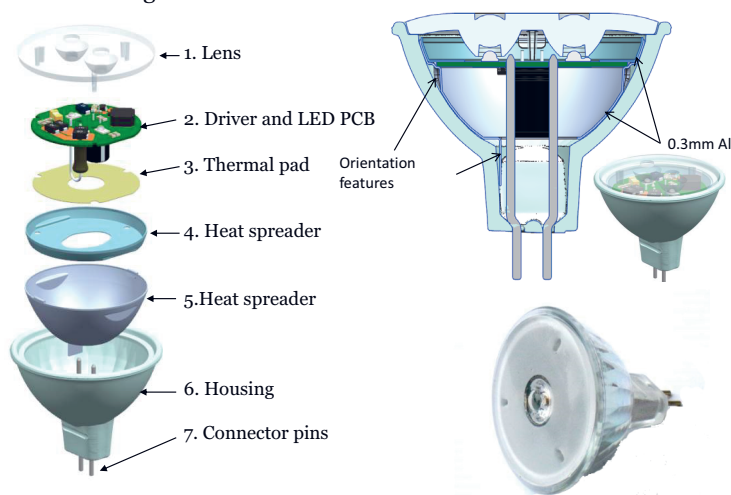


Figure 4.9- Exploded view of redesigned standard spot lamp: glass housing design. Image provided by Philips Lighting.

A small-scale shredding test with 100 pieces of the glass MR16 using the roller mill technique showed that the brittle glass house breaks into many small fragments, while all other parts essentially remain intact and can be separated as homogeneous fragments (see Figure 4.10). Although the glass fraction theoretically can also be recovered, it should be noted that glass usually is not recovered from electronic waste. This will thus limit the actual recovery in terms of weight fraction.



Figure 4.10-Redesigned spot lamp with glass housing, before and after shredding. Images provided by Johan Felix, CIT Recycling Development AB.

Summarizing, the bottleneck in mechanical disintegration of standard MR16 is the presence of the screw connection. The application of design guidelines to the redesign of the standard MR16 LED spot lamp resulted in redesigned lamps denoted here as standard MR16 with fracture lines, stacked MR16 and glass MR16. All these redesigns clearly improved the homogeneity of the fragments resulting from the shredding process, thus enabling considerably improved separation for further recovery processes. This case is especially interesting because it shows how designers in practice considered a multitude of directions to transform the limiting factor (screw connection) into a variety of design opportunities that lead to improvements in recyclability. The results that were obtained in small scale tests convincingly demonstrate that following the design guidelines for DfR enables large improvements in recyclability. Also when working within the limits given by an existing design, improvement could be envisioned in multiple directions and was successfully tested for the application of fracture lines that pass screw holes. Without restrictions on materials and built of the product, completely different design solutions can be explored, of which two successful examples have been demonstrated.

4.4.4 Bulb redesign

The design guidelines were also explicitly taken into account for the design of a A19 LED bulb that replaces a 60W incandescent lamp. However, the main assignment with this lamp was to develop the least expensive 60W LED replacement available in the market. Further, boundary condition were given by the A-bulb standard regarding the outer envelope. Heat spreading needs special attention. A 60 W incandescent lamp produces about 800 lm. A LED replacement with 145 lm/W LEDs (high efficiency grade in 2014) needs 10.5 W input power, while the heat dissipation will be about 5 W. This puts considerable demands on the heat dissipation. For the LED bulbs studied in Chapter 3 a traditional bulb geometry was used (mainly because of the fixed form factor of a light bulb) and a large and heavy die-casted aluminium heat spreader was applied to spread the heat to the lamp envelop for dissipation to ambient. Assisted by the increased efficiency of the LEDs, implying lower heat generation than by the previous generation of LEDs, the demands on heat dissipation could be met in a different way. Instead of using an aluminium heat spreader, heat spreading was taken care of by enlarging the PCBA with the LEDs. The shape of the lamp was drastically changed (while staying within the A-bulb envelop boundaries) by flattening the 'bulb', which was entirely made out of polycarbonate. In this way the enlarged PCBA was connected to the polycarbonate over a relatively large area. Heat dissipation to ambient could thus be achieved without the need of an additional heat spreader. The resulting lamp, shown in Figure 4.11, is basically a flat version of a bulb.

Easy break-down of the connections was taken care of by building the lamp from only 5 parts, i.e. the enlarged LED PCB, a driver PCB, socket and two polycarbonate parts. The latter two parts, which enclose the electronics and connect to the socket, are joined together by ultrasonic welding. The LED PCB is directly connected to the driver PCB and clamped to the polycarbonate housing.

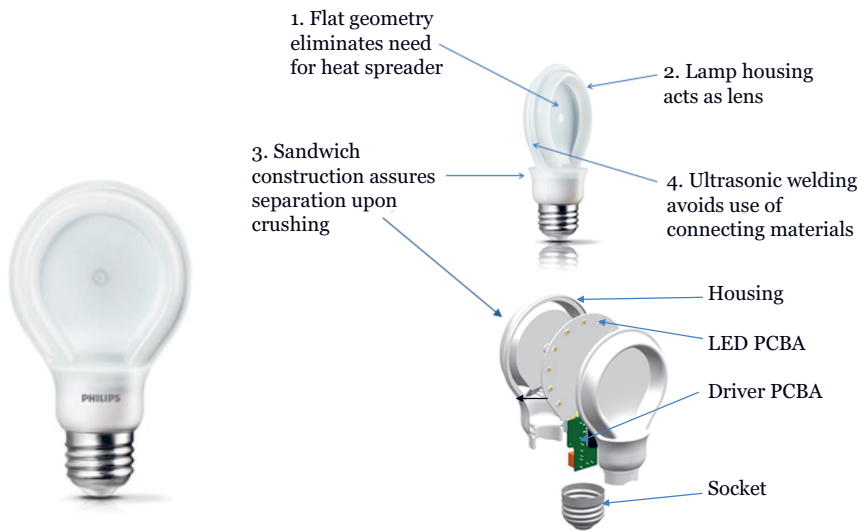


Figure 4.11-Exploded view of the SlimStyle. Image provided by Philips Lighting.

Like the other redesigned lamps, the SlimStyle lamp was subjected to a small-scale disintegration test involving 4 lamps. Figure 4.12 shows the fragments resulting from shredding of the SlimStyle lamp. As shown in the figure, the housing breaks down and all the other parts can be easily separated into proper material fractions.

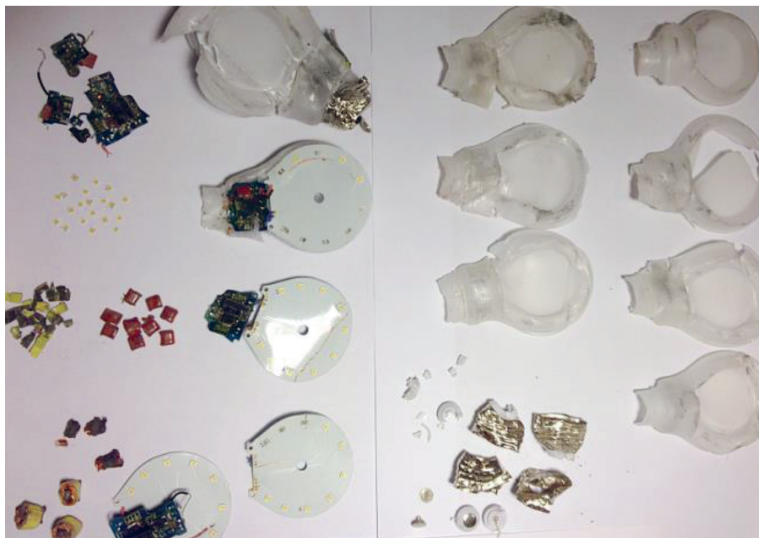


Figure 4.12-Fragments obtained from shredding the SlimStyle lamp. Images provided by Johan Felix, CIT Recycling Development AB.

The Slimstyle clearly demonstrates the ability to improve on disintegration resulting in homogeneous fragments when following DfR guidelines. This lamp is especially interesting as an example because it demonstrates the ability to combine DfR with improved performance

and low-cost price. The lamp emits light all around in contrast to the majority of the bulbs discussed in Chapter 3, which only have a hemispherical light distribution (the only exception being a lamp with a highly-complicated structure). Also, the limited number of parts and the simple construction make this a low-cost LED lamp from a manufacturing perspective. The lamp is already for several years successfully for sale in the US market. It is therefore interesting to look into the major design decisions and discuss their impact, not only on recyclability, but also regarding other aspects of interest for commercially available products. Major design decisions regarding recyclability were the small number of parts (eliminating aluminium heat spreader and separate lens), the absence of permanent internal connections and the choice for recyclable materials.

4.5 Discussion

4.5.1 Recyclability

In Chapter 3, disintegration tests were conducted in order to identify product design features that facilitate or hamper the disintegration of case study products. The insights obtained from the disintegration results were used to derive a set of generic DfR guidelines. The generic design guidelines are consistent with the generic design guidelines found in the literature review (Chapter 2). In this study, designers in case study companies were explicitly asked to utilize these generic guidelines to redesign the case study products. The purpose was to evaluate the effectiveness of DfR methods.

In this study to test the effectiveness of DfR guidelines the following cycles were carried out, as described in this chapter and in Chapter 5: 1. the case study products were subjected to manual and mechanical disintegration tests, 2. products design features that facilitate or hamper the disintegration test were identified (chapter 3), 3. insights obtained from disintegration tests led to a set of generic design guidelines, 4. these guidelines were utilized to redesign the case study products and 5. again the redesigned case study products were subjected to manual and mechanical disintegration to test the effect of the application of the guidelines (Chapter 4).

The results demonstrate that the design guidelines, when applied, are effective and lead to improved disintegration results. The generic design guidelines provided designers with the necessary information in combination with some tables with overviews regarding materials, connections and structures and their effect on recyclability, allowed them to develop various redesign solutions.

In the GreenElec project, the recycling of the materials contained in the PCBAs of LED lamps has been assessed by advanced simulations of the metallurgical processes (Reuter & van Schaik, 2015). Estimated average composition of fragments sorted into a specific waste stream was used as input. Further, average conditions for technology and operating of metallurgical processing were assumed. This is used to compare various design processing effects. The reported recovery data refer to the metal weight-fractions that are actually regained for reuse. Recovery of polymer and glass are not considered. Recovered metal fractions are determined not only by the fragment composition, but also by imperfections in the sorting process, losses due to generation of fine dust that is not sorted, and by the yield of the final metallurgical processes. This leads to inevitable losses due to the recycling processes, even in the case of perfect separation.

In the case of the standard MR16 38% of the total weight is finally recovered (whereas the original metal weight fraction of this lamp is 64%). For the lamp with fracture lines this increases to 48%, clearly showing the improved quality of the resulting fragments. The amount of metal recovered for reuse from the stacked MR16 (with an original metal weight fraction of 70%), in which the housing is folded over the electronics in the disintegration process, is 41%. This is because the composition of the folded fragments is such that the aluminium, which constitutes the largest part of the weight, is then still recovered. In comparison with the standard MR16 it should further be noted that the weight of aluminium per lamp is considerably less. Adding potting material leads to an apparently small improvement to 46%. However, it should be noted that to this lamp a considerable amount of potting material is added (reducing the metal weight fraction to 62%). In the case of the glass lamp the recovery of metal for reuse is 15% of the total lamp weight, which is compared to the initial metal weight fraction of 19% relatively high. Here the metal weight fraction is low due to the use of glass, which as such has a low environmental impact, as a housing material. This also illustrates that the use of recovered *weight* percentages can be quite cumbersome and misleading as this does not reward the use of less materials and also neglects the environmental impact of the materials used. Further, looking beyond weight percentages shows that especially the amounts of PCB-related metals increases for the properly redesigned lamps (i.e. the standard MR16 with fracture lines, the stacked MR16 with potting and the glass MR16) compared to the less ideal standard MR16 and stacked MR16. These metals, like lead, tin, silver and gold, are relatively valuable and exhibit a relatively high environmental impact. This makes the improved fragmentation, that is already interesting from a weight-based perspective, especial interesting from also the environmental and economic perspective.

4.5.2 Environmental and economic impact

Recyclability is of key importance in closing loops at the level of materials, but a focus on recyclability alone might lead to sub-optimization of the environmental impact and neglect of economic viability. Building upon the environmental and economic validation as carried out in the GreenElec project, we will therefore in this section put the recyclability results a broader context.

The recyclability and environmental impact of the MR16 redesigns have been calculated using QWERTY. QWERTY is a decision support tool for the environmental and economic planning of end of life treatment (take back systems) for materials and components from end of life electronics. The QWERTY/EE method is based on a comprehensive end-of-life unit process modelling approach that characterizes the environmental burden and processing costs of the discrete process steps in end of life treatment. This includes collection of end of life products, disassembly, shredding and separation, secondary material and final waste processing (Huisman, 2003).

In the QWERTY calculations it is assumed that the redesigned products at end-of-life become part of a large volume of mixed small electronic appliances. The recovery results are based on statistical averages for recovery rates per element present in mixed electronics waste (data supplied by major recovery companies).

The effects of the redesigns have been evaluated by assessing the net environmental burden over a complete life cycle, i.e. including recycling (Balkenende et al., 2015; Balkenende et al., 2014). This is shown in Figure 4.13. For the standard MR16 the environmental burden is

relatively high due to the losses of aluminium as well as materials present on the PCBs (Copper and precious metals). This is attributed to the incomplete fragmentation that is caused by the screw connections between the PCBs and the heat spreader. The redesigns led to an improved quality of the disintegration fragments. This reduces the losses of Al and precious metals, which results in a significantly lower environmental burden.

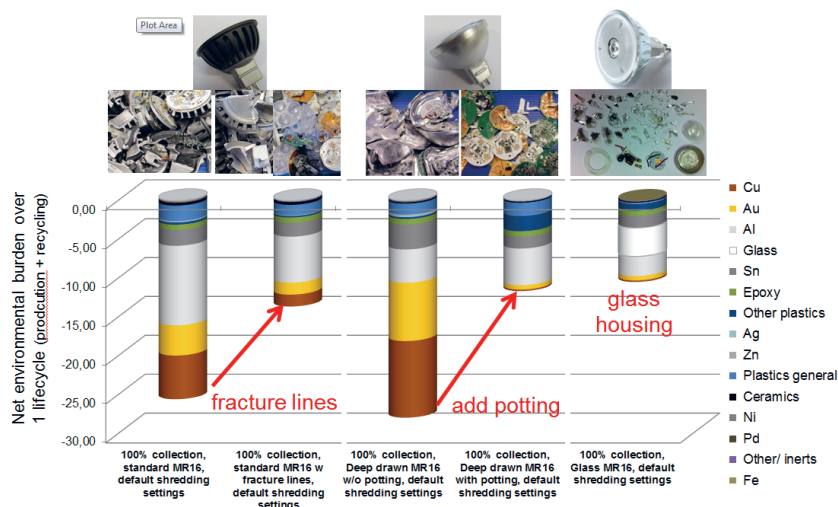


Figure 4.13-Overview of net environmental impact of various MR16/GU10 redesigns according to QWERTY analysis

The stacked design based on deep-drawn parts has a high environmental impact upon mechanical disintegration due to the folding action (as shown in Fig. 4-5a), which leads to encapsulation of PCBAs in aluminium. In recycling/recovery this results in a large loss of precious metals if it is assumed that these Al-rich fragments end in Al-recycling. By increasing the stiffness (through adding potting) the PCBAs are almost perfectly separated, resulting in a considerable reduction of losses and an associated lower environmental burden.

The case of the glass housing is particularly interesting. The brittleness of the glass results in easy separation of the constituting parts, thus limiting the losses largely to the glass as such (Figure 4.10). In addition, the glass itself has relatively low environmental impact (compared to metals and plastics). When it is assumed that the redesigned product is properly recycled, the net environmental difference with the samples based on fracture lines and stacking of parts is not large. Moreover, when it is taken into consideration that a significant fraction of small lamps does not end up in the appropriate waste stream, the losses in the case of the glass lamp will be smaller than in the other cases, simply because the amount of aluminium that can be lost, has been strongly reduced.

If, instead of using the recovered weight fractions mentioned above, recovery is expressed in terms of avoided environmental impact (again based on QWERTY data), the following results are obtained. The standards MR16 then has a 'recovered impact' score of 36%, which increases to 80% for the lamp with fracture lines. The stacked MR16 has a score of 51% (relatively low due to the folding), which increases 81% when adding potting (now the relatively low impact

of the potting material is much better expressed than with the weight percentages). Finally, the glass MR16 has a score of 80%. This indicates that from an environmental perspective all redesigns lead to a similar improvement.

For the displays environmental impact calculations are less evident as the environmental impact is mainly determined by the PCBAs present and these are all recovered due to the manual dismantling procedure that has been carried out. This implies that recovery is similar in all cases. Of course, economic feasibility of recovery in such a way will depend on the speed of the dismantling process.

4.5.3 Design practice and use of DfR guidelines

As all products have been designed by experienced design teams following their usual company procedures and considering performance and manufacturing cost as important additional parameters (and in the case of the SlimStyle even the primary parameter), all redesigns have been considered for production. In the end the Slimstyle lamp and the redesigned television have actually been taken into production. In the other cases factors not related to the direct manufacturing costs, like the need for a new supply chain or additional reliability testing, were hampering the final step towards production. An interesting case in this respect is formed by the glass MR16. Further improvements in LED efficiency in the meantime (since the redesign were made in 2014) have reduced the need for heat spreading. Instead of an aluminium insert, filling of the glass bulb with helium (a gas with a high thermal conductivity) is now sufficient. This has, due to the potential for cost reduction, led to a large number of manufacturers making glass LED bulbs.

Overall, this convincingly demonstrates that application of DfR guidelines as an addition to the normal design process, potentially leads to products that are both economically and environmentally interesting in addition to their improved recyclability.

Looking into the design process, it is of interest to note that designers carried out the design process as they were used to. Aspects like performance, product cost and manufacturability were addressed as usual. As intended, they didn't consider the design guidelines as additional requirements, but used the design guidelines to determine suitable strategies to improve recyclability. As the guidelines are generic and don't prescribe how the intentions that are expressed should be achieved, the designers were able to operate in such a way that could truly follow the guidelines. This was evident from the way in which the aims expressed by the guidelines were revisited during the design process and at the decision points within the process. Strikingly, in the case of the LED lamps this did not lead to trade-offs in the way in which the DfR guidelines were dealt with in all cases where lamps were completely redesigned (i.e. the stacked MR16, the glass MR16 and the SlimStyle bulb). In those cases that existing products are redesigned (fracture line MR16, television and medical display), limitations in the extent to which the guidelines can be applied become evident. In the case of the lamp, materials were not adapted, implying that some non-recyclable materials remain in use. Also for the television the focus was on improving connections, without significant attention for the materials used. In the case of the medical display some parts that didn't really fit to the redesign needed to be used. This actually led to a (explainable) decrease in the ease of manual dismantling. This stresses that it is important to take DfR already into account in the initial design stages. Optimal recyclability is very hard to reach when redesigning existing products.

The design guidelines as applied in this study are similar to many of the design guidelines as reported in Chapter 2. Thus, it would be expected that if such design guidelines are followed, disintegration of electronics would lead to relatively homogeneous fragments that are well-suited for further reprocessing. However, usually shredding of electronic products results in fragments that consist of materials that are not mutually compatible in the subsequent recovery processes, as was shown in Chapter 3. Therefore, it is concluded that in spite of their ability to improve the recyclability electronic products, DfR guidelines are usually not applied in practice.

4.6 Conclusion

This aim of this chapter was to investigate:

RQ3. How effective are design for recycling methods in improving the recyclability of electronic products?

To answer this question, the use of DfR design guidelines based on recycling insights has been evaluated. These guidelines are largely similar to the DfR design guidelines found in literature (Chapter 2). LED lamps and displays have been redesigned taking into account these DfR design guidelines. The redesigns were validated by conducting a manual disintegration test of redesigned displays and by small-scale mechanical disintegration tests on the redesigned LED lamps.

The evaluation of recyclability of the redesigns shows that the application of design guidelines enables improved disintegration of the redesigned lamps and television, that enables significantly better subsequent separation: resulting fragments that are homogenous or consist of materials that can be recovered from the same recycling process. This turned out to be the case for the lamps that are mechanically disintegrated as well as for the televisions, which are manually disintegrated. In the case of the medical displays the result was obscured due to boundary conditions imposed on the redesign that didn't allow for full implementation of the guidelines as well as different disassembly conditions.

The way in which the redesigns have been carried out shows how designers in practice can implement the DfR design guidelines. This basically shows that, at least for the products studied, existing DfR guidelines, if taken into account explicitly, are effective in assisting designers to improve the recyclability of electronic products. The generic nature of the design guidelines allowed the designers to consider a broad solution space and to generate a variety of opportunities.

4.7 References

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Painting by Farzaneh Fakhredin

Chapter 5: Examining the current corporate design for recycling practices of product developers and designers

5.1 Introduction

The previous chapter showed that existing design for recycling (DfR) guidelines, if taken into account explicitly, are effective in assisting designers to increase the recyclability of electronic products. The generic nature of the DfR guidelines allowed the designers to consider a broad solution space and to generate a variety of opportunities. As shown by Bovea and Perez-Belis (2012), design choices and decisions made at early stages of design process greatly facilitate or hamper product recyclability. It was shown that the existing DfR guidelines are effective in guiding this product design process. The question however remains *why* such guidelines are not applied widely in industry. This question is relevant, because electronics are still not optimally disintegrated and separated in actual recycling processes. The aim of this chapter is to investigate and analyse the current DfR practices in the GreenElec electronic companies, in order to provide insight in the reasons why product developers and designers do not seem to apply the current DfR methods. The central question of this chapter is:

RQ4. What are the current design for recycling practices, based on the experience of product developers and designers in electronic companies?

To answer these questions, a total of seven product developers and designers from Philips Lighting, Barco and TP Vision were interviewed who were involved in the GreenElec project (Balkenende et al., 2014; GreenElec, 2012). The product developers and designers had been working on the redesigns discussed in the previous chapters and were thus, at the time of the interviews, well aware of DfR guidelines and their use. The focus was to interview these front-runner companies that apply DfR and are knowledgeable in this field. Under the assumption that the challenges and opportunities these frontrunners face in relation to DfR will give a reliable impression of the DfR status in the electronics industry. Section 5.2 describes the interview development, and analysis of the interviews data. Section 5.3 introduces the Roozenburg and Eekels's (Roozenburg & Eekels, 1995) product innovation process in order to establish a common language regarding the stages of the product development process as described by the interviewees. Doing this enables direct comparison of similarities and differences of company approaches and provides background information. Section 5.4 presents the results of the interviews. Section 5.5 discusses the key findings.

5.2 Research method

Semi-structured in-depth interviews were conducted. After transcription, the interview data were analysed to find the similarities and differences in terms of content, and to draw conclusions. The interview sessions followed up by a roundtable table discussion.

5.2.1 Interview development

The interviewer developed a list of interview questions and main topics for discussion. Formulating open ended questions gave the interviewer the opportunity to explore new ways of perceiving and understanding DfR. The interviewer sent the list of questions to companies contact person one month before the actual interviews took place:

1. What are the design stages to develop a medical display/LED lamp/TV?
2. What decisions are made at each stage?
3. What are the early design stage tasks and activities?
4. What are the tools/techniques/ methods used during the early design stages?
5. At which stage are parts/materials and connections selected?
6. Until which design stage are changes to parts/materials and connections still possible?
7. Which design stage is appropriate for incorporation of recycling information?
8. Is recycling information already incorporated in the design process? If yes, which stage?
9. How should DfR methods be presented? Should they be incorporated in existing tools?
10. Do you think recycling methods can be used individually? If yes, by whom?

The interviewer requested to interview design and engineering practitioners at TP Vision, Philips Lighting and Barco, and had no further influence on the selection of the participants. The interviewees of a single company were interviewed simultaneously. Table 5.1 shows the number of interviewees per company, their role in the design process, date and place of interviews. All interviewees were aware of early stage DfR guidelines and were involved in the GreenElec project but had different levels of involvement in the project. This implies that they had a reasonable amount of background information on DfR. Prior to formal interviews, various informal interview sessions were conducted with Philips Lighting interviewees who were actively involved in setting up DfR practices in Philips. This helped with the formulation of the interview questions, and also, during the formal interviews, Philips Lighting interviewees could provide more elaborate answers to some of the interview questions. All the interviews took place in 2014, and in the interviewees' office settings. Further technical information about the interviews can be found in appendixes A, B and C.

Table 5.1-Number of interviewees participated per company, area of expertise, dates and places of interviews

Companies	Interviewees (#)	Date of interview	Place of interview
Barco	<ul style="list-style-type: none">• Project leader (1)• Research and development manager (1)• Senior product development engineer (1)	2 October 2014	Barco/ Kortrijk
Philips Lighting Philips Research	<ul style="list-style-type: none">• Mechanical engineer (1)• Principal scientist (1)	22 April 2014	Philips Lighting/ Eindhoven
TP Vision	<ul style="list-style-type: none">• Mechanical engineers (2)	27 November 2014	TP Vision/ Gent

5.2.2 Analysis of interview data

All interviews were recorded using notes and voice recorders. The recordings were transcribed and checked with the participants for accuracy. The interviews took between 42 and 87 minutes. During the interviews, some interviewees provided the interviewer with company documents related to their design processes, stages and decisions made at each stage.

During analysis the transcripts and company documents were read carefully and the relevant parts related to each interview question were highlighted, using the KJ method. By analysing the interview data, it was observed that some of the original interview questions (as stated in subsection 5.2.1) and given answers have overlap with one another. Therefore, it was decided to merge some of interview questions together for further analysis to avoid duplication and repetition of answers. Then the interviewer grouped relevant quotes, resulting in three main topics (see table 5.2). Each topic was further analysed to find similarities, differences and further insights. A schematic structure of the procedure that was used for analysing and comparing the interview data is shown in Table 5.3.

Table 5.2 - Three main topics addressed during the interviews: design process, current design for recycling practices and needs

Group 1: companies' approach to the design process and decisions	
1.	What are the design stages to develop a medical display/LED lamp/TV?
Group 2: investigating current design for recycling practices	
2.	Is recycling information already incorporated in the design process? If yes, which stage?
3.	At which stage are parts/materials and connections selected?
Group 3: needs and wishes of designers regarding incorporation of DfR in the early design stage	
4.	Which design stage is appropriate for incorporation of recycling information?
5.	How should DfR methods be presented? Should they be incorporated in existing tools?

The first topic (see step II in Table 5.3) aims to collect background information about the way the company's plan their product development process and the relevant decisions made at each stage. It was important to 'translate' terms used by interviewees into a common language. For this purpose, Roozenburg and Eekels's description of the product innovation process was used (see Section 5.3). The second topic aims to collect information about current DfR practices in Barco, Philips Lighting and TP Vision. The third topic aims to collect information about needs and wishes of designers regarding incorporation of DfR in the early design stage.

Table 5.3-Schematic structure of the procedure that was used for grouping, analysing and comparing the interviews data

<i>Step I: Fining answers per interview question, per company</i>			
Interview questions	Barco	Philips Lighting	TP Vision
The first list of interview questions as stated in subsection 5.2.1 is condensed to the list questions in Table 5.2	Answers	Answers	Answers
↓			
<i>Step II: Grouping the interview questions based on specific topics for comparison and drawing conclusions</i>			
Topics	Comparison and conclusion		
1. Company's product development process	<ul style="list-style-type: none">• Comparing the answers to find similarities and differences• The comparison of case companies to generate insights		
2. Investigating current design for recycling practices			
3. Needs and wishes of designers			

5.2.3 Roundtable discussion

Interviews were followed up by a roundtable discussion held in TP Vision headquarters in Bruges, Belgium on 15th July 2014. Participants attended the roundtable discussion included one or two representatives from TP Vision, Philips Lighting and Barco, of whom at least one participated in the interview sessions. Further, participants from Delft University of Technology and Netherlands Organization for Applied Scientific Research (TNO) were also present with relevant expertise to the topic of DfR. During the roundtable discussion, designers from Barco, Philips Lighting and TP Vision were asked to what extent they feel they can influence the DfR process within their companies.

5.3 Roozenburg and Eekels' product innovation process description

In order to discuss the result of interview topics and compare the three product innovation processes, it was important to use a framework for consistency in terminology. This is because different companies name their phases differently. For this reason, the Roozenburg and Eekels's model of the product innovation process has been selected. It is called product innovation process because it consists of all the activities which lead to the introduction of a new product to the market that differs from earlier products. As shown in Figure 5.1 according to Roozenburg and Eekels the product innovation process is composed of four main phases: policy formulation, idea finding, strict development and realization.

In the policy formulation phase, the producer of the product checks internally and externally if the new product meets its promises. A good or bad experience will change the consumers' behaviour and can lead to changes in advertisement, changes of price, changes in product or the worst case withdraw of the product. Based on the brand and mission of the company and feedback from consumers needs and market, it will be decided if further development of a product is welcomed or updating and changes are required. The analysis of the internal core competencies and external opportunities in the market leads to goals, priorities, strategic ideas about the future (Roozenburg & Eekels, 1995).

In the idea finding phase two elements come together: 1. technical possibilities and 2. market needs (derived from policy formulation phase). In this phase, more detailed analysis of consumers' needs, market information, company competencies and priorities are conducted to generate product ideas. At this stage, many ideas are freely and widely generated. Various ideas will be evaluated according to a list of criteria. After detailed evaluation of various product ideas, the most promising product and service ideas will be formulated in the official design brief for further development. The design brief is composed of the important features, delivery date, target client, functions, technologies, cost and competitive offering of a product (Roozenburg & Eekels, 1995).

The "strict development" stage starts with a "new product idea". At this phase, the promising ideas evolve into detailed plans for product designing, production development and marketing planning. During product designing, materials, connections, shape and dimensions of parts, arrangement and position of parts and subassemblies are specified. The production development includes making different parts of a product and their assembly. Various possible choices and options are considered at this stage of the design process. Marketing planning outlines a company's advertisement and marketing effort to launch the "new product idea" to the market. Product design, product development and market plan interact and integrate with one another at this phase to be able to estimate the technical and economic feasibility of a new product idea. This can be an iterative process until the detailed planning is complete and fit together. It will also increase the quality of the product. The outcome of this phase is a prototype (Roozenburg & Eekels, 1995).

The realization phase is concerned with production, distribution, sale and use of the product. At this phase, detailed plans change to reality and the product is placed on the market. In the final phase the business case will be assessed and become input to the policy formulation stage again (Roozenburg & Eekels, 1995).

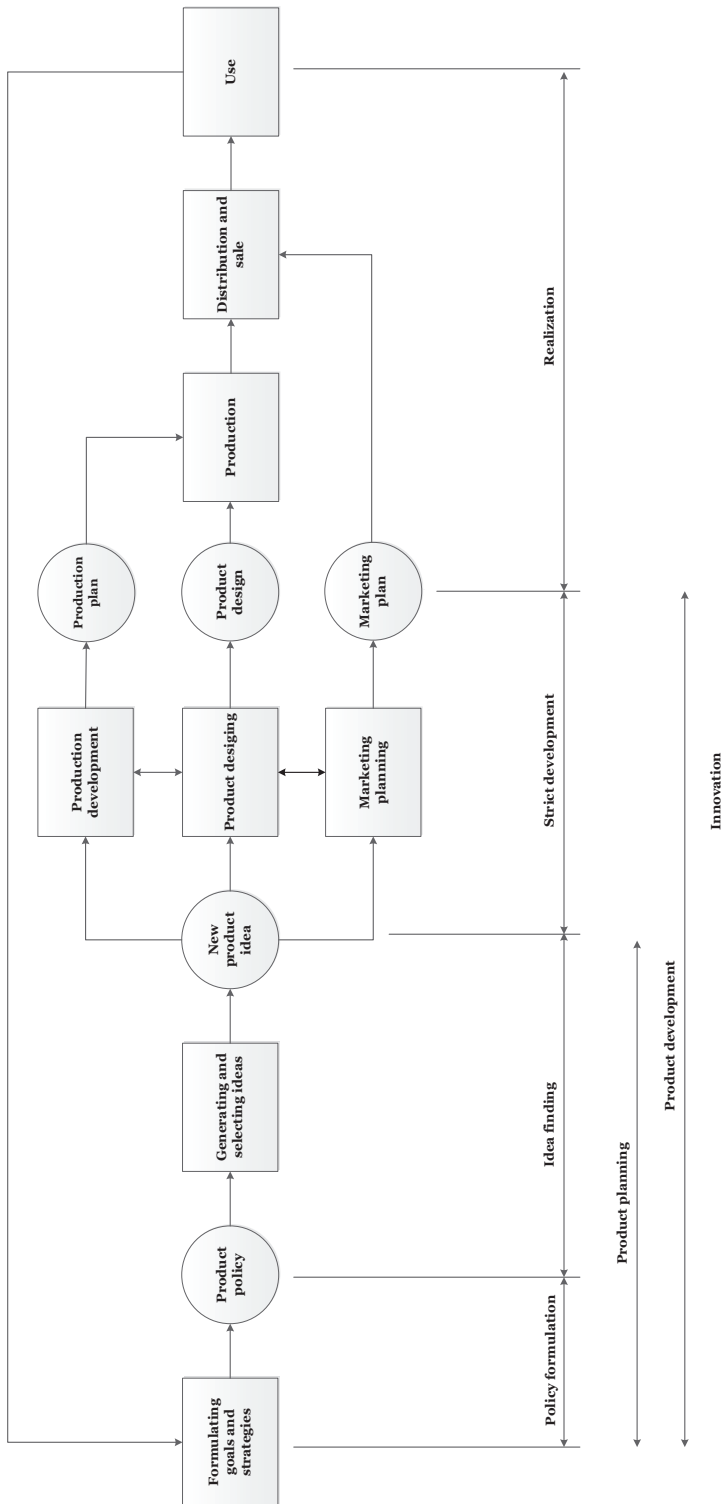


Figure 5.1- The four phases of the product innovation process (Roozenburg & Eekels, 1995)

5.4 Results

Table 5.2 summarizes the three main topics and their corresponding interview questions that will be consecutively addressed in subsections 5.4.1, 5.4.2 and 5.4.3. Further, subsection 5.4.4 reports the results of the roundtable discussion.

5.4.1 Companies' approach to the design process and decisions

In general, there is a similar pattern between the three companies in terms of activities and decisions made throughout the entire product development process. Normally, it starts with project definition, followed by a draft of specification and requirements, concepts development, embodiment design, validation and pilot studies, mass production and phase out. This is in line with the four phases of the Roozenburg and Eekels's product innovation process. In Table 5.4, the Barco, Philips Lighting and TP Vision's design stages are mapped on the Roozenburg and Eekels's product innovation process.

Table 5.2- Mapping Barco, Philips Lighting and TP Vision design processes on Roozenburg and Eekel's product innovation process to establish a common language which enables comparisons between the various answers (note: all the answers are derived from companies' documents and transcripts)

Roozenburg & Eekels	Barco	Philips Lighting	TP Vision
Policy formulation	Business Case Evaluation: product management team agrees on the project definition, fix responsibilities, discuss the risk and revenue associate with the project.	Project Definition: "Obtain a clear understanding of the assignment, allocate resources and agree on the initial project plan." (Company document)	Not mentioned
Idea finding	<u>Preliminary Design Prestudy</u> : Draft the requirements and the specifications of the product. In fact, at the end of this stage it should clear what is going to be made and there should not be any major risks anymore. If it is known and well discussed then it is possible to develop various design options without problem."	<u>Requirements Architecture & Design</u> : "Complete all relevant requirements, define scope of application in target markets, select architecture and building block re-use, choose product concept, commit to final project planning, including a committed business case and market introduction plan." (Company document)	<u>Finished design</u> : Finished design means a complete TV shell is designed, developed and is ready to be filled in by mechanical parts.
Strict development	<u>Prototyping</u> : The aim of this stage is to evaluate various design options. Evaluation of different design options is based on testing, simulations, building prototypes, peer review meetings and pros and cons of various design options on all aspects and develop different design concepts. It is in fact mostly a group decision weighting of all the pros and cons from different choices. By end of Prototyping stage most of the time the electrical and mechanical choices for platforms are frozen sometimes with a prototype. The purpose of prototyping is to investigate if the new design will work. This stage is also known as detailed design stage.	<u>Realization & Verification</u> : "Finalize product design to meet requirements, verify specifications on full functionality, complete technical documentation." (Company document) <u>Validation and Pilot</u> : "Validate specifications, optimize for manufacturing, prepare pilot-run, ensure supply chain, define final product costs, complete commercial documentation." (Company document)	<u>Model stage</u> : After this stage, in one to three weeks the first fully operational model will be made. By this stage, a list of all subassemblies and different parts that are needed in a TV become clear. The main reason to make the first operational model is to make a visual and tangible experience of the TV set. The lessons learnt from the model leads to product optimization. In fact, the first model is not also the last model that is going to be launched in the market. While, depending on the complexity of the project two to three more models are developed before the final market launch. The aim of the second or third model is to do some adaptations to the first model and make it work better.

	<p><u>Qualification Zero-series:</u> After prototyping stage, the first series are developed together with production unit/ production department at qualification zero-series stage. the aim of this stage is to validate production process.</p>		<p><u>Test plan:</u> After the model stage a complete test plan is crucial to check on heat and noise or make sure if it is robust enough. After the test, there are two possibilities:</p> <p><u>Final prototype:</u> Either the evaluation of the final prototype will be based on the models and the prototype is ready to be launched in the market. The final outcome of this stage is a prototype which is ready for mass production.</p>
Realization	<p><u>Production Series:</u> After validation of the prototype the next stage is production series, that is already when mass production starts and a product is introduced to the market.</p> <p><u>Phase Out:</u> The last phase is phase out when the production of the product stop.</p>	<p><u>Start Up Production:</u> “Finalize approbation, pilot production, verify product quality, complete all supporting systems.” (Company document)</p> <p><u>Ramp Up Production:</u> “Support manufacturing and sales to achieve business objectives, transfer documentation and knowledge.” (Company document)</p> <p><u>Product Maintenance:</u> “Update product definition where needed, organize release testing, keep documentation up-to-date.” (Company document)</p>	<p><u>Market study:</u> or the model will be first launched in big commercial events like CES fair or the IFA fair to receive feedback from the market. There are cases that the design of the final model is not appreciated and big changes are crucial.</p> <p><u>Mass production:</u> mass production starts by contacting suppliers and many different parts of the organization that need to be involved.</p>

5.4.2 Investigating current design for recycling practices

Referring to Table 5.5, Barco, Philips Lighting and TP Vision interviewees state that compliance with the RoHS directive (RoHS Directive, 2011) has been the main DfR activity so far. In case of Philips Lighting, DfR guidelines are only practiced in a few product case studies related to European recycling projects (e.g.: GreenElec). But generally, in all three companies, recycling information is not formally incorporated into the design process beyond compliance.

Table 5.3-Recycling information incorporated into the design process

Interview question	Barco	Philips Lighting	TP Vision
Is recycling information already incorporated in the design process? If yes, which stage?	<ol style="list-style-type: none"> 1. Recycling is not formally incorporated into the design process. 2. Complying with RoHS directive. 3. No guidelines. 4. Not part of product specification list. 	<ol style="list-style-type: none"> 1. Complying with RoHS directive. 2. Design guidelines. So, from a recycling perspective it is better to incorporate the design guidelines at early design stage on a general level without too much detail that extends the list of guidelines. 	<ol style="list-style-type: none"> 1. TP Vision complies with RoHS directive on usage of certain materials which are not environmentally friendly. 2. There is no recycling guideline, checklist or tool applied. 3. There is an expert in the organization who keep tracks of the latest rules and regulations in terms of recycling and environmental issues.

As discussed in Chapters 2 and 3, material and connection selection are essential to enhance product recyclability and are considered as core activities of DfR practices. Referring to Table 5.6, all the interviewees stated that materials and connections are selected at early phases of design process, in particular in the “idea finding” and “strict development” phases, but changes are still possible until realization phase before the product is launched to the market. However, as the product development process proceeds, making changes to material or connections becomes increasingly more expensive.

Table 5.4-Materials and connections selection

Interview question	Barco	Philips Lighting	TP Vision
At which stage are parts/materials and connections selected?	<p>Selection of materials and joints happens at prototyping stage (strict development phase).</p> <p>By end of prototyping stage (strict development phase) everything should be frozen. However, changes are still possible until the production series stage (Realization phase).</p>	<p>Joints are selected at requirements architecture and design stage (idea finding phase), materials are selected at realization and verification stage (strict development phase).</p> <p>At realization & verification stage (strict development phase) choices become really detailed but until that there is a certain fuzziness and design cycle on purpose to go back and forth between requirements architecture and design stage (idea finding phase) and realization and verification stage (strict development phase).</p>	<p>Mainly finished design (idea finding) and modelling stages (strict development phase).</p> <p>Changes are still allowed until the mass production (realization phase). Meaning that before the market launch, changes are still possible. However, it is better that change happens in the first and second models (by end of strict development phase). Otherwise, it costs a lot of money to make big changes after second model, and it is better to avoid it.</p>

5.4.3 Needs and wishes of designers regarding incorporation of DfR in the early design stage

Through the interview sessions at Barco, Philips Lighting and TP Vision it has been found that there are three phases of the product innovation process namely “policy formulation phase”, “idea finding phase” and beginning of “strict development” where DfR could most effectively be embedded. The ideal would be, as the TP Vision participant stated, that DfR “should be a mindset” that would influence the product design right from the start. All interviewees agreed that incorporating recycling information should start at the beginning of the product development process, and could involve business case review meetings, specification list, sketching, brainstorming, pre-studies, first models and prototyping review meetings. Table 5.7 lists the main results.

Table 5.5-The appropriate design stages to incorporate recycling information

Interview question	Barco	Philips Lighting	TP Vision
Which design stage is appropriate for incorporation of recycling information?	<ol style="list-style-type: none"> 1. At business case evaluation (policy formulation phase) review meeting for quick reviewing. 2. In preliminary design pre-study (idea finding phase) in the specification list. 3. Before prototyping (strict development phase) final review meeting because after this meeting the product is frozen and redesigning the entire work is a waste of time and money. 	<ol style="list-style-type: none"> 1. During three sub-stages between idea finding and strict development phases: a. Sketching when designers freely generate ideas with a pen and piece of paper (Idea). b. Brainstorming session: adding criteria for recycling in criteria matrix (criteria) and assign a person for checking on that and c. Morphological chart and different design concepts. 2. Another possibility is to incorporate the recycling information on a prototype, but that is already outside conceptual design stage since in that case it is just a validation that it does not play a role anymore in the actual design (end of strict development phase). 	<ol style="list-style-type: none"> 1. It should be as a mindset even before starting the design to make the incorporation possible. 2. By creating of the first model (= strict development phase) the discussion about recycling information and decisions have to be finalized and everyone have to be clear. 3. The recycling information is not relevant for finished design stage (idea finding phase). Mainly because in this stage designers select certain material as finishing look of the shell. They do not know anything about the inside construction, for example how two different parts are going to be connected inside the shell, or how the inside parts are going to be connected to the housing/shell/external design. However, recycling information is more useful for model stage because it is only in this stage that engineers have insight on design of internal parts, and the way in which they are connected to each other and the shell.

Assuming that DfR would be considered strategically important for the company, the interviewees proposed various ways to present DfR information during the product development process. Table 5.8 lists the main results.

In general, the interviewees felt that additional training and tools would be helpful. Barco states that “presenting, training and a new tool are interesting”, “a new tool should inform the engineers on what is possible, what choices can be made”, and “.. so indeed we need to be educated .. we need to have some tools which guide us”. Further, Philips Lighting proposed the use of “a simple look up table before/during brainstorming/peer review meeting session which takes only 1 to 2 min to scan”, and TP Vision said “thinking about recycling should be part of the mindset”. Also, TP Vision stated that “the best thing is to have a kind of design guideline, rules to take in mind when developing the set.”.

There was also a need for more detailed recycling information. For example, Barco states that they need a new DfR method that says “certain design options are not good” and “how will their design choices influence the outcome”. Further, Philips Lighting states that they need “look up tables to rate various concepts and find a design scenario which is most recyclable”. And lastly TP Vision states that they need an “ecological footprint of recycling”.

Beside the above options interviewees had other wishes: Barco stated that general DfR tools are preferred over company specific tools. That is because normally the company specific tools are customized, and the company remains responsible for development and maintenance, which are costly and time consuming. Philips Lighting and TP Vision state that a new DfR method should be quick and simple without providing too much detail, to prevent it from adding to designers’ workloads.

Table 5.6-Presentation of design for recycling methods

Interview question	Barco	Philips Lighting	TP Vision
How should DfR methods be presented? Should they be incorporated in existing tools?	<ol style="list-style-type: none"> 1. Presenting, training and a new tool are interesting. 2. A tool which says certain things are not good or recommends better options. 3. Guidelines are useful. 4. A new tool should inform the engineers on what is possible, what choices can be made, how will that influence the outcome, so indeed, we need to be educated we need to have some tools which guide us. 5. General tools are preferred over company specific tools. By company specific tools we mean tools that are specifically designed for products, materials and joints that Barco uses. The reason is because normally the company specific tools are customized, and the company is responsible for its development and maintenance. As a result, most of the time the tools are outsourced. 6. The presentation of a new tool or method depends for which stage of design process it is developed. Meaning that different stages of design process could lead to different form of presentation of a new tool. 	<ol style="list-style-type: none"> 1. A simple look up table before/during brainstorming/peer review meeting session which takes only 1 to 2 min to scan followed by an assembly tree for visualization. 2. Another way is to develop various design options/paths with morphological chart (generate different concepts), and then based on look up tables rate various concepts and find a design scenario which is most recyclable, and further develop prototypes based on the outcome of morphological chart. 	<ol style="list-style-type: none"> 1. Thinking for recycling should be part of the mindset. 2. The best thing is to have a kind of design guideline, rules to take in mind when developing the set. For example, a specific part has to be easily detachable or avoid certain materials. 3. An ecological footprint of recycling would be interesting too. What is the environmental burden during recycling of certain metal. 4. A tool for complete system/product will not work. Developing a tool which gives information for every single part will be a lot of work, while designers do not have the time. Because in three weeks designers and engineers have to come from scratch to a final working model. Therefore, adding extra workload. (design guidelines or tools in very detailed level will not work). 5. It should be something really fast simple, and only a final check if anything missed.

5.4.4 The result of the roundtable discussion

During the roundtable discussion, some of the interviewed designers explained how they personally explored ideas to improve product recyclability - throughout the design process - by framing it as a direct company interest. For instance, designers in TP Vision clearly stated DfR as one of the requirements in the design brief of a product. Further, designers in Philips used design for sustainability rules and searched for different material options and design alternatives (i.e. modular designs) to improve environmental impact and recyclability of a product which could at the same time reduce the cost the product. Barco improved the serviceability/repairability of a product, which at the same time can facilitate manual disintegration of the product during the recycling process. These, of course, only has a limited impact as it only affects products in which these designers are directly involved, and the success of such measures is highly dependent on the designer's personal motivation to engage with sustainability and recycling issues.

5.5 Discussion and conclusion

This chapter aimed to answer the following questions:

RQ4. What are the current design for recycling practices, as experienced by product developers and designers in electronics companies?

All interviewed designers stated that their companies do not have a strategic focus on recyclability. Compliance with directives, especially regarding potentially hazardous materials, is usually the main reason to engage with sustainability issues. This implies that taking into account recyclability is not explicitly asked for in the design briefs. The designers do therefore not have a direct incentive to take DfR into account. During the roundtable discussion the designers also explained that they could explore ideas to improve product recyclability by framing it more in terms of direct company interest, such as design for improved assembly or design for minimum value loss at end-of-life. This, of course, only has a limited impact, as it only affects products in which these designers are directly involved. Interviewed designers also stated that the DfR methods are not easily accessible to designers and mostly are not comprehensive. Only well-informed designers will be able to find and combine the suitable methods. In the interviews it was indicated that access to a more heuristic methodology ("quick and dirty") was desirable, especially in the early design stages.

The conclusion drawn from this study is supported by the findings from Deutz et al. (2013); Waage (2007); Boks (2006); Åkermark (2003) and Stoyell et al. (1999) who stated that electronics industry is mainly focused on compliance with directives, and without these directives DfR activities is not likely to get a lot of priority during product development and design. However, Ueda (2015); Deutz et al. (2013) and Åkermark (1999) in their studies showed that there are designers who are individually proactive and have serious personal concerns and knowledge about environmental issues. They further conclude that designers' personal willingness to participate in DfR and environmental initiatives is necessary but not enough, as DfR requires more proactive drivers (Stoyell et al., 1999) and more design-related regulatory requirements (Deutz et al., 2013; Deutz et al., 2010; Lindahl, 2009; Waage, 2007; Åkermark, 2003) in order to be implemented. The most apparent opportunities and challenges

for electronics companies to apply DfR to the design of electronic products will be discussed in more details in the next chapter.

A limitation of this interview study is the number of interviewees. Conclusions are drawn based on insights provided by seven product developers and designers of electronic products, and therefore the results may not be generalizable to other product developers, designers and companies in electronic industry who may have different level of understanding and involvement in DfR activities. It is important to note that the results of this study are just what interviewees at that moment in time wanted to highlight, and not necessarily provide the complete overview of how the company acts. Not in term of design stages and also not in term of what they do in specific stages. For future studies, it would be interesting to see if similar findings emerge from interviewing a larger sample size of product developers and designers in more diverse sample of electronic companies. Doing this will provide a more comprehensive understanding of current DfR practices and product developers, designers and electronic companies' efforts toward DfR.

5.6 References

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Chapter 6: Understanding the effects of societal and business context of companies on implementation of design for recycling

6.1 Introduction

Chapter 4 showed that actual product recyclability of electronics can be improved if designers take into account the design for recycling methods, but from interviews with selected designers as reported in Chapter 5, it became evident that in practice this often is not the case as design briefs usually do not pay attention to design for recycling beyond legal compliance. This indicates that the interviewed designers are not encouraged to apply design for recycling methods. In order to understand why DfR methods are often not applied in actual design practice, it is important to find out the drivers and barriers associated with it from business and societal perspectives. Therefore, the central question of this chapter is:

RQ5. What factors stimulate or hinder the application of design for recycling methods by electronics producers in general?

To answer this question, a literature review on the drivers of and barriers to application of DfR in companies was conducted. Section 6.2 describes the research method. Sections 6.3 and 6.4 elaborate the main drivers and barriers. Section 6.5 puts the findings of previous chapters into a broader societal and business context and discusses why the combination of all drivers and barriers often does not lead to application of design for recycling methods.

6.2 Research method

The literature search started by formulating the research question of this chapter: what are the drivers and barriers which producers of electronics perceive as stimulating or hampering the application of design for recycling to the design of electronic products. In the next step, to conduct keyword search, the research question broke down into its main topics. In this case, the main topics are: drivers, barriers, design for recycling, producers and electronics. Then, a thesaurus was consulted to develop a list of synonyms for the main topics.

Table 6.1-Determining the key topics and identifying more search terms for each of key topics

Topic 1: Drivers	Topic 2: Barriers	Topic 3: Design for recycling	Topic 4: Producers	Topic 5: Electronics
Stimuli	Challenges	Eco-design	Business	Electrical and
Motivations	Constraints	Resource efficiency	In industry	electronic
Opportunities	Obstacles	Design for sustainability	In industrial	(products/equip
Solutions	Difficulties	Design for environment	companies	ment)
Benefits	Drawbacks	Sustainable product	Companies	Electric and
Motives	Restrictions	development	Small and	electronic
Stimulators	Preventions	Environmental	medium	Electronic
Critical	Limitations	management	enterprises	products
success factors	Hinder	Eco-efficiency	Large companies	Electrical
Driving forces		Green innovation		
Stimulate		Sustainable		
		manufacturing		
		Ecology and green		
		innovations		
		Sustainability		
		Environmental processes		
		Environmental strategies		

The reason for identifying synonyms for main topics is because different authors may refer to the same topic with different wording. The aim was to develop a list of possible ways these topics could appear in literature. To prevent missing other keywords, the key topics (e.g.: drivers, barriers and design for recycling) were searched for in Google Scholar, then the titles, abstracts and results were scanned and skimmed to look for other possible keywords and were further added to Table 6.1.

In addition to literature focused on design for recycling, the literature describing the drivers and barriers that affect implementation of eco-design, environmental management, sustainable product development, design for sustainability, eco-efficiency, green innovation and other similar topics were also examined as listed in Table 6.1. This is because design for recycling falls under the umbrella of design for environment, and therefore the drivers and barriers of design for environment encompass the topic of design for recycling. Also, few research studies were found that particularly investigate the drivers and barriers of design for recycling (Marwede et al., 2016; TNO, 2014; Tojo, 2001); the majority of papers focus on drivers and barriers of design for environment in general which makes the review of the umbrella topic essential.

First, publications about drivers for design for recycling (topic 1 and topic 3 as presented in Table 6.1) were searched. Then, articles about barriers for design for recycling (topic 2 and topic 3 as presented in Table 6.1) were searched. Further, drivers, barriers and design for recycling (topic 1, topic 2 and topic 3) were combined using Booleans and truncations. This led

to articles that contain all the three topics. The literature search process was repeated with combinations of all other terms presented in Table 6.1.

Scopus, Proquest, Web of Science, JStor, Google Scholar and Narcis were searched for peer reviewed English-language studies covering the timespan between 1993 and 2016. Further, legislative and government databases (European Commission) were also searched for relevant information. A large number of papers are published regarding drivers and barriers for implementation of design for recycling, eco-design and other related topics in companies. The most relevant papers were selected based on the following criteria:

- the authors claim that they have studied drivers and/or barriers of design for recycling or similar topic like eco-design, etc.
- the terms drivers and/or barriers or their synonyms are explicitly mentioned in the title, abstract and/or result sections of the publications.
- The subject and content of the publications is relevant and discuss one or more particular drivers and barriers, even if the publication title and abstract doesn't contain the words drivers, barriers or their synonyms.

When assessing reliability, it was made sure key authors, key publishers and high cited papers are also included among the selected literature sources. Table 6.2 shows the number of publications assessed in this chapter per reference type.

It is important to note that out of 41 reviewed studies, 32 studies focused on electronics sector. The reviewed studies also focused on other sectors such as automobiles, packaging, textiles, foods and drinks, aerospace, transportation, paper and printing. Including other industrial areas in this study enabled us to developed a broader perspective on companies' drivers and barriers. Especially since there is no reason to expect that drivers and barriers at societal and business context of electronic companies will be different from any other product areas. Literature review papers were reviewed until saturation of data was achieved. Saturation is the point at which data with respect to companies' drivers and barriers replicates and sampling more papers did not necessarily lead to new information related to the main research question.

Table 6.2- Number of publications per reference type

Reference type	#
Journals	21
European commission reports and directives	6
Reports	5
Conference papers	4
Doctoral dissertations/ thesis	4
Books	1

6.3 Results: drivers for implementation of design for recycling

Only two publications addressed design for recycling as such (TNO, 2014; Tojo, 2001). However, the comparison of drivers of design for recycling mentioned in TNO (2014) and Tojo (2001) with the eco-design drivers mentioned in the rest of reviewed references shows that drivers of eco-design and design for recycling match to a large extent. Drivers are classified into internal and external ones. External drivers are those factors imposed on a company from outside that shape the company's attitude toward design for recycling. Internal drivers are those factors that emerge directly from inside of companies through companies' internal culture and values, commitment to environmental issues and whether they have concerns regarding the recyclability of their products (Boks, 2006; Van Hemel & Cramer, 2002). According to these authors, without understanding the internal drivers, it would be difficult to manage the pressures originating from outside the companies. The following subsections (6.3.1 and 6.3.2) identify and elaborate the most mentioned internal and external drivers that affect implementation of design for recycling.

6.3.1 External drivers

Table 6.3 summarizes the external drivers for implementation of design for recycling identified through the consulted body of literature and grouped into 5 major external drivers: regulations, customer demand, pressure from competitors, suppliers' development, and pressure from business associations. In the literature examined, regulations and customer demand are repeatedly addressed as the most powerful external drivers. These two main external drivers will be discussed in more detail.

Table 6.3- External drivers that foster implementation of design for recycling as identified in literature sources and number of times referred to in literature sources

External drivers	References	#
The need to comply with European Union regulations which require producers to enhance the recyclability of electronic products	TNO (2014), Epstein and Buhovac (2014), De Medeiros et al. (2014), Agan et al. (2013), WEEE directive (2012), Veshagh et al. (2012), RoHS Directive (2011), Fernández-Viñé et al. (2010), Lauridsen and Jørgensen (2010), Ecodesign Directive (2009), Bhamra (2004), Jeganova (2004), Dalhammar et al. (2003), Van Hemel and Cramer (2002), Tojo (2001), Azzone and Noci (1998), McAloone (1998), Post and Altma (1994)	18
Demand for recyclability and environmentally friendly products from customers at the consumer and industrial market	Iranmanesh et al. (2018), De Medeiros et al. (2014), TNO (2014), Agan et al. (2013), Veshagh et al. (2012), Fernández-Viñé et al. (2010), Boks (2006), Zutshi and Sohal (2004), Bhamra (2004), Jeganova (2004), Dalhammar et al. (2003), Johansson (2002), Van Hemel and Cramer (2002), Tojo (2001), Azzone and Noci (1998), McAloone (1998)	16
Pressure from competitors who already improved recyclability of their products and/ or launched recyclable products to the market	Jeganova (2004), Dalhammar et al. (2003), Van Hemel and Cramer (2002), Azzone and Noci (1998), McAloone (1998)	5
Suppliers offer materials, components and parts that enhance products recyclability	Bhamra (2004), Van Hemel and Cramer (2002), Johansson (2002)	3
Pressure from business associations which are founded and funded by producers that operate in electrical and electronic equipment sector and set environmental standards within the sector	Fernández-Viñé et al. (2010), Van Hemel and Cramer (2002)	2

Compliance with regulations

A significant body of literature indicates that compliance with law, directives and other regulations is the foremost important driver externally imposed on companies to act on design for recycling (see references in Table 6.3). Companies must fulfil the minimum requirements posed by these directives, otherwise the companies are subject to penalties, fines and legal costs (Epstein & Buhovac, 2014; Agan et al., 2013; Veshagh et al., 2012).

An important requirement with respect to recycling is producer responsibility. In the EU, producers are physically and financially responsible for all activities and processes related to the waste of the products they produce. This is called Extended Producer Responsibility (EPR). The establishment of EPR within the Waste Electrical and Electronic Equipment (WEEE) directive is meant to motivate producers to encourage design and production of electronics for end of life treatment (WEEE directive, 2012; Lauridsen & Jørgensen, 2010).

The WEEE directive for instance demands the removal of batteries at end-of-life. The directive also requires companies to decrease the amount of e-waste that goes to landfill or incineration at end of life stage. This is achieved through better collection and treatment of e-waste at end of life phase by setting collection rates and recovery and recycling targets for WEEE. Referring to ANNEX V and as calculated based on Article 11(2) of WEEE directive, starting from august 2015, minimum recovery targets must be between 75% and 85% and minimum preparation for reuse and recycling targets must be between 55% and 80% conditional to the type of electronic product (Seyring et al., 2015; WEEE directive, 2012).

Further, the recast WEEE directive encourages producers of electronic products to design products that can facilitate dismantling, reuse and recycling processes of WEEE (WEEE directive, 2012). This is clearly stated in the following quote from WEEE directive:

“Member States shall [...] encourage cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating re-use, dismantling and recovery of WEEE, its components and materials. In this context, Member States shall take appropriate measures so that the ecodesign requirements facilitating re-use and treatment of WEEE established in the framework of Directive 2009/125/EC are applied [...]” - Article 4 of the recast WEEE Directive 2012/19/EU.

The WEEE directive, does not further give any concrete recommendations on how to improve product recyclability and leaves it up to member states to develop and implement specific measures to facilitate DfR.

The Restriction of Hazardous Substances (RoHS) directive affects the material choices a designer can make by restricting, reducing or substituting harmful/toxic materials. For producers of electronic products this means to restrict and/or reduce the content of hazardous substances including mercury, cadmium, lead, polybrominated diphenyl ether (PBDE) and hexavalent chromium, polybrominated biphenyls (PBB) or substitute certain quantities of hazardous materials with safer materials in electrical and electronic equipment (RoHS Directive, 2011).

The Ecodesign Directive (2009), finally, aims to decrease energy use and other negative environmental impacts of electronic products (European Commission, 2018b;2009). Beside energy-related requirements, Ecodesign Directive (2009) contains a number of parameters for assessing and enhancing product recyclability, as mentioned in the following quote:

“ease for reuse and recycling as expressed through: number of materials and components used, use of standard components, time necessary for disassembly, complexity of tools necessary for disassembly, use of component and material coding standards for the identification of components and materials suitable for reuse and recycling (including marking of plastic parts in accordance with ISO standards), use of easily recyclable materials, easy access to valuable and other recyclable components and materials; easy access to components and materials containing hazardous substances.” – Annex I of Ecodesign directive 2009/125/EC

All these directives have clear statements about the important role of product design in facilitating the recycling process. Such statements within the directives could affect design choices and decisions and shape the boundary conditions for effective design for recycling tools and methods.

Customer demand

The literature studies point to customer demand as the second most important driver for implementation of design for recycling (see references in Table 6.3). Developing a new product or redesign projects typically starts with needs analysis that aims to understand customer needs and requirements related to product design (Jeganova, 2004; McAloone, 1998). If there is a customer demand - either from consumers or professional purchasers - regarding design for recycling, then it is companies' responsibility to convert customer demands into product specification list and give it a high priority during the design process (TNO, 2014; Jeganova, 2004; Zutshi & Sohal, 2004; Bhamra, 2004; McAloone, 1998).

Iranmanesh et al. (2018), Agan et al. (2013), Azzone and Noci (1998) and Dalhammar et al. (2003) findings show that consumers put demand on electronic producers, and electronic producers put demand on their suppliers to act on design for recycling. In their studies, Dalhammar et al. (2003) found examples where producers of electronic products set requirements for suppliers based on anticipated legislations or based on their environmental strategies.

Further, in recent years, a growing amount of attention has been devoted to end of life of electronics and design for recycling issues by NGOs and media. NGOs and media play an important role in creating awareness, introducing successful products designed for recycling and encouraging consumers to support these products and suppliers who have design for recycling concerns. The NGOs and media do this by closely monitoring the end of life management and DfR activities of companies and suppliers and launch campaigns. In addition, they raise public awareness through audio-visual reports (Dalhammar et al., 2003).

Customer demand with respect to recycling is twofold. First, customers request from producers and suppliers to improve products recyclability through design. Example of several specific customer demands are: use recyclable materials, use recycled materials, reduce/substitute hazardous substances, improve product design features for end of life treatment including disassembly and shredding (TNO, 2014; Agan et al., 2013; Boks, 2006; Van Hemel & Cramer, 2002; Azzone & Noci, 1998). Second, customers demand electronic producers to provide facilities for collection and recycling of end of life electronics (Tojo, 2001; Azzone & Noci, 1998).

6.3.2 Internal drivers

Table 6.4 summarises the internal drivers that affect implementation of design for recycling. These factors are grouped into 8 major aspects: cost reduction, management commitment and responsibility, brand image, competitive advantage, competence, product development process, innovation, and motivation. The majority of the papers consulted indicate that cost reduction as well as management commitment and responsibility are the two main internal drivers to implement design for recycling. These two factors will be discussed in detail.

Table 6.4- Internal drivers that foster implementation of design for recycling as identified in literature sources and number of times referred to in literature sources

Internal drivers	References	#
Cost reduction	Epstein and Buhovac (2014); TNO (2014), Agan et al. (2013), Veshagh et al. (2012), Mohr et al. (2012), Borchardt et al. (2011), Fernández-Viñé et al. (2010), (Chen et al., 2009), Bhamra (2004), Zutshi and Sohal (2004), Van Hemel and Cramer (2002), Jin (2002), Tojo (2001), McAloone (1998), Post and Altma (1994)	15
Management commitment and responsibility	TNO (2014), Epstein and Buhovac (2014), Agan et al. (2013), Boks (2006), Bhamra (2004), Jeganova (2004), Zutshi and Sohal (2004), Johansson (2002), Tojo (2001); Azzone and Noci (1998), Post and Altma (1994), McAloone (1998)	12
Gaining competitive advantage from competitors	TNO (2014), De Medeiros et al. (2014), Veshagh et al. (2012), Van Hemel and Cramer (2002), Tojo (2001), Azzone and Noci (1998)	6
Improving companies image	TNO (2014), Agan et al. (2013), Veshagh et al. (2012), Fernández-Viñé et al. (2010) , Van Hemel and Cramer (2002)	5
Having the competence to implement DfR successfully. E.g.: a competence team of environmental specialists	TNO (2014), Jeganova (2004), Johansson (2002), Azzone and Noci (1998)	4
Consideration of design for recycling early in the product development process	TNO (2014), Boks (2006), Johansson (2002)	3
The producer perceives the design for recycling option as an interesting innovation opportunity	De Medeiros et al. (2014), Bhamra (2004), Van Hemel and Cramer (2002)	3
Employees motivation to take an active role in implementation of design for recycling	Bhamra (2004), Johansson (2002)	2

Cost reduction

The first most important internal driver for companies to implement design for recycling is cost reduction (see references in Table 6.4). Although the aim of design for recycling is to enhance product recyclability at end of life stage, cost reduction (cost-led design) is in a business context always an important factor. Companies are in favour of product developments or redesigns that also lead to cost reduction or at least add no extra cost (Borchardt et al., 2011; Jin, 2002; McAloone, 1998). In their studies Epstein and Buhovac (2014); Borchardt et al. (2011); Zutshi and Sohal (2004), Jin (2002), Chen et al. (2009) showed that product design for recycling can increase financial benefits of companies in three ways: by reducing the cost of recycling treatment (e.g.: decreasing the disintegration time and cost), by reducing production and purchasing cost in consequence of reusing secondary components and materials, and by avoiding regulatory penalties cost. Further, design for recycling can increase the quality and purity of fractions which in turn can increase the economic value of these fractions (Epstein & Buhovac, 2014; Chen et al., 2009). For example, in Chapter 4, it was shown that designers in Philips proposed to apply fracture lines that to a large extend improved the mechanical disintegration of LED lamps without significant changes in the product design, the production process or causing extra cost.

Management commitment and responsibility

The second most frequently mentioned internal driver that affects implementation of design for recycling is management commitment and responsibility (see references in Table 6.4). Managers can support implementation of design for recycling in a number of ways: they can arrange the resources needed (Johansson, 2002; McAloone, 1998), set specific recycling goals, set requirements at the level of product development projects (Johansson, 2002), expand on vision statements (Boks, 2006; Johansson, 2002; McAloone, 1998), support trainings and employees' development in design for recycling (Epstein & Buhovac, 2014; Zutshi & Sohal, 2004), become members of business associations and design for recycling forums, set internal standards (McAloone, 1998) and give the same amount of weight to design for recycling considerations as other business considerations (Boks, 2006). Further, managers can create a corporate culture that encourages designers to design more environmentally friendly products (Epstein & Buhovac, 2014; McAloone, 1998).

6.4 Results: barriers for implementation of design for recycling

The comparison of barriers of design for recycling mentioned in (Marwede et al., 2016; TNO, 2014; Tojo, 2001) with the eco-design barriers mentioned in the rest of the reviewed references shows that barriers of eco-design and design for recycling match to a large extent. Some factors confirmed earlier as a driver, are now here demonstrated as a barrier. The external and internal barriers that affect implementation of design for recycling will be discussed in the subsequent subsections (6.4.1 and 6.4.2).

6.4.1 External barriers

In the literature consulted, it was found that 'lack of consumer demand for recyclable products' and 'lack of specific measures and inconsistencies in application and interpretation of directives' are the two main external barriers that hinder companies to implement design for recycling followed by significant changes in supply chain and lack of stakeholders' support. Table 6.5 summarize the external barriers for implementation of design for recycling.

Table 6.5- External barriers that hinder implementation of design for recycling as identified in literature sources and number of times referred to in literature sources

External barriers	References	#
Lack of specific measures and inconsistencies in application and interpretations of directives	Marwede et al. (2016), European Commission (2015b;2014); Lifset et al. (2013); Gui et al. (2013); Brouillat and Oltra (2012); Atasu and Subramanian (2012); Murillo-Luna et al. (2011), Dahlmann et al. (2008), Tojo (2004); Van Hemel and Cramer (2002), Tojo (2001), Post and Altma (1994), Williams et al. (1993)	13
Lack of consumer demand for recyclable products	Marwede et al. (2016), Hsu (2016), TNO (2014), Veshagh et al. (2012), Dahlmann et al. (2008), Boks (2006), Jeganova (2004), Dalhammar et al. (2003), Van Hemel and Cramer (2002), Tojo (2001)	10
Finding alternatives for materials, components and parts requires significant changes in supply chain	Marwede et al. (2016), TNO (2014), Azzone and Noci (1998)	3
Lack of stakeholder support to implement design for recycling	Veshagh et al. (2012), Tojo (2001)	2

Lack of specific measures and inconsistencies in application and interpretations of directives

Awareness created by directives and generic statements on importance of design for recycling could affect design choices and decisions and improve product recyclability (see subsection 6.3.1). However, compliance with WEEE, RoHS and Eco-design directives does not guarantee improvement in product design to facilitate recycling (Lifset et al., 2013; Gui et al., 2013; Brouillat & Oltra, 2012; Williams et al., 1993). This is because the current directives, except for RoHS, which puts clear restrictions on the use of particular materials, do not focus on design aspects to improve product recyclability by taking measures that will directly affect design such as more specific measurements, mandatory design requirements and implementation of IPR (Atasu & Subramanian, 2012; Tojo, 2004; Williams et al., 1993).

For example, the WEEE directive sets weight-based recycling targets for 10 different classes of electronic products. The recycling targets are primarily based on the amounts (on a weight-basis) that are collected (relative to the amount sold). In addition, targets are set for the amounts that enter recovery facilities and recycling facilities. No targets are set for the actual recycled amount, i.e. the overall yield of the recovered materials (Gui et al., 2013). In practice, this implies that collection targets are the dominant incentive for producers, rather than design for recycling.

Further, under the extended producer responsibility (EPR) scheme, producers are physically and financially responsible for all activities and processes related to the end of life of the products they put on market. Producers can decide whether they want to comply with EPR individually (IPR) or collectively (CPR).

In case of Individual Producer Responsibility (IPR), the financial benefits of design changes directly come back to the individual producer of the recyclable product. However, in practice the large majority of producers are collectively (CPR) in charge of collection and recycling treatment of their e-waste and share the cost, dependent on the market share of each producer (products put on market), and not the amount of e-waste collected per producer or the recyclability of products at end of life stage.

In this case, producers who have designed more recyclable products or collected more e-waste must pay the same or higher recycling cost as other producers who have zero collection and/or no design changes. This implies that producers are not rewarded for design changes that would make recycling of a particular product less expensive or more effective. This implies that the WEEE directive, although stimulating recycling in general, has not directly stimulated improved recyclability of specific products and did hardly affect the design of products (Lifset et al., 2013; Atasu & Subramanian, 2012).

In the case of the eco-design directive, the analysis of implementing regulations for each product group shows that specific requirements that are obliged are directly related to environmentally relevant product characteristics, such as energy consumption and/or resource consumption, limiting the use of hazardous substances and providing necessary information for consumers (European Commission, 2015b). The majority of requirements regulate energy efficiency during use phase, and there is only one requirement concerning resource efficiency and recycling as follows: *“manufacturers should provide information on disassembly, recycling and disposal”*. According to implementing directives, this information must be provided via the website of the producers or through the products catalogues/brochures.

This requirement has no implication on design. It can only provide information for consumers to better dispose the product and for recyclers to know what disassembly tools to use, and to learn the disassembly steps for safety, maintenance purposes or better recovery.

In 2014, the European Commission (2014) conducted a study to find out if any actions concerning product design – as stated in article 4 of the WEEE directive - have been taken into consideration by the EU member states (European Commission, 2014). The analysis shows that some member states i.e. Austria, Belgium (Flemish region), Czech Republic, Denmark, Finland, France, Germany, Ireland, Latvia, Netherlands, Sweden, UK took initiative and defined projects to find new design solutions that enhance products recycling. Some member states such as Bulgaria and Portugal expect companies to annually report actions taken into account to improve product design or to release actions to be taken as to how they plan to improve the product design features with regard to recycling (Seyring et al., 2015).

The lack of electronics production facilities, importing of electronic products from other countries and lack of specific design requirements are mentioned as the main reasons why design for recycling is not regulated by some member states i.e. Cyprus, Estonia, Greece, Hungary, Italy, Luxemburg, Poland, Romania, Slovenia and Slovakia. This clearly shows that not every company and every country has the same maturity and experience for implementation of design for recycling. While some member states and producers proactively invest, and explore new design opportunities, others are less influential. Lack of specific measures in directives and existence of multiple policy makers and agents at national level of each country lead to inconsistencies in interpretation and different ways of adaptation and implementation of design for recycling (Dahlmann et al., 2008).

Lack of consumer demand

The lack of consumer demand is indicated as the main barrier for successfully putting recyclable or recycled products to the market (see references in Table 6.5). From the literature review it became evident that this mainly refers to business-to-consumer market; while there might be a growth in environmentally conscious consumers, there is still no evidence that a large portion of consumers give priority to recyclable products or products made of recycled/recyclable materials at the time of purchase. In many cases consumers today are not willing to ignore product features or pay more in order to get a recyclable or recycled product. They are rather more inclined to pay for more energy efficient products or other product features or products with lower price which they can directly benefit from (Veshagh et al., 2012; Dahlmann et al., 2008; Tojo, 2001). According to Tojo (2001) and Marwede et al. (2016) it is hard to convince consumers as to why they need a recyclable product or a product made of recycled materials. Section 6.3.2 shows that implementation of design for recycling can lead to cheaper products, however as Tojo (2004;2001) observed there are also cases when products turn out to be more expensive, for example, high price and low demand for particular recycled materials, implies a relatively higher product price.

In these cases, Hsu (2016) observed that consumers only want to spend 1-5% extra for a recyclable product in comparison to less or non-recyclable products. Further, she found that a higher fraction of consumers shows willingness to pay for low-priced recyclable products, comparing to high-priced recyclable products. However, on the business-to-business market, recyclability is increasingly becoming important (Boks, 2006). With legislative pressures, business customers are requesting suppliers for more recyclable parts and materials.

6.4.2 Internal barriers

In the literature consulted, it was found that lack of financial benefits and lack of recycling knowledge are the two main internal barriers that hinder implementation of design for recycling. Table 6.6 summarize the internal barriers for implementation of design for recycling.

Table 6.6- Internal barriers that hinder implementation of design for recycling as identified in literature sources and number of times referred to in literature sources

Internal barriers	References	#
Lack of financial benefits	Marwede et al. (2016), TNO (2014), Veshagh et al. (2012), Murillo-Luna et al. (2011), Dahlmann et al. (2008), Murillo-Luna et al. (2007), Jeganova (2004); Van Hemel and Cramer (2002), Tojo (2001), Post and Altma (1994)	10
Lack of recycling knowledge and skilled experts	TNO (2014), Reuter et al. (2013), Veshagh et al. (2012), Veshagh et al. (2012), Murillo-Luna et al. (2011), Dahlmann et al. (2008), Jeganova (2004), Van Hemel and Cramer (2002), Tojo (2001); Post and Altma (1994)	10
Lack of management commitment	Dahlmann et al. (2008), Murillo-Luna et al. (2007), Boks (2006), Jeganova (2004), Dalhammar et al. (2003), Van Hemel and Cramer (2002), Tojo (2001), Post and Altma (1994)	8
Lack of internal communication and exchange of information between different departments and actors	Murillo-Luna et al. (2011), Boks (2006), Jeganova (2004), Post and Altma (1994)	4
Lack of technological capabilities required to enhance the recyclability of products	Murillo-Luna et al. (2011), Van Hemel and Cramer (2002), Tojo (2001)	3
Lack of sufficient time	TNO (2014), Veshagh et al. (2012), Van Hemel and Cramer (2002)	3
Conflict with functional requirements of product	TNO (2014), Van Hemel and Cramer (2002)	2
Improving product recyclability is not an innovation opportunity for the company	Murillo-Luna et al. (2007), Van Hemel and Cramer (2002)	2

Lack of financial benefits

Lack of financial benefits is mentioned as the most important internal barrier for implementation of design for recycling (see references in Table 6.6). From producers' perspective, a number of actions can be taken in order to enhance product recyclability, but all of these require financial investments. For example, producers can observe the behaviour of their product design during the recycling process and feed the lessons learnt back to the design process. Further, producers can enforce the application of design for recycling methods internally and conduct recyclability assessment studies or bring in design for recycling consultants to sort out the implementation process (TNO, 2014; Dahlmann et al., 2008; Jeganova, 2004). The financial investments required (Post & Altma, 1994) might in some cases bring direct financial benefits to producers. However, most of the time, producers do not gain any direct financial benefit from changing their products' designs (see references in Table 6.6). Various reasons are mentioned in the literature as why producers do not gain financial benefits by investing in DfR. The first reason is because in some cases changing product design to facilitate the recycling process would increase the manufacturing cost (TNO, 2014; Murillo-Luna et al., 2007; Tojo, 2004). For example, according to a study conducted by Tojo (2004) use of particular recycled materials instead of virgin materials or replacing metals with plastics to facilitate the recycling process increased the manufacturing cost. The second reason is because collection and treatment of end of life electronics and development of new technologies and infrastructure would be more expensive than producing new products (TNO, 2014; Dahlmann et al., 2008; Tojo, 2004; Jeganova, 2004). Further, under collective scheme of EPR, the benefits of enhancing product recyclability goes to recyclers rather than producers (Tojo, 2004). Lack of financial benefits cause producers to prefer other kinds of investments, particularly under considerable competitive pressure (Post & Altma, 1994).

Lack of recycling knowledge and skilled experts

Lack of recycling knowledge is mentioned as the second most important internal barrier for implementation of design for recycling (see references in Table 6.6). As stated by TNO (2014), Murillo-Luna et al. (2011), Dahlmann et al. (2008), Van Hemel and Cramer (2002), Tojo (2001); Post and Altma (1994), often designers do not know what is recyclable and which product design features can improve product recyclability. Design for recycling aims to increase the recycling potential of products. It takes into account design choices including chemical content, the material combinations used, the shape of the parts, and the type of connections between parts. These features can affect the way in which the products will likely be liberated into fractions, concentrated into material streams and reprocessed into secondary materials (Reuter et al., 2013). Therefore, awareness and tools that enable to find the appropriate knowledge is required. Lack of explicit knowledge and skilled experts in these areas are considered as a barrier for companies to improve product recyclability (Veshagh et al., 2012; Jeganova, 2004).

6.5 Discussion

In Chapter 6 the findings of previous chapters are placed into a broader societal and business context with the aim of understanding the reasons that design for recycling methods are hardly applied to the design of electronic products. Understanding this will contribute to establishing measures that lead to actual implementation of DfR.

Companies have internal as well as external drivers and barriers for recyclability. Findings from this literature review show that compliance with regulations is the most important driver for companies to act upon design for recycling. For producers of electronic products this means to comply with RoHS, WEEE and eco-design directives. In Chapter 5, the interviewed designers from Barco, Philips Lighting and TP Vision indicated that compliance is the main driver for activities regarding product recyclability. The literature review also showed that, even though regulations form an important driver, inconsistency in interpretation and application of directives still leads to very different outcomes in terms of product recyclability across EU member states. These findings imply that developing measures that directly affect design such as more specific regulations, mandatory design requirements and implementation of IPR might lead to a considerable improvement in the recyclability of products.

The European Commission is currently working on the development of a Circular Economy Package (European Commission, 2018a) which intends to strengthen the incentives for design for recycling in WEEE and eco-design directives by adding relevant measures that directly affect product design. The key actions accepted and to be implemented under this new package include (European Commission, 2015a):

- Promote resource efficiency requirements in addition to energy-efficiency requirements under the eco-design directive, and
- Proposes that the share of recycling cost among producers must be based on “end of life costs of their products” (European Commission, 2015a), rather than market share. This could provide direct financial incentives for producers to improve the recyclability of their products under collective scheme.

Further, literature findings show that management commitment and responsibility is the second most important driver that affects implementation of design for recycling. Managers can support implementation of design for recycling by setting specific recycling goals, prerequisites and requirements at the level of product development projects, expand on vision statements, fulfil the external regulations posed on the companies and set internal standards and give the same amount of weight to design for recycling considerations as to other business considerations. In Chapter 5, the interviewed designers at Barco, Philips Lighting and TP Vision state that taking into account recyclability is not explicitly asked for in the design brief. These designers do therefore not have a direct incentive to take DfR into account. Further, they state that in this context the project management team plays an important role when it comes to incorporating recycling information at an early design stage. This is mainly because at this stage project management teams work towards a clear understanding of the assignment and an agreement on the project definition and requirements and discuss the viability of a new product development and the risks and revenues associated with design for recyclability.

Moreover, in the present study, it was demonstrated that, in spite of the obligations to deal with the waste they generate, companies don't have a direct financial incentive to improve recyclability. This is because of the distribution of financial benefits between producers and recyclers under collective scheme of EPR, with the benefits of increased product recyclability going to recyclers rather than producers (TNO, 2014). This can reduce producers' incentives for design for recycling. One of the findings of the literature review, i.e. that the collective way in which EPR is currently operationalized gives no incentive to improve on recyclability of electronic products, is strongly supported by the recycling results obtained in Chapter 3. IPR could create economic incentives to increase products recyclability through design, which could lead to better disintegration and separation of products.

Additionally, the literature findings show that lack of recycling knowledge is considered as another major barrier. Often, product developers and designers do not know what is recyclable, and which product design features can improve product recyclability. However, Chapter 2 showed that considerable amount of methods and tools are available that can provide designers with required recycling knowledge (in Chapter 2) and Chapter 4 demonstrated that these methods, if applied, lead to significantly improved recyclability. These findings imply that implementation of design for recycling is not limited by the lack of availability of recycling knowledge to designers. Apparently, the available recycling knowledge is not (properly) taken into account in practice. The important role of acquainting designers with design for recycling methods and its impact on improving product recyclability was presented and evaluated in Chapter 4.

6.6 Conclusion

This chapter aimed to answer the following question:

RQ5. What factors stimulate or hinder the application of design for recycling methods by electronics producers in general?

To fulfil the aim, a literature review study was conducted. The literature review concluded that regulations, management commitment and responsibility, financial incentives and knowledge of design for recycling methods are the main factors that foster implementation of design for recycling. However, there is still room for improvements with respect to these factors. New regulations are required which focus on design aspects to improve products recyclability by taking measures that will directly affect design such as mandatory design requirements. Recyclability must be explicitly addressed in the design brief so that designers do have a direct incentive to take design for recycling into account. Under EPR scheme, there is a need to create direct financial incentives for producers that enables them to be willing to improve the recyclability of their products. Further, there is a need to acquaint designers with design for recycling methods.

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Chapter 7: Conclusions and recommendations

7.1 Introduction

Various design for recycling (DfR) methods have been developed since 1990. These methods aim to assist designers to improve the recyclability of their designs. Despite the high number of DfR methods developed and what they claim in theory, electronic products are still not optimally disintegrated and separated in actual recycling processes. The starting point of this thesis was the observation that this is either because existing DfR methods are not effective, meaning they do not assist designers to improve the recyclability of their design and have no real effect in producing better disintegration results, or the DfR methods are not applied in practice, meaning that the application of DfR methods in practice is still challenging for designers and producers of electronic products. Therefore, the main goal of this thesis was to determine the actual cause of the mismatch between theory and practice in DfR. It addressed the following main research question:

What is the role of design in the effective recycling of electronic products?

This was addressed in five studies:

- A literature review of the characteristics and reported effectiveness of existing DfR methods.
- A case study on how electronic products behave in the actual recycling process.
- A case study on the extent to which actual product recyclability can be improved if designers are explicitly asked to take existing DfR methods into account.
- An interview study on designers' ideas about current DfR practices and their needs and desires for incorporation of DfR into the early design process.
- A literature review of company drivers and barriers, as a means of understanding why DfR methods are, or are not, applied in practice, and contributing to the improvement of application of DfR methods.

Below, Section 7.2 presents the main conclusions of each study, Section 7.3 outlines the contributions of this thesis, while Section 7.4 provides recommendations for design practice and future research.

7.2 Answers to the research questions

7.2.1 First study (Chapter 2)

RQ1. What are the characteristics of existing design for recycling methods that aim to improve the recyclability of electronic products?

To answer this question, a literature review was conducted to examine in detail the characteristics of 36 DfR methods published between 1993-2018. One common characteristic of the methods reviewed is that they aimed to assist product designers to improve the recyclability of a product through product design. Other characteristics examined include: (1) design features considered most important for product recyclability, (2) the suitability of methods for use in the early design stage, (3) the suitability of methods for electronics, and (4) the reported effectiveness of methods.

By analysing the underlying data on the DfR methods, it was found that three product design features were repeatedly considered the most important for product recyclability: materials, connections and product structure. The literature offers a number of practical recommendations for each of these design features that may help to optimize product recyclability. For example, the recommendations for material selection were: use compatible materials, use recyclable materials and avoid toxic materials. For connections, it was found important to use easy-to-disintegrate connections, and minimize the variety and number of connections, while for product structure, it was found important to make scarce, valuable or harmful materials/parts easily accessible.

Based on the literature review, it also became apparent that DfR methods fall into two major categories: heuristic and systematic methods. Heuristic methods such as DfR guidelines, tables of connections and material compatibility matrixes work best at the early design stage, when changes are still possible. In contrast, systematic methods work best at late design stages, when more detailed data about a product is known. At this stage, a product is often 'frozen' and changes are no longer possible. The analysis of the literature review showed that the majority of the DfR methods reviewed (23 out of 37) were systematic and less suitable for the early stages of the design process.

Furthermore, it was found that DfR methods were mainly tested on vehicles and electronics. For electronics, the case studies mainly cover large equipment (washing machines) and screens (LCD TVs, CRT TVs). In most cases, the methods were developed and applied based on hypothetical case studies, without further testing of the actual recyclability of these products in practice to determine whether the application of DfR methods had any real effect in producing appropriate disintegration results.

The chapter concluded that control over product design features (product structure, materials used and connection technologies) is needed to improve product recyclability. However, for electronics, the effectivity of DfR methods has rarely been tested in practice.

7.2.2 Second study (Chapter 3)

RQ2. How do product design features of screens and LED lamps affect the fragmentation results in recycling experiments?

To answer this question, an investigation was conducted into how electronic products behave in actual disintegration processes. This led to the identification of product design features that affect the disintegration of electronics from a practical point of view. This chapter specifically looked at partial manual disintegration of displays and the mechanical disintegration of LED lamps.

The results obtained from manual disintegration tests showed that the products studied did not enable optimal manual disintegration. This was based on the time required to manually remove the key components. The great amount of time it took to gain access to and remove the key components indicated the unfavourable design features for manual disintegration. The results of the study revealed that design aspects that prolong dismantling time were related to the high number and different types of connections, intermediate parts (including covers, shields and brackets) and the necessity of changing tools.

The results obtained from the mechanical disintegration tests showed that the products studied did not enable optimal mechanical disintegration. This was based on the fragments obtained from the disintegration tests. Analysis of the fragments showed that the products studied broke down to a large extent into heterogeneous fragments, with incompatible materials still combined. This could negatively affect further separation and recovery of materials. Studying the fragments led to the identification of a number of key design features that affect the mechanical disintegration of products into homogeneous fragments upon shredding. These design aspects are related to materials, connections and product structure, and require specific attention.

A comparison of findings from this study with the findings of the literature survey in Chapter 2 revealed that both consider that a specific set of product design features have an important role in improving product recyclability. Moreover, both address the same issues and recommendations regarding these design aspects. However, there is evidently a gap between what DfR methods claim in theory, and the results obtained from disintegration tests of electronic products in practice. This implies that DfR methods are either not applied or not effective.

7.2.3 Third study (Chapter 4)

RQ3. How effective are design for recycling methods in improving the recyclability of electronic products?

To test the effectiveness of DfR methods, a number of designers at Philips Lighting, Barco and TP Vision were explicitly asked to take a set of generic DfR guidelines into account and redesign the case study products – LED lamps and displays – accordingly. The generic guidelines were based on product design features mentioned in the literature review (Chapter 2) as well as obtained from the initial disintegration tests (Chapter 3), and included materials, connections and accessibility of key components. The guidelines were summarized into three points: (1) Use recyclable materials; (2) Use connections that allow break down into homogeneous fragments; and (3) Electronic parts (such as the PCBA) should be released without connection to other parts. The application of design guidelines led to various redesign strategies. Each redesigned solution was manufactured and subjected to a disintegration process, as described in Chapter 3.

The results obtained from the manual disintegration of displays and the mechanical disintegration of the LED lamps showed that the application of design guidelines significantly improved the recyclability of the case study products. In the case of LCD TVs, the total dismantling time was reduced and the key components could also be removed in a shorter amount of time. This was because of a reduction in the number of connections, covers, shields and brackets. In the case of the medical displays, the result was less clear, due to boundary conditions imposed on the redesign that did not allow for full implementation of the guidelines, as well as different disassembly conditions. In the case of the LED lamps, the analysis of fragments showed that the redesigned lamps were optimally disintegrated into homogeneous fragments, which also led to better separation and recovery of materials. Overall, this study observed that, if applied, generic DfR guidelines could lead to significant results and indeed improve the recyclability of products.

7.2.4 Fourth study (Chapter 5)

RQ4. What are the current design for recycling practices, based on the experience of product developers and designers in electronics companies?

To answer this question, a number of designers and product developers from Philips Lighting, Barco and TP Vision were interviewed, all of whom were involved in the application of design guidelines and the redesign of case study products. All of the designers interviewed stated that their companies did not have a strategic focus on DfR. Furthermore, they stated that the main DfR activity in their companies was compliance with directives, particularly compliance with the RoHS directive on the usage of hazardous materials. This implies that DfR is not specifically mentioned in the design brief and therefore designers do not have a direct motive to consider DfR in their designs. Nevertheless, the designers interviewed explained that they could explore ideas to improve product recyclability by framing it more in terms of direct company interests, such as design for improved assembly or design for minimum value loss at end-of-life. This, of course, only has a limited impact, as it only affects products in which these designers are directly involved.

7.2.5 Fifth study (Chapter 6)

RQ5. What factors stimulate or hinder the application of design for recycling methods by electronics producers in general?

The analysis of the literature suggests that compliance with directives is the most important driver behind producers adopting DfR. WEEE, RoHS and Ecodesign directives have clear statements that require producers to promote the design and development of electronic products that can facilitate the recycling process. Among the directives, RoHS has specific measures on the use of hazardous materials, while the Ecodesign directive has limited specific measures on how to improve product recyclability.

In addition to the regulations, in recent years, the level of public awareness regarding e-waste and its associated problems has increased. As a result, customers are putting more pressure on electronics producers to design and deliver more sustainable products and provide facilities for the collection and recycling of end-of-life electronics. This makes customer demand the second most important driver of the implementation of DfR by producers.

Another major driver behind the adoption of DfR is management commitment and responsibility. Managers can play an important role in promoting design changes for better recycling by setting specific goals both at the company and project level and by training and educating designers. Another major driver that would encourage producers to take DfR into account is the potential to reduce costs through making such changes. Although the combined effects of these stimuli can encourage producers to implement DfR, there are still a number of factors that hinder its implementation.

Currently, the specific and concrete measures that can be used to improve product recyclability are lacking in regulations and directives. This is challenging for producers, since not every company has the same experience, expertise and maturity to know how to enhance product recyclability. This can further lead to inconsistencies in the application and differing interpretations of directives. Therefore, there is a need for directives to set specific measures and mandatory design requirements concerning how to improve product recyclability.

Furthermore, despite the growth in environmentally conscious customers, there is still no evidence that a large proportion of consumers give priority to easily recyclable products. This is yet another challenging factor for producers, which hinders the implementation of DfR. In the future, there is a need for more market research and the creation of awareness in consumers about the benefits of products that are easy to recycle.

Another major barrier is that companies do not have a direct financial incentive to improve recyclability. As producers are allowed to deal with the waste they generate through a collective scheme of extended producer responsibility (EPR), the burden is shared across all producers in such a way that direct responsibility is lacking. There is a need to create direct financial incentives for producers through the EPR scheme which will make them willing to improve the recyclability of their products.

7.3 Thesis contributions

The main contributions of this thesis are:

- There are several reviews to be found in the literature on design for sustainability and eco-design tools and methods. However, as far as the author is aware, no study has reviewed existing DfR methods. In this thesis, 36 DfR methods were identified and reviewed, with a focus on investigating design features important to recycling; assessing the suitability of existing DfR methods for the early design stage; assessing the suitability of DfR methods for electronics; and their reported effectiveness.
- In the DfR literature, the product case studies are mostly limited to vehicles, washing machines, LCD TVs and CRT TVs. These practical cases can teach us valuable lessons about how DfR issues have been dealt with in practice. However, in particular, there is a need for more contextualized and detailed case studies and examples. Thus, another contribution of this thesis is the detailed case studies of the small- and large-scale recycling of LED lamps, LCD TVs and medical displays, and the identification of design features that affect the disintegration process for these electronic products from a practical point of view. The case studies selected differ significantly in their recycling treatment, design features and complexity of the electronics, which makes them interesting case studies.
- The field of DfR is rich in its development of methods but poor in testing the effectiveness of these methods. A major scientific contribution of this thesis is testing the effectiveness of generic DfR guidelines for improving the recyclability of specific electronic products (LED lamps, LCD TVs and medical displays). To test the effectiveness of DfR guidelines, designers in the companies studied were explicitly asked to utilize generic DfR guidelines to redesign the case study products. Furthermore, the redesigned case study products were subjected to manual and mechanical disintegration to test whether the application of guidelines could enhance the disintegration process in practice. In addition, an analysis with QWERTY (Huisman, 2003) showed that application of DfR guidelines led to products that were both economically and environmentally interesting in addition to their improved recyclability.
- Despite the importance attributed to DfR, this thesis showed that the influence of product designers who work in a business context is relatively modest. The findings of this thesis put the responsibility for successful product recycling into the hands of government and company strategic management. Government needs to create boundary conditions, and companies need to make the strategic decision to include DfR in their operational processes. With these conditions in place, designers demonstrated that they are very capable of developing easy-to-recycle products. The thesis has shown that the DfR tools currently available are useful and effective, and that heuristic DfR guidelines work well when applied in the early stages of the design process.

7.4 Recommendations for design practice and future research

In this section, a number of recommendations are made to improve the DfR of electronic products, based on the studies undertaken in this thesis.

More education and training for designers

This thesis showed that the recyclability of the electronic products studied is not limited by the lack of suitable guidelines. In fact, suitable guidelines are available (Chapter 2) and, if applied, are effective and can lead to significantly improved recyclability (Chapter 4). The limiting factor was found to concern the fact that the available guidelines are not adequately taken into account in practice, and designers do not receive sufficient training and education regarding existing DfR methods; in other words, they lack recycling knowledge (Chapters 5 and 6). For future research, it is recommended that universities and companies spend more time and effort on education and application of existing DfR methods, which are already sufficient to allow designers to build knowledge and develop new ideas for designing or redesigning products for recycling.

In addition to education and the application of DfR methods, it is recommended that designers visit recycling plants and become involved in the process of deconstructing a product alongside recyclers (also known as ‘disintegration’ or ‘teardown’) to better understand what is in a product and which product design features hamper manual and mechanical disintegration, separation and recovery of materials. For example, in this thesis, it was observed that some displays can have up to 83 screws of different types, which require frequent changes of screw bits to undo the screws before being able to access other parts (see Chapter 3). From this example alone, designers would learn that a reduction in the number and variety of connections used in a product is valuable. Direct observation can help designers to understand how their early design decisions can have a huge effect on recyclability and material recovery.

It is also recommended that universities and companies provide designers with the opportunity to participate in in-house recycling demonstrations (e.g. teardown practicals as part of a course on DfR), pilots and projects (e.g. GreenElec project). Another opportunity is that universities, companies and institutions active in the field of DfR introduce events, expos or workshops where designers can meet producers and recyclers, learn about products and recycling processes and become directly involved in design or redesign assignments.

Regulations concerning DfR

Chapter 5 demonstrated that compliance with legislation has been the main DfR activity thus far. The analysis of the literature and European Union legislation on resource efficiency (Chapter 6) revealed that the legislation has achieved much in terms of the restriction of hazardous substances, reducing the amount of e-waste going into landfill or being incinerated, and reducing the energy consumption of products. However, there are still considerable challenges regarding DfR of electronic products. For instance, future developments point towards the increasing integration of electronics in all kinds of products, such as for example in smart textiles. This will seriously impact their recyclability, and it follows that design for recycling considerations should be part of the early stages of the design process of, for instance, smart textiles. This is currently not the case (Köhler et al., 2011). Regulations are also not likely to adequately address this issue in a proactive manner, given the long lead time of regulatory processes, the dynamic nature of the innovations and the general lack of data on

the recyclability of integrated electronic materials. One way forward could be to create an ambitious governmental program at EU level, that supports innovation-led growth that is also more sustainable, such as for instance the mission-oriented policies advocated by Mazzucato (2018). Such a mission-oriented policy could drive creativity and design innovation strategies that will include extending product life, reuse and recycling.

Management commitment and the cost issue

The implementation of DfR requires the serious commitment of managers. This is because products are designed and manufactured by companies and managers have a crucial role in enforcing specific requirements in the design brief and design process so that designers can change product design in such a way that facilitates the recycling process. At the same time, DfR can affect every aspect of a business: from product design, which requires changes in materials, parts, connections and product structure, to changes by and the active engagement of manufacturers, suppliers and logistics processes. Additionally, e-waste management at the product's end-of-life, and investment in recycling facilities either collectively or individually, also requires the attention of management.

Thus, it is clear that changing product design and business processes with a view to implementation of DfR is complex and time intensive, and also requires an initial financial investment. It appears that companies still do not clearly understand how investment in DfR will lead to both greater business profits as well as environmental benefits (Chapter 6). There is a need for further research to address the business costs and environmental benefits associated with the implementation of DfR to show business managers how their additional investments will pay off both economically and environmentally, as well as determine whether customers are willing to pay more for recyclable products. Furthermore, there is a need for more examples that demonstrate the changes required on a product and business level and the associated business costs and environmental benefits.

More empirical data on products and recycling process

This thesis mainly focused on specific brands of LED lamps (spot and bulbs), LCD TVs and medical displays. The main construction elements of these case studies were identified. Furthermore, these products were manually and mechanically disintegrated to determine the design features that hamper or facilitate the disintegration process. However, data on the composition of different product categories and data on manual and mechanical disintegration of different product categories is still incomplete (see Chapter 2). In future research there is need to focus on other electronic product categories and differences between brands to collect more empirical data about the electronic products, including lists of materials and parts, lists of connections and structural layout. In addition, more empirical data is required on how different electronic products behave during the disintegration process, and in what ways designs can be changed to improve recyclability. Although lessons learnt from other cases may be applicable to other products and may also improve a product's recyclability, it is important to realize that every electronic product consists of a unique mix of materials, connections and structure and, therefore, also has a unique recycling profile.

Need for a larger sample size

In Chapter 5, conclusions were drawn based on insights provided by seven product developers and designers of electronic products, and therefore the results may not be generalizable to other product developers, designers and companies in the electronics industry, who may have

different levels of understanding and involvement in DfR activities. In future studies, it would be interesting to see if similar findings emerge from a larger sample of product developers and designers from a more diverse sample of electronics companies. Such a study would provide a more comprehensive understanding of current DfR practices and the role of product developers, designers and electronic companies in DfR.

7.5 References

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- Köhler, A. R., Hilty, L. M., & Bakker, C. (2011). Prospective impacts of electronic textiles on recycling and disposal. *Journal of Industrial Ecology*, 15(4), 496-511.
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This thesis is dedicated to my father, who ascended to heaven before I could complete it. Baba Ali, words cannot describe how much I wish that you were here to share this happy occasion. I miss you every day. I am glad to know that you saw this process through to its completion, offering both the support to make it possible and plenty of friendly encouragement. And even after your departure, I had a very clear picture of you in my mind and I remembered our talks, which kept me going. I can hear your voice clearly when you say *inam migzare baba. negaran nabash*.

Baba Ali, I am so grateful to have you as my father, and I am beyond blessed to be your daughter. Babayi, I cannot thank you enough for all the good things you have done for me. If I were to list all your acts of kindness, I would be writing forever. But here are some of the essentials. Baba Ali, thank you for opening my mind and heart to all the differences and similarities in the world. If I am a global traveller, it is because of you. Babayi, you always made travelling back and forth to check on my wellbeing a priority, no matter which country I was in. You always supported and empowered me in all possible ways to go after my dreams. You were always a very sympathetic and caring dad that any daughter would wish for. I remember that when I was a child, you and Mom always got involved in our school assignments and handicrafts, and made them more fun and fruitful. I miss your hugs, hands and phone calls every day, especially when I am ill or going through challenging times. Babayi, I hope that this thesis make you proud. I will always love you.

Maman Sima, all my life, I've never felt that you are just my mother. In essence, you've always been my best friend and closest companion. I have always been totally free and myself when I'm with you, and we have always been able to talk freely about anything. Maman Sima, not only during my PhD but throughout my life, you have been my Sun (main source of energy). You have always kept me calm and given me strength through your unconditional love, support and kindness. I remember you saying "Just keep swimming" and "Everything is going to be alright". Maman Sima, thank you for all the mother-daughter times we shared in Tehran, in Beijing, in Delft and everywhere else. Thank you for always being my best buddy and partner on new adventures. I hope that one day I will be like you – calm, patient, kind and friend in need. There is no love beyond my love for you and Baba Ali. Thank you for everything. *Doosteton daram va dastaton ro mibosam*.

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Farzaneh Fakhredin

Delft, December 2018



Painting by Farzaneh Fakhredin & Mohammad Taleghani

About the Author

Farzaneh Fakhredin was born on 8 August 1988 in Tehran, Iran. Her early interest in exploring different cultures and lifestyles led her choose to continue her education path in different countries.

After finishing secondary school in Iran, she moved to Beijing, China, to pursue her high school diploma. During her time in Beijing (2002–06), she also attended various language institutions to study Chinese (Mandarin). She then moved to Melaka, Malaysia, where she did her Bachelor's degree in Information Technology Management at Multimedia University. She graduated cum laude in 2009.

Farzaneh then moved on to Lund, Sweden, where she earned her Master's degree in Information Systems at Lund University. During her studies, she did a course on 'IT, Innovation and Sustainability', which was her introduction to environmentally conscious design. During the course, she was given examples of computers designed with the environment in mind. She graduated in 2011.

Farzaneh's interest in environmentally conscious design led her to apply for a related PhD programme. In 2012, she started her PhD research on design for the recycling of electronic products at the Faculty of Industrial Design Engineering of Delft University of Technology. The work presented in her thesis was carried out in the framework of 'Greenelec: Product design linked to recycling'. The aim of this project was to bring together suppliers, producers, designers, recyclers and knowledge institutes to improve the recyclability of electronics.

During her PhD, Farzaneh worked directly with GreenElec partners to explore the role of product design in the effective recycling of electronic products. She also authored several industrial reports and presented the results of her studies at several international conferences. After completing her doctoral studies, Farzaneh will continue her career path in Manchester, UK.

Publications

Fakhredin, F., Bakker, C., & Geraedts, J. (2014). *Designer focused quickscan recyclability assessment method*. Paper presented at the Proceedings of CARE Innovation 2014 'Going Green' Conference, Vienna, Austria, 17-20 November 2014.

Fakhredin, F., Bakker, C., Huisman, J., & Geraedts, J. (2013). *Five perspectives on design for end of life: highlights of a literature review*. Paper presented at the Proceedings of the EcoDesign 2013 International Symposium.

Fakhredin, F., & Huisman, J. (2013). *Analyzing End of Life LCD TV WEEE Flows in Europe*. Paper presented at the EcoDesign, Jeju Island, South Korea.

Propositions accompanying the thesis
Design for Recycling of Electronic Products:
How to bridge the gap between design methods and recycling practices
By Farzaneh Fakhredin

1. Materials, connections and product structure are considered as critical design features for improving a product's recyclability. *This proposition pertains to this dissertation.*
2. Design for Recycling guidelines, when applied in practice, are effective and lead to increased recyclability of electronic products. *This proposition pertains to this dissertation.*
3. Designers of electronic products have little or no incentive to take into account Design for Recycling. Better legislation, clearer financial benefits and management commitment are needed to encourage uptake of Design for Recycling. *This proposition pertains to this dissertation.*
4. Travel often and you will get to know yourself.
5. One's identity should not be defined by one's nationality or citizenship, but the places one has lived, people one has met, customs and rituals one has performed and experiences one has gone through.
6. Mental hygiene is as important as personal hygiene and they both must be equally maintained.
7. "Only when we are brave enough to explore the darkness will we discover the infinite power of our light." – Brown, B. (2015). *Daring greatly: How the courage to be vulnerable transforms the way we live, love, parent, and lead*. New York: Penguin.
8. "If greater levels of high-quality recycling are to be reached, design issues must be addressed far more systematically." European Commission. (2018). A European Strategy for Plastics in a Circular Economy.
9. "Designers are no longer the black sheep of the design professions but a powerful force forging new and innovative areas of design and planning activity." Francis, M. (1983). Community design. *Journal of Architectural Education*, 37(1), 14-19.
10. Plastics are the most striking threats to marine life and human health.

These propositions are regarded as opposable and defendable, and have been approved as such by the promoters Prof. dr. ir. C. A. Bakker, Prof. dr. A. R. Balkenende and Prof. dr. ir. J.M.P. Geraedts.

Stellingen behorende bij het proefschrift
Design for Recycling of Electronic Products:
How to bridge the gap between design methods and recycling practices
door Farzaneh Fakhredin

1. Materialen, verbindingen en productstructuur worden beschouwd als ontwerpkenmerken die van kritiek belang zijn voor het verbeteren van de recyclebaarheid van een product. *Deze stelling heeft betrekking op dit proefschrift.*
2. Richtlijnen voor ontwerpen gericht op recycling (*Design for Recycling*, DfR) zijn, wanneer deze in de praktijk worden toegepast, effectief en leiden tot een betere recyclebaarheid van elektronische producten. *Deze stelling heeft betrekking op dit proefschrift.*
3. Ontwerpers van elektronische producten hebben weinig tot geen reden om rekening te houden met DfR. Betere wetgeving, duidelijkere financiële voordelen en commitment van het management zijn noodzakelijk om de toepassing van DfR te bevorderen. *Deze stelling heeft betrekking op dit proefschrift.*
4. Wie vaak reist, leert zichzelf kennen.
5. Je identiteit moet niet worden bepaald door je nationaliteit of burgerschap, maar door de plaatsen waar je hebt gewoond, de mensen die je hebt ontmoet, de gebruiken en rituelen die je hebt uitgevoerd en de ervaringen die je hebt meegemaakt.
6. Mentale hygiëne is even belangrijk als persoonlijke hygiëne en beide moeten even goed worden onderhouden.
7. “Alleen als we moedig genoeg zijn om de duisternis te verkennen, ontdekken we de oneindige kracht van ons licht.” – Brown, B. (2015). *Daring greatly: how the courage to be vulnerable transforms the way we live, love, parent, and lead*. New York: Penguin.
8. “Om meer hoogwaardige recycling te realiseren, moeten ontwerpaspecten veel systematischer worden benaderd.” Europese Commissie. (2018). A European Strategy for Plastics in a Circular Economy.
9. “Ontwerpers zijn niet langer het zwarte schaap in de professionele ontwerpwereld, maar een belangrijke factor die nieuwe, innovatieve activiteiten op het gebied van ontwerp en planning creëert.” Francis, M. (1983). Community design. *Journal of Architectural Education*, 37(1), 14-19.
10. Kunststoffen vormen de meest in het oog springende bedreiging voor het leven in zee en de menselijke gezondheid.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren Prof. dr. ir. C. A. Bakker, Prof. dr. A. R. Balkenende en Prof. dr. ir. J.M.P. Geraedts.