Transdisciplinary Lifecycle Analysis of Systems
R. Curran et al. (Eds.)

doi:10.3233/978-1-61499-544-9-3

Developments and Challenges in Design for Sustainability of Electronics

A.R. BALKENENDE[a,1] and C.A. BAKKER[b]
[a] *Philips Research, High Tech Campus 4, 5656 AE Eindhoven, Netherlands*
[b] *Delft University of Technology, Faculty of Industrial Design Engineering, Delft, Netherlands*

Abstract. Sustainability of electronic products until recently mainly focused on improving the energy efficiency. Recently, resource efficiency has become of growing importance. Due to the use of relatively small amounts of many valuable and scarce materials, often intimately mixed, the design of electronic products deserves specific attention. From a materials perspective measures are needed to improve on recyclability. In addition to the use of recyclable materials, the ability to break connections between materials that are not compatible in recycling processes is crucial. Environmentally and economically more interesting than recovery of materials is the reuse of components or products. To enable multiple product lifecycles, product design should also explicitly address maintenance, upgradeability, modularity and disassembly. Design guidelines will be presented and challenges with respect to impact assessment and business model development will be discussed.

Keywords. Sustainability, product design, design tools, electronics, resource efficiency, recycling, re-use, circular economy, electronic waste, end-of-life treatment

Introduction

Sustainability describes our potential to maintain the well-being of humans and our environment over the long term. As we create, design and manufacture globally increasing volumes of electronic products, the sustainability of scarce and critical resources for new electronic products, as well as the treatment of electronic waste, become critical. The notion of sustainability for electronics in the past decades predominantly has been focused on energy efficiency. This is reflected in the Ecodesign Directive [1]. Examples are provided by the large reduction in standby power consumption of electronic devices and by the replacement of incandescent lamps by compact fluorescent lamps and LED-lamps.

In the past decade we have seen increased concerns about materials, focusing on both physical scarcity and economic criticality [2]. Demand and competition for finite and critical resources will continue to increase, and pressure on resources is causing greater environmental degradation and fragility.

In the field of Design for Sustainability this primarily leads to a focus on improved recyclability of products. The high complexity of electronic products with

[1] Corresponding Author, E-mail: ruud.balkenende@philips.com

their intimate mixing of many materials limits the amount of valuable materials that are actually recovered. Further, material value is usually only a small fraction of the actual product value in the case of electronic products. The economic perspective of recycling of electronics is thus limited. Higher value can be retrieved if modules or the product as an entity are used again. Therefore, the idea of transitioning to a circular economy, in which product life is extended to multiple lifecycles, is currently being explored.

This paper will give an overview of the product requirements, business models and environmental assessment methods needed to enable this transition to a circular economy. Examples from lamps recently developed by Philips Lighting will be used.

1. Circular economy

Since the industrial revolution, our economies have developed a 'take-make-consume and dispose' pattern of growth. Valuable materials are easily lost upon disposal of a product at the end of its lifecycle. The transition to a more circular economy requires changes throughout value chains, from product design to new business and market models, and from new ways of turning waste into a resource to new models of consumer behavior [3].

The transition to a circular economy will result in a more efficient use of resources. This is particularly relevant in the electronics area, where products contain a large variety of valuable and critical materials. Enabling effective recycling, i.e. recovery of the materials is therefore a prerequisite. However, as such this is insufficient: 80%-90% of the value and energy is lost during recycling, where highly functional electronics are simply turned into a kind of ore from which only part of the materials are eventually recovered.

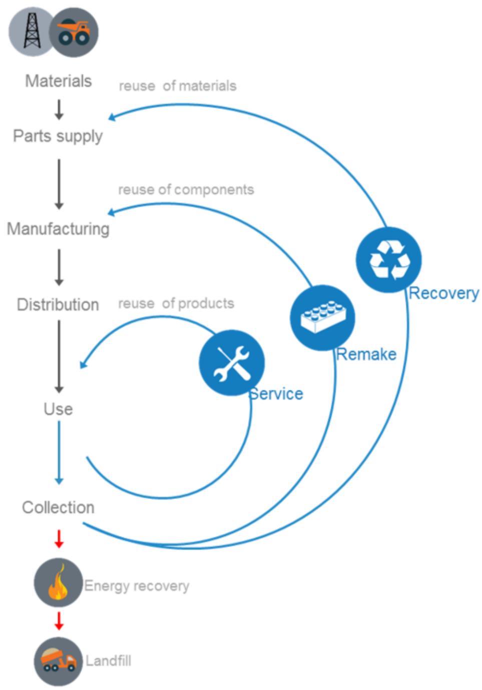

Figure 1. Product life cycles in the technological product sphere.

In addition to optimizing for recycling (materials recovery), electronic products should therefore also be designed for reuse, repair, and refurbishment (implying recovery/harvesting at the level of the product) as well as parts harvesting (recovery at the component level). This is represented in the circular structure of figure 1 by the three loops Service, Remake and Recovery.

In the following we will focus on recent developments of increasing the resource efficiency of electronic products. The focus is on product design. This leads to specific challenges in a number of areas. Primarily, this requires design methodologies and tools. Such tools must be based on proper insights in dealing with products at the end of a lifecycle. This in turn requires insight in the relation between product and business model: services lead to other requirements than sales. To enable assessment of the environmental impact reliable and transparent assessment methods are required. Finally, in the case of electronics specific challenges arise from miniaturization and increasing integration of functionalities as well as embedding of electronics in other materials. In the next sections these aspects will be addressed in more detail.

2. Product requirements for multiple lifecycles

Insight in the way in which a product a product can be designed for multiple lifecycles provides an essential starting point. Knowledge on the way in which a product is dealt with during and at the end of a lifecycle must thus be acquired and related to the design properties. In the case that the product will be re-used suitability for appropriate maintenance and cleaning is a prerequisite. Ultimately, the product might be disposed of when it is at the end of its functional life as an entity. In that case optimal recycling, i.e. maximum recovery of the constituting materials is the target. In between are options like refurbishment, remanufacturing and parts harvesting.

A recent analysis of Philips and TU Delft based on product use and service requirements distinguishes a number of aspects that need specific attention when designing for multiple lifecycles [4].

- *Maintenance* enables the prolonged use of products and consists of all aspects related to delivering performance for as long as possible in the use phase when the product is with the customer. Lifetime prognostics, which allows to predict the remaining future performance of a product, is a useful addition.
- *Upgradeability and adaptability* describes products that will last long (functionality), are used long (desirability) and take into account a change in expectations from a product. Time becomes an explicit factor in design.
- *Disassembly* is part of every circle. It is the first step in most actions performed to the product in order to either extend its lifetime or to give a new life to the components or materials. In general, disassembly needs to be non-destructive if the product or component will be reused, implying that also re-assembly has to be taken into account.
- *Modularity* implies the ability to reuse components or refurbish or remanufacture a product and consists of all actions performed when a product is returned from the customer
- *Recycling* enables the reuse of materials and consists of recovery of pure materials at end-of-life to secure real resource efficiency and as the last option to recover any remaining value that a product or component has. This means that, in contrast to the previous aspects, recyclability is a mandatory requirement for every product. In a circular economy, however, recycling must be postponed as long as possible.

Figure 2 depicts these focal areas and their main intention. Challenges that need to be addressed in design are the complex relationship between product design and business models, technological versus economical life time of a product (family) and its components, as well as insight in the behavior of users during product life and at the end of a product life cycle.

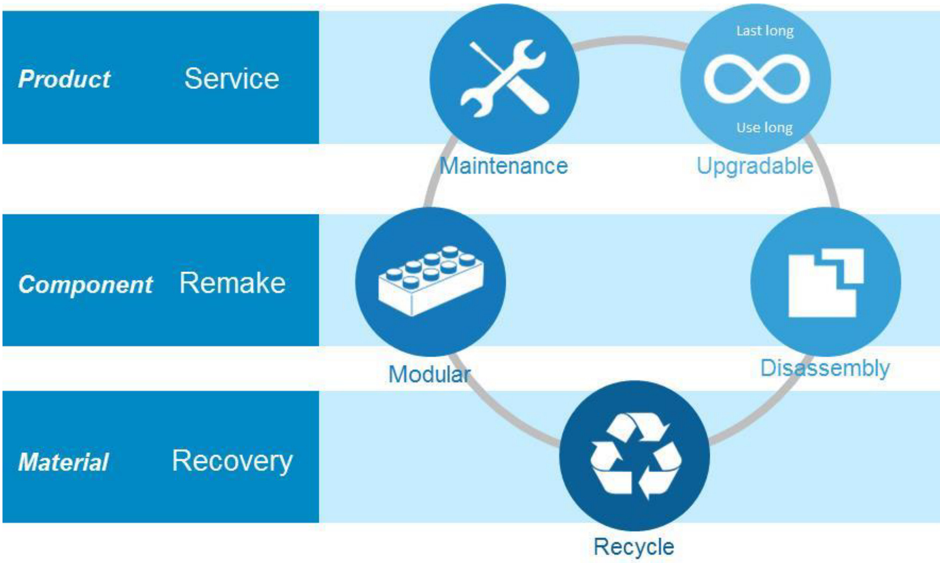

Figure 2. Main topics in circular product design.

3. Design guidelines

Product design usually aims at producing a product with a particular performance at minimum cost, the latter implying particular material choices and – in the case of most electronic products – suitability for mass production. Increasingly, end-of-life treatment is taken into account, but usually limited to a compliance level. Ideally, the topics outlined in the previous section are taken into account.

Recyclability is essential for all electronics products, irrespective of their use and associated business model. To obtain insight in the effect of pre-processing (i.e. shredding) conditions and separation procedures, a large batch of 'standard' LED lamps has been processed By studying the resulting fragments, the recycling yield could be directly linked to various design aspects. Some results of the test recycling runs are shown in Figure 3. Similar experiments have been done on LCD displays, also involving (partly) manual disassembly [5].

The basic requirement for improved recyclability is to establish well-defined material streams. It turns out that, even if recyclable materials are used, the way in which different materials are connected is crucial. An example is the screwed connection between a LED PCB and the heat sink. This causes that the aluminum heat sink cannot be separated effectively from the electronics, thus limiting the recyclability of both aluminum and electronics.

Based on such recycling insights guidelines were derived that strongly focus on the ability to break connections under actual disintegration or dismantling conditions. Electronic components are considered separately; as effective recycling routes exist for recovering many elements from complex electronic parts. The resulting guidelines for recyclability are summarized in Figure 4.

Figure 3. LED lamps and material fractions from large scale shredding of LED lamps [5].

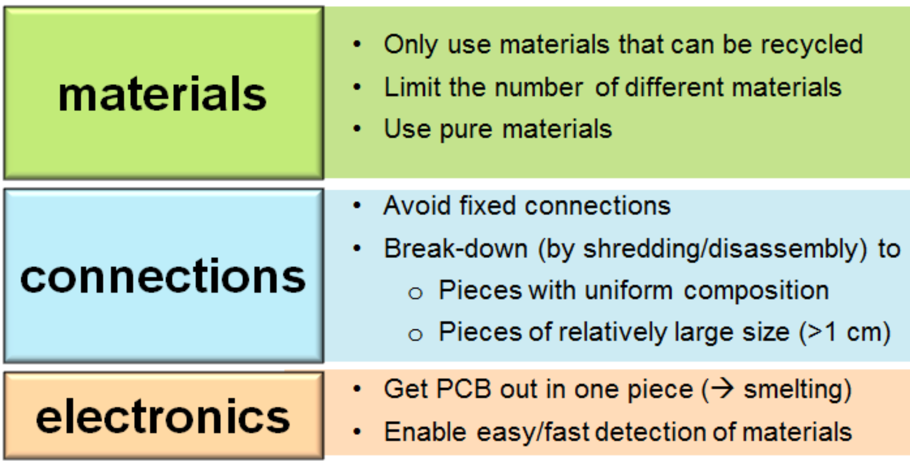

Figure 4. Design guidelines for recycling [5].

To enable re-use of components and products instead of recovery of materials, this approach should be extended to enable resource efficiency at all stages of the product life cycle taking also into account maintenance, upgradeability, modularity and disassembly. This leads to additional aspects that deserve specific attention in design as is shown in Figure 5 [4].

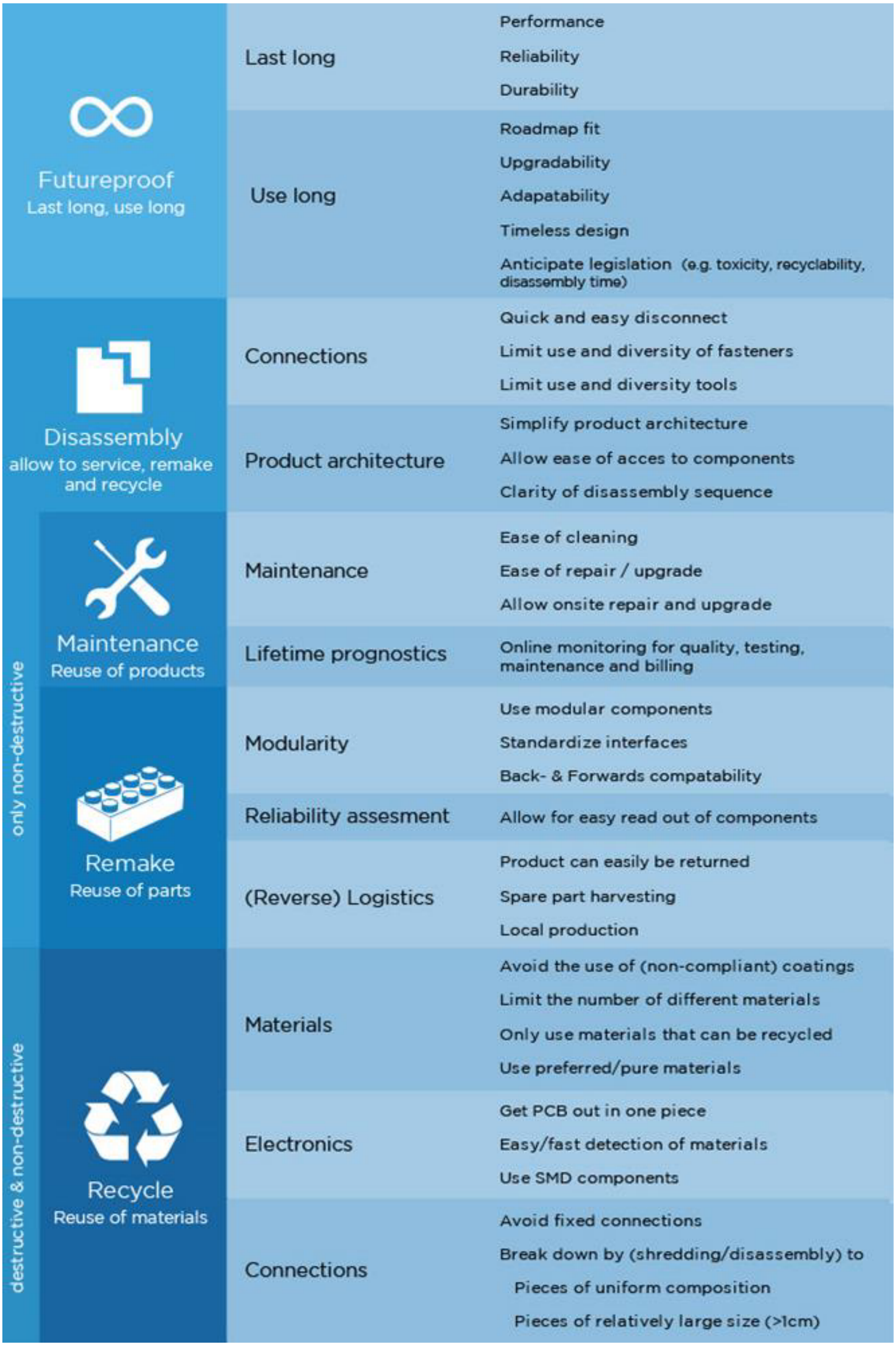

Figure 5. Design guidelines for design for multiple lifecycles.

4. Environmental impact assessment

The ability to assess specific properties is crucial for product specification as well as impact evaluation. Life cycle analysis provides a useful starting point in determining the environmental impact of an existing product. The level of detail required and the uncertainty in many database values makes this method less useful for the initial design stages. The development of transparent (semi-)quantitative methods to enable feedback on choices early in the design process is therefore a major challenge.

The commonly used methodology is Life Cycle Assessment (LCA). Dealing with the end-of-life stages of products (i.e. reuse, remanufacture, recycling) is one of the significant challenges facing LCA, because the assessment needs to take into account the lifespan of the products and the technological changes over time. There is currently no generally accepted approach in LCA about how to deal with reuse, remanufacture and recycling. The international LCA standards (ISO 14040/44) only give general guidelines. However, the details of different treatments at the end of a lifecycle may have a decisive influence on the results.

Proper assessment needs accurate insight in the way in which a product is dealt with at the end of a lifecycle. This implies that knowledge on the end-of-life treatments of a product is not only essential to take into account during the design stage, but also is a critical starting point in assessing the environmental impact.

Most assessment methods for recyclability determine the fraction of a product that is recycled, usually based on the weight of the materials involved. Such an approach does not take into account fixation of materials that are not compatible in the final recovery processes. It also neglects the actual environmental impact of different materials, implying that recovery of bulk materials is rewarded above recovery of critical materials. This is illustrated in Figure 6 for the materials present in a LCD television.

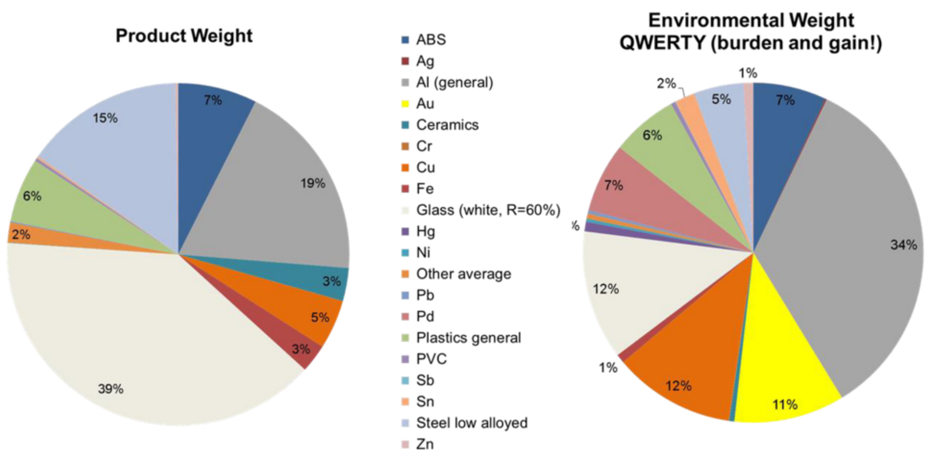

Figure 6. Product composition and environmental weighted composition of a LCD television [6].

The concept of avoided losses (in terms of materials, environmental impact and value) meets the objections mentioned above and deserves further development. Also, aspects like dematerialization, services, identification at end-of-life and life time prognostics, will be rewarded, whereas these in current methods often appear unfavorable. A complication is that methodologies based on avoided losses require detailed knowledge on end-of-life treatments and their associated limited yields.

As illustration we will consider a ‘standard’ LED spot (MR16) which constitutes a relatively large heat spreader made of die-casted aluminum to which both the PCB containing the driver electronics and the PCB with the LEDs are screwed. Upon shredding the PCBs to a large extent remain attached to the heat spreader. By introducing fracture lines in the aluminum heat spreader along the screw holes, fracturing of the aluminum is controlled. This leads to release of the screws and detachment of the PCBs, which can now be separated into a suitable stream for further recovery as is shown in Figure 7.

The actual recyclability that is subsequently calculated depends on the definition used; the table shows values assuming optimal separation of the fragments resulting from shredding.

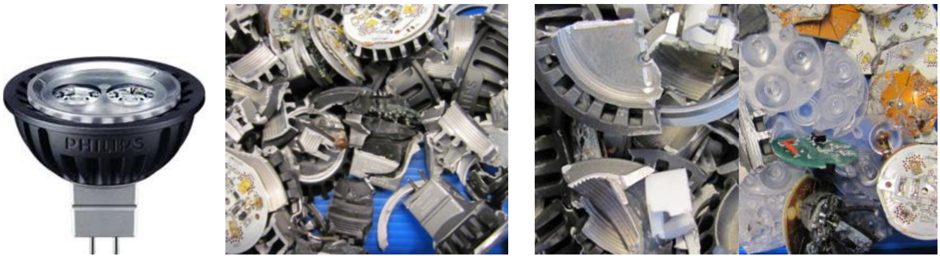

Figure 7. MR16 spot light, fragmentation resulting from shredding, and fragmentation resulting from shredding with fracture lines.

Table 1. Recyclability rating according to various definitions assuming optimal separation of fragments.

In recycling-%	**standard**	**+fracture lines**	
WEEE (wt)	82	92	Weight-basis, determined after separation, i.e. neglecting recovery yield
Strict (wt)	41	67	Weight-basis, determined after actual recovery
QWERTY (env)	63	80	Environmental impact-basis, determined after actual recovery

Notably, it has been found that current WEEE recyclability targets do not always provide the right design incentives. The focus on overall weight neglects the importance of recovery of valuable and critical materials. The detrimental effect of unbreakable connections between incompatible materials is ignored and actual recovery yields are not taken into account. Regulations in which these aspects are addressed, although likely more complicated, are needed to drive towards increased resource efficiency.

5. Service-based business models for electronic products

Service-based business models already exist in B2B (e.g. Rolls Royce jet engines) and B2C markets (e.g. mobile phones). In many cases this is accompanied by transfer of ownership. However, if extension of product life to multiple lifecycles is of interest, business models access to a product becomes more important than its ownership. Understanding intrinsic remaining product value and tracking its change over time is fundamental to set up such product-service systems in an economic sound way. In various product categories manufacturers are exploring opportunities for setting up and further developing such business models.

As an example we discuss the Light-as-a-Service (LaaS) concept. Shifting from sales to 'light as a service' requires changes in every part of the value chain. It starts with the product design. Products for sale are optimized to have the highest value for the lowest price at the moment of sale. Products for LaaS require optimization for serviceability and total lifetime. Technological advancements and changes in consumer demand should be foreseen through roadmaps that incorporate expected technological developments as well as consumer behavior. A shift will occur from reliance on ownership to optimal service of space and quality of light.

Handling of a product during its lifetime requires an integrated service organization that manages the servicing needs of the product, whilst taking care of the reverse logistics to get the product or part back to the right place in the company (production, parts storage, etc.). Predictable whole life performance of building assets, including performance systems and maintaining a high standard of efficiency will be crucial. The marketing will be different and the products need to be financed upfront.

Setting up LaaS as a business requires the right products, business logistics that fit the model, partners that serve parts of the ecosystem, marketing concepts and an organization that can and will set the right targets and propositions. A concrete example is provided by the 10-year performance lighting contract between Philips and the Washington Metropolitan Area Transit Authority (WMATA) [7]. Over 13,000 lighting fixtures are being upgraded to a custom-designed LED lighting solution at no upfront cost to WMATA providing lighting-as-a-service in 25 WMATA parking garages. Philips will monitor and maintain the system during the life of the contract, and also reclaim and recycle any parts of its system that must be replaced. The luminairs used (Figure 8) feature the latest Philips LUXEON LED technology, as well as a modular design that can be configured to the lighting needs of each garage. An adaptive motion response system and innovative wireless controls allow the system to dim when no one is present and seamlessly increase light levels when a space is occupied – creating a safe environment while achieving even higher energy savings.

Figure 8. Modular luminairs (right: G3; left: EcoForm) used in WMATA Light-as-a-Service contract.

Providing services also opens new ways to product trust and attachment. Prolongation of product life span by stimulating an emotional bond between user and product is often considered as an interesting way to improve on sustainability by affecting behavior. However, such an approach links to personal interests and is therefore difficult to achieve on a large scale merely though product design. For service-based circular products trust and attachment might be achieved in different, more predictable ways. Key here is the recognition that product reliability and regular direct interaction with customers on a service basis may lead to different form of trust and attachment: not only to the product, but also to the manufacturer or service provider.

6. Specific challenges for electronics

From sustainability perspective especially technologically advanced products (e.g. electronics, ICT, automotive, medical equipment) pose special challenges and deserve dedicated attention. In part this is due to their intrinsic complexity. Recent developments like the *embedding of electronics* in all kind of other items largely complicate end-of-life treatment: electronics are diluted with other materials to the extent that high yield recovery becomes almost impossible. As an example we refer to an analysis of disposal and recycling of electronics embedded in textiles [8].

On the other hand, increased functionality might also be used to determine the optimal treatment at a particular stage of product use. Connectivity opens opportunities for identification and life-time prognostics. This enables improved handling at the end of a lifecycle. Addressing customer behavior and setting up product service systems is also especially interesting in the context of advanced systems.

For introducing services into the *complex market of relatively small medium-valued electronic products*, lessons can be learned from experience with large and valuable electronic products. An example of a service based business model for this type of equipment is in the professional copier/printer business. The (professional) customer buys a service from the producer, which comprises the delivery of the device, service, disposal at end of life, change of toner cartridges, and sometimes even supply of paper. The producer invoices per page printed. Producers are forced to understand the need of their customers in a very precise way. This has led to robust and modular appliances on one hand and high reactivity on customer requests on the other. The difficulty in the transition is linking producer, service company, logistics, sorting, harvesting and final treatment. This difficulty becomes significantly more pronounced for lower valued electronics.

7. Conclusions

Design for sustainability increasingly is driven by challenges in resource efficiency. Electronic products in particular contain a diversity of valuable and critical materials, often intimately mixed and in small quantities. In order to retrieve materials, preferably at the level of components or products, it is essential that already at the stage of product design the likely treatments at the end of a product lifecycle are considered.

To improve on the recyclability of products not only recyclable materials should be used, but also the ability to break connections between materials should be explicitly taken into account

To enable multiple product lifecycles, product design should also explicitly address maintenance, upgradeability, modularity and disassembly.

Proper assessment of the environmental impact needs accurate insight in the way in which a product is dealt with at the end of a lifecycle. Methodologies to account for multiple product lifecycles are still in an initial stage. Further, the development of methods based on avoided losses instead of recovered fractions deserves further development.

Acknowledgement

The authors wish to acknowledge the contributions of and discussions with Maarten van den Berg (TU Delft) on design guidelines for circular product use and Maurice Aerts (Philips Lighting) on light as a service. The insights discussed here are partly based on results obtained in the GreenElec project that received funding from the ENIAC Joint Undertaking under grant agreement n° 296127.

References

[1] *Ecodesign of Energy Related Products* Directive 2009/125/EC.
[2] Committee on Critical Mineral Impacts of the U.S. Economy, Committee on Earth Resources, National Research Council, *Minerals, Critical Minerals, and the U.S. Economy*, National Academies Press, 2008.
[3] Ellen MacArthur Foundation, *Towards the Circular Economy. Economic and business rationale for an accelerated transition*, 2012.
[4] M.R. van den Berg and C.A. Bakker, A product design framework for a Circular Economy, in '*Proceedings of the PLATE conference*', Nottingham Trent University, 17-19 June 2015.
[5] A.R. Balkenende, V. Occhionorelli, W. van Meensel, J. Felix, S. Sjölin, M. Aerts, J. Huisman, J. Becker, A. van Schaik, M. Reuter, Greenelec: Product Design Linked to Recycling, in '*Proceedings of Towards a Resource Efficient Economy, Going Green - Care Innovation 2014*', Vienna, Austria, 17-20 November 2014.
[6] J.Huisman, *The QWERTY/EE concept: quantifying recyclability and eco-efficiency for end of life treatment of consumer electronic products*, Delft University of Technology, Delft, 2003.
[7] S. Casanova, Philips North America, 2013, *Washington Metro Goes Green & Saves Green with Philips Performance Lighting Contract, Delivering on Sustainability Goals with 15 Million kWh Saved Annually,* Accessed 01.06.2015 [Online]. Available: http://www.newscenter.philips.com/us_en/standard/news/press/2013/20131112-philips-wmata.wpd,
[8] A.R. Köhler, C.L. Hilty, and C.A. Bakker, Prospective Impacts of Electronic Textiles on Recycling and Disposal, *Journal of Industrial Ecology* 15, 496-511, 2011.