Chapter 9

Circular Product Design: Addressing Critical Materials through Design

Conny Bakker*,‡, Marcel den Hollander*, David Peck†, Ruud Balkenende*
**TU Delft, Faculty of Industrial Design Engineering,*
Landbergstraat 15, 2628 CE Delft, The Netherlands
†TU Delft, Faculty of Architecture and the Built Environment,
Julianalaan 134, 2628 BL Delft, The Netherlands

For product designers, the world has traditionally been one of resource abundance. Introducing them to a resource-constrained world thus requires new design strategies. This chapter explores how embedding circular economy principles into design practice and education could help product designers take critical material problems into account. We introduce four product design strategies that address materials criticality: (1) avoiding and (2) minimizing the use of critical materials, (3) designing products for prolonged use and reuse, and (4) designing products for recycling. The 'circular' strategies (3) and (4) are elaborated, as these sit most firmly within the remit of product design. This leads to a typology of circular product design that redefines product and material lifetime in terms of obsolescence, and introduces a range of approaches to resist, postpone or reverse product and material obsolescence. The typology establishes the basis for the field of circular product design, bringing together design approaches that were until this date unconnected and paving the way for the development of detailed design methods.

9.1 Introduction

> "Product designers have never been taught to regard materials as anything but commodities to be employed as necessary or convenient."[1]

Product designers and engineers have traditionally focused on achieving increasingly higher performance in products, using the full range of elements in the periodic table. Whilst this has delivered an amazing range

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‡Corresponding author: Conny Bakker, c.a.bakker@tudelft.nl

of products and technologies, it has also resulted in increasing material complexity, decreasing recycling rates and thus increasing criticality risks.[2] In this chapter we will discuss the lack of awareness of product designers with regards to critical materials and explore how embedding circular economy principles into design practice and education could mitigate some of the concerns raised. Criticality of materials is defined by their perceived supply risk, the environmental implications of mining and processing the materials, and a company's (or country's) vulnerability to supply disruption.[2]

9.2 Four Product Design Strategies to Address Criticality

Even though product designers are increasingly asked to consider energy efficiency and recyclability when making a choice of materials, criticality aspects have hardly received any attention so far.[3] This can be explained in part by understanding the way product designers choose materials: they usually base their choice on a trade-off between functionality, quality (grade) and cost. These trade-offs are done both for engineering material requirements[4] and for more subjective aspects, such as the user perceptions of material qualities and meanings.[5] When it comes to specific metal alloys or components such as printed circuit boards, designers choose the constituent materials, which often contain critical elements, only implicitly.[3]

In the case of mobile electronics, for instance, the highly competitive market seeks designs that are thinner, lighter, higher performance, more power efficient (e.g. battery) and robust (e.g. waterproof).[6] This has driven designers to select high performance components that use critical materials, and this increases the risk of critical materials problems. At the same time societies, companies and governments have rapidly become dependent on electronics and the impact of any restriction in the supply of the critical materials used in these technologies could be severe.[3,7] Duclos *et al.*, when assessing criticality risks for the company GE[8] argue: "Elements that are determined to be high in both impact to the company and in supply and price risk require a plan either to stabilize their supply or to minimize their usage." In this chapter we set out to develop such a 'plan' for product designers.

What possible strategies are there for product designers to address critical materials? Following the European waste framework hierarchy of prevent, reduce, reuse, recycle[9] there are basically four strategies: 1) avoiding the use of critical materials, 2) minimizing the use of critical materials, 3) designing products for prolonged use and reuse, which results in a decreased use of critical materials over time, and 4) designing products that are easy to recycle, which results in the recovery and reuse of critical materials. We will address these four strategies in more detail here.

9.2.1 *Strategy 1: Avoid the use of critical materials*

If product performance specifications allow, designers can specify alternative materials that do not contain critical elements. Substituting one material for another is however not always possible. Sometimes the characteristics of a product are such that material substitution results in unwanted changes in a product's properties and/or performance.[3] And for some critical elements, there simply are no known substitutes, meaning that extensive research would be needed to develop a suitable alternative.[8] Designers who want to avoid using critical materials may choose to work with material scientists and process engineers to explore material substitution options. This will require that product designers have a good knowledge and understanding of materials properties and production processes. To give an example, the production of PET (polyethylene terephthalate) plastic bottles requires the use of germanium (a critical material) as polymerization catalyst. During the production of PET the catalyst material dissipates completely into the PET and is not recovered.[10] A designer who wants to address this issue needs to work closely with material scientists and process engineers to find substitute catalyst materials.

Designers could also take a more systemic perspective and look for alternative products and technologies that could address a user's needs.[8] A case study of wind turbines was for instance presented by Habib & Wenzel.[11] The case study demonstrates, using a product design tree approach, the availability of several viable (and non-critical) alternatives to the direct-drive wind turbine technology that currently utilizes neodymium and dysprosium in its permanent magnet generator.

9.2.2 *Strategy 2: Minimize the use of critical materials*

This is a less radical strategy than avoiding the use of critical materials altogether. Greenfield *et al.*[7] describe the example of the electronic component manufacturer TDK, that managed to reduce its dependence on dysprosium by 20–50% through process redesign. In some cases, improving processes might be relatively straightforward, as the use of critical materials was never scrutinized in much detail before. For product designers to apply this strategy successfully, they again need to work closely with material scientists and process engineers. On a more systemic level, efficiency improvements can be made through a change in the basic technology, for instance the move from fluorescent light bulbs to LED lighting.[12] Nevertheless, minimizing the use of critical materials in products has potential drawbacks: even though the amount of critical materials per product may decrease, the total volume of product sales may increase. This may negate any advances made in reducing the use of critical materials. And secondly, ever smaller amounts of critical materials in complex components (such as printed circuit boards) may make critical material recovery through recycling even harder.[3]

9.2.3 *Strategy 3: Design products for prolonged use and reuse*

Designing products that last, and that can be repaired, refurbished and remanufactured easily and economically, will result in a decrease in the use of critical materials over time. In the words of Stahel[13] this reuse of products results in: "a slowdown in the flow of materials and goods through the economy, from raw materials production to recycling or disposal." Like in the previous strategy, creating products with a longer service-life will not avoid the use of critical materials, but it will reduce their overall consumption. Hampus *et al.*[14] calculate that in general, the extension of the use phase of electronic products (through repair) leads to a decreased use of critical materials, but they also see limitations of this approach. For instance, if the prolonged lifetime comes at the cost of an increased critical material content per product or component. This is especially problematic if high-quality recycling is lacking.[14]

9.2.4 *Strategy 4: Design products for ease of recycling*

Design for recycling is aimed at recovery of materials from end-of-life products. Its essential objective is "to keep the quality of the old material as high as possible".[15] Designers should therefore ensure that products consist of materials that are compatible in the recycling process, or that can be separated in compatible material fractions after manual or mechanical disassembly. In spite of the extensive body of literature on design for recycling, there is hardly any literature on design for recycling of critical materials. This may prove to be an important research gap, because the current recycling rate of most critical materials is extremely low: around 1%.[16] This is partially because they are used in very small quantities in products, and are often highly mixed with other materials (as alloys for example), which makes them difficult to separate.[3] According to Ylä-Mella & Pongrácz,[17] other reasons for the low recycling rates of critical materials are missing economic incentives for recycling, and a lack of appropriate recycling technologies and infrastructure. Complicating factors are the current trend of product miniaturization and increased integration of materials, which is good from the perspective of minimization of the use of critical materials, but which may hamper their recovery.

These four strategies are complementary and interdependent. Focusing only on one strategy may have adverse effects, as was illustrated in the examples above. Furthermore, the concept of critical materials is relative and subject to regular change.[2] Materials become more or less critical over time as geopolitical circumstances change, new mines open up or old mines close down, new technologies develop with different material requirements, or new data becomes available about physical reserves or environmental impacts of mining and processing. Designers therefore need to take a systemic perspective, and if the use of critical materials cannot be avoided (strategy 1), they should aim at using the three other strategies in conjunction, all the while monitoring the possibility of trade-offs and negative side-effects over time.

The critical materials problem puts the work of product designers in sharp perspective. Designers are familiar with the general solutions described in strategies 1 and 2: creating innovative new technologies, developing substitutions and making efficient use of resources. They have just not applied their skills to critical materials problems very often (if at all).

Designers are however quite unfamiliar with strategies 3 and 4: creating products for prolonged use and reuse, and designing for recycling. The current product design methodology, taught at design schools, has a bias towards product acquisition and first use. Strategies 3 and 4, however, deal with everything that happens, or could potentially happen, to a product (and its constituent materials) in its subsequent lives. The current product design methods that address reuse, repair, remanufacture or recycling lack a coherent framework and common language, they are severely out of date and are fragmented throughout design research literature and practice. Strategies 3 and 4 therefore need further exploration and development. As they fit well within the remit of Circular Product Design, in the remainder of this chapter we will refer to circular product design when discussing strategies 3 and 4. We will attempt to create an organisational structure and common language for circular product design that can guide designers when addressing critical materials through design.

9.3 Circular Product Design

Circular product design aims at keeping products, components and materials at their highest economic value and lowest environmental impact for as long as possible, by designing for long product life and by looping back used products, components and materials into the economic system through repair, refurbishment, remanufacture and recycling.

9.3.1 *Design for product integrity*

Instead of discussing the design of products for 'prolonged use and reuse', we introduce the term Product Integrity. This is defined as the extent to which a product remains identical to its original (e.g. 'as manufactured') state, over time. The idea of preserving as much of the original product as possible was captured by the Ellen MacArthur Foundation in their descriptions of the principles of a circular economy: "The tighter the circle, i.e., the less a product has to be changed in reuse, refurbishment and remanufacturing, . . . the higher the potential savings on the shares of material, labor, energy and capital embedded in the product. . .".[18] This echoes the ideas of Walter Stahel who introduced the Inertia Principle in his book *The Performance Economy*[13]: "The smaller the loop, the more profitable it is. Do not repair what is not broken, do not remanufacture something that can be repaired, do not recycle a product that can be remanufactured." The starting point is the original product, and the intention of the Inertia principle is to keep the product in this state, or in a state as close as possible to the original product, for as long as possible, thus minimizing and ideally eliminating environmental costs when performing interventions to preserve or restore the product's added economic value over time. Design for product integrity is a more precise way of saying 'design for prolonged product use' because it also gives guidance: there is a priority order; As the Inertia principle starts from the highest level of product integrity, moving down the hierarchy may be inevitable in the real world, but is not the preferred direction.

9.3.2 *Design for recycling*

Recycling of materials implies loss of function and value. Nevertheless, recycling is the necessary 'last resort' option when products or parts are no longer useful. This means that, in contrast to the previous strategy, recyclability is a mandatory requirement for every product.[19]

The goal of design for recycling in a Circular Economy is to create closed loop, or primary, recycling. This is mechanical, physical and/or chemical reprocessing, where the reprocessed materials have properties equivalent to the original materials. In the field of recycling, primary, secondary, tertiary and quaternary recycling is distinguished,[20] creating a priority order of decreasing materials integrity. In the case of secondary recycling, the reprocessed materials have lower properties than the original materials. This is also referred to as downcycling or downgrading.[20] Tertiary recycling (recovery of chemical constituents, or feedstock recycling) and quaternary recycling (recovery of energy) are not considered in this chapter, as in these instances materials integrity is fully lost.

9.4 Typology of Circular Product Design

In order to understand how 'Design for product integrity' and 'Design for recycling (or materials integrity)' can be used to address critical materials challenges, they need to be brought together in a coherent framework that gives guidance to product designers, and that allows for a discussion of the interaction between the strategies. In this section the development of a typology for circular product design is described: a categorization of design approaches based on product and materials integrity.

The development of a typology for circular product design is important because of the following reasons[21] (1) a typology helps designers decide how to proceed when developing a product, (2) a typology helps establish a common language for the field of circular product design. No such common language exists today, but we need it if we want to begin addressing issues of critical materials. (3) A typology provides circular product design with an organizational structure which is currently missing, (4) a typology helps legitimize the nascent field of circular product design by providing a range of clearly distinct and ordered design approaches, and (5) a typology can be used in education. As materials' criticality is not currently taught in design education,[22] a typology could be a valuable tool for increasing design students' awareness of critical materials issues.

The first ordering principle of the typology is the hierarchy imposed by the inertia principle and the recycling priority order, as described above. This is not enough, however, because this hierarchy exists in a linear economy as well. We need a second ordering principle in order to create design approaches relevant for a circular economy. One of the fundamental principles of a circular economy is that ‘waste’ no longer exists. A circular economy is, in principle, a closed loop system. From a material flow perspective, resources that have entered the circular economy have to remain accounted for at all times: before, during, and after their lifetime as useful products.[23] It follows that product lifetime is a key concept in a circular economy, and will be used as a second ordering principle.

9.4.1 *Defining product lifetime*

A product lifetime can end for many reasons. Often, definitions focus on the functional lifespan of a product.[24] It is however well-know that products stop being used for non-functional reasons as well. Ashby,[4] for instance, distinguishes the end of a product’s physical life, functional life, and technical life, as well as economical life, legal life and desirability life. In order to include both objective and subjective reasons for the end of a product’s useful life, we propose to define product lifetime in terms of obsolescence. A product becomes obsolete if it is no longer considered useful or significant by its user.[25] Obsolescence does not have to be permanent, it can often be reversed. This leads to the following definitions[23]:

> “**Product lifetime** is the duration of the period that starts at the moment a product is released for use after manufacture and ends at the moment a product becomes obsolete beyond recovery.”[23]
>
> “**Recovery** is a term for any operation with the primary aim of reversing obsolescence.”[23]

These definitions can be applied to materials as well, by substituting ‘product’ with ‘material’. The difference between a material and a product is not as clear-cut as it may seem at first sight, but for the clarity of the typology presented here, we will assume that ‘product’ mainly refers to finished end-products and components.

9.4.2 *Resisting, postponing and reversing obsolescence*

We can now build on the concept of product and materials integrity by arguing that designers in a circular economy should firstly aim to prevent a product or material from becoming obsolete (i.e. by resisting and postponing obsolescence) and secondly, make sure that resources can be recovered with the highest level of integrity (i.e. reversing obsolescence). These goals can be pursued at the level of products and components, referred to as

Table 9.1: A Typology of Circular Product Design.

Circular product design	
Design for Product integrity	Design for recycling (materials integrity)
Inherently **long** product use (resisting obsolescence) Physical durability: designing a product resistant to degradation over time Emotional durability: designing a product that stimulates feelings of attachment	Inherently **long** materials use (resisting obsolescence) Physical durability: choosing materials resistant to (or stabilized against) degradation during reprocessing and subsequent use Emotional durability: creating pleasing aesthetics with reprocessed materials
Extended product use (postponing obsolescence) Maintain: designing a product that can, with regular servicing, easily retain its functional capabilities and/or cosmetic condition Upgrade: enhancing a product's functional capabilities and/or cosmetic condition, relative to the original design specification	**Extended** materials use (postponing obsolescence) Upgrade: using additives to enhance the functional capabilities or cosmetic condition of reprocessed material, relative to the original material properties
Product **recovery** (reversing obsolescence) Recontextualize: designing a product to be re-usable in a different context than it was originally designed for, without any remedial action Repair, refurbish and remanufacture: designing a product to be easily brought back to working condition. In the case of remanufacture, the product is brought back to at least OEM original specification. In the case of repair and refurbish, the condition of the repaired or refurbished product may be inferior to the original specification	Materials **recovery** (reversing obsolescence) Repair, refurbish and remanufacture: ensuring it is easy to separate a product's materials from potential sources of contamination during the recycling process. In the case of primary recycling, the reprocessed materials have equivalent properties compared to the original materials (equivalent to remanufacture). Secondary recycling results in lesser properties (equivalent to repair or refurbishing)

design for product integrity, or at the level of materials, referred to as design for recycling (or materials integrity).

Table 9.1 gives a typology of Circular Product Design, with different design approaches to resist, postpone and reverse obsolescence. For instance, products with a high physical and emotional durability that are intended to be used for a long time, 'resist' obsolescence and operate at a high level of product integrity. Similarly, choosing materials with a high physical durability (i.e. that are resistant to, or stabilized against, degradation during reprocessing and subsequent use) helps 'resist' obsolescence in the recycling process.[20] And, creating a new aesthetic with reprocessed materials could contribute to the acceptance of imperfection as a unique material experience[26] and strengthen a product's emotional durability.[27]

In order to extend product use, or 'postpone' obsolescence, designers can create products that are easy to maintain and/or upgrade. Where maintenance is done to *retain* a product's functional capabilities and/or cosmetic condition, 'upgrading' is usually done to *enhance* its functionality or cosmetics, and is instigated by a change in the product's context of use. From a recycling perspective, 'upgrading' refers to adding virgin material or other 'additives' to a reprocessed material, in order to enhance its functional and/or cosmetic capabilities.

In order to recover products and materials, in other words, to 'reverse' obsolescence, designers can create products that are easy to re-use in a different context, and that can be repaired, refurbished or remanufactured. Repair, refurbishment and remanufacture are differentiated according to the quality of the recovered product relative to the original.[28] In the case of remanufacturing, the product is brought back to at least Original Equipment Manufacturer (OEM) specification. In the case of repair and refurbishing, the condition of the repaired or refurbished product may be inferior to the original specification.[28] This same line of reasoning is valid for recycling, with primary recycling resulting in reprocessed materials with equivalent properties as the original materials, and secondary recycling leading to a lower quality result.

9.5 Discussion

In this section we discuss the value of the typology for addressing critical materials. The typology of circular product design has the following advantages and limitations:

(1) It gives guidance. When for instance developing an electronic product, designers will first consider its physical and emotional durability. Without this, designing for ease of maintenance makes little sense, and a product that isn't durable may also not have enough residual value to be considered for repair or refurbishment. The typology has its limitations,

however. It is not suitable for materials that are supposed to biodegrade (product and material integrity is less relevant here). Also, the typology doesn't work very well for fast moving consumer goods such as toiletries and detergents. Critical materials however, occur mostly in durable goods, so this is not a major limitation.

(2) The typology establishes a common language. A first step has been made by redefining product lifetime in terms of obsolescence and bringing together the relevant design approaches for circular product design. The typology can now be used as a basis for a detailed development of design approaches and methods for circular product design.

(3) The typology provides an organizational structure. The hierarchies for product and materials integrity create a clear organizational structure. The typology brings out the parallels between product and materials integrity, stimulating designers to take both into account. However, the typology doesn't (yet) give guidance on how to address potential trade-offs and developments over time. For instance, given the current low recovery rates of critical materials, a long product life with robust and upgradeable products is possibly preferable to losing critical materials through inefficient recycling. Over time, with innovations in recycling technology, this could change and we may need to start looking at different product 'speeds' in a circular economy. Also, the typology doesn't address the potential environmental impacts of the different design approaches. The underlying assumption is that a longer product lifetime leads to an overall decrease in environmental impact, but there are possible exceptions that need to be acknowledged.[29]

(4) The typology establishes the basis for the field of circular product design. It brings together diverse and to this date unconnected design approaches under the umbrella of circular product design. One of the next steps should be the exploration of suitable circular business models. For example, in order to make a product that was designed for remanufacturing really work, obsolete products need to be consistently returned to the OEM to be remanufactured. This requires arrangements for reverse logistics and a transactional model that allows the (re)manufacturers to retain economic control of their product over time.[23] Some other interesting next steps have been indicated above, like temporal aspects and environmental impact assessments.

(5) Educational tool. The typology can be used for educational purposes, in line with the remarks made in the previous points.

9.6 Conclusion

In 2010, John Voeller[30] coined the term 'insufficient plenty' to discuss a world with "plenty of resources out there, but no guarantee that we . . . will have access to them." Preparing product designers for such a possible world will require them to develop skills and competencies beyond what their current design education offers. Three knowledge gaps were identified in this article. Firstly, product designers often lack even a basic understanding of what 'critical materials' are, and the instrumental role these materials have in creating high-performance products. Addressing this knowledge gap will require close collaboration with materials scientists and process engineers.

Secondly, designers need practical skills and up-to-date methods to enable them to design for maintenance, upgrading, repair, refurbishment, remanufacture and recycling; in other words: to do circular product design. The typology of circular product design presented in this chapter is a first step. Thirdly, designers need to learn how to adopt a systemic perspective towards critical materials. They need to understand the interdependencies between the different design strategies for addressing critical materials presented in this chapter, and need to be able to imagine trade-offs and possible negative consequences of their design interventions. In a circular economy, this would require designers (and companies) to monitor and manage their products and materials much closer, over time, in order to understand where these interdependencies and trade-offs might occur in practice.

These three knowledge gaps spell out a critical materials agenda for design education and design research on a methodological and a practical level. It includes bringing back a material culture in design education, invoking a deep understanding and love of the materials and processes involved in product design.

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