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Material Scarcity: A Reason for Responsibility in Technology Development and Product Design

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Abstract There are warning signs for impending scarcity of certain technology metals that play a critical role in high-tech products. The scarce elements are indispensable for the design of modern technologies with superior performance. Material scarcity can restrain future innovations and presents therefore a serious risk that must be counteracted. However, the risk is often underrated in the pursuit of technological progress. Many innovators seem to be inattentive to the limitations in availability of critical resources and the possible implications thereof. The present shortages in industrial supply with technology metals may be interpreted as a wake-up call for technology developers to tackle the issue with due consideration. The article reviews the materials scarcity phenomenon from the viewpoint of sustainable development ethics. The following questions are discussed: 'Should preventative actions be taken today in order to mitigate resource scarcity in future?' and 'Should technology developers feel responsible to do this?' The discussion presents arguments for industrial designers and engineers to create a sense of responsibility for the proactive mitigation of material scarcity. Being protagonists of the innovation system, they have the opportunity to lead change towards resource-aware technology development. The paper concludes by outlining ideas on how they can pioneer sustainable management of critical materials.

Keywords Eco-design · Eco-innovation · PGM · REE · Resource depletion · Precautionary principle · Sustainability ethics · Sustainable resource management

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Introduction

Recent disruptions in the industrial supply of certain exotic technology metals have focused new attention on a well-known sustainability issue: resource scarcity. Concern has been voiced over the limits in the future availability of special raw materials, such as rare earth elements (REE), platinum group metals (PGM) and other exotic elements (Angerer et al. 2009; Lifton 2009). Those elements are referred to as 'critical' with regard to their high supply insecurity and their economic and technological importance (EC 2010). Critical elements not only enable the design of high-tech products, but are also key constituents of clean or resource-efficient technologies. The current scarcity with regard to technology metals gives new impetus to the discussion about resource-preserving innovation strategies.

Sustainability experts and economists have repeatedly warned of the consequences of resource depletion throughout the past four decades (Meadows et al. 1972; Simpson et al. 2004; Gordon et al. 2006; inter alia). Although economists have often challenged the notion of resource scarcity (Tilton 2003), the fact that the industrial supply of raw materials is becoming more and more constrained cannot be ignored. There are numerous warning signs that some of the key enabling factors of material abundance (e.g. low energy prices) may not prevail in future. Satisfying the increasing demand will become difficult for geopolitical, environmental and economic reasons (Mudd and Ward 2008).

Nowadays, material scarcity is regarded as an economic and environmental dilemma (Kooroshy et al. 2010). The US Environmental Protection Agency (EPA) points out that "business-as-usual cannot continue" because the "rapid rise in material use has led to serious environmental effects" (EPA 2009). But it is not only the environmental risks that must be considered; the phenomenon also represents a serious risk to the welfare and prosperity of society because our modern technologies have become fairly dependent on critical elements. Many innovations could come to a halt if critical raw materials become unavailable or are subject to erratic price fluctuations. Emerging businesses, such as the renewable energy sector, will be immediately affected. Low-carbon technologies generate a growing demand for critical elements, but the newcomers on the resource market often lack reliable supply connections. Material scarcity can result in a development barrier for those countries that have few resources of their own and are dependent on raw material imports.

In spite of this, new technology and products have often been developed with little attention to possible constraints in the availability of critical materials. Over many decades, the paradigm of planned obsolescence has governed the design of industrial products (Cooper 2004). This marketing-driven attitude has resulted in enormous squandering of valuable materials in waste streams. The business-as-usual method has proven to be remarkably successful thus far, which is one of the reasons why many professionals who design and develop new products are under the false impression that the material scarcity phenomenon is a far-fetched problem. Technology developers seem to be relatively unaware of material scarcity and enterprises usually are not well-prepared to tackle the issue (PwCIL 2011). They are still optimistic that technological progress in combination with free market forces will continue to resolve material scarcity just as it has done in the past. However, this kind of resource optimism means that the societal, economic and environmental risks are underrated (Richards 2006). The World Resources Forum (WRF) warns that "we are losing ever more the freedom to shape the future of humanity" by continuing the business-as-usual mode of economic growth (WRF 2009).

Limits in the supply of raw materials and energy must be accounted for in the course of technological innovation (Richards 2006; Davidson et al. 2010). Industrial designers and engineers, for example, are directly affected by the symptoms of material scarcity as it limits their freedom of choice in the design process. At the same time, they have a large influence on the consumption of resources. They determine which and how many materials are incorporated into goods. Moreover, their design choices determine how long users will keep a product before replacing it with a new one. Hence, the design engineering discipline has the capacity to lead the change towards the efficient utilisation of resources.

This article discusses the question of whether technology developers should feel responsible for counteracting the risk of material scarcity. The first part of the article reviews the relevance of critical elements for technological innovation and recapitulates the different interpretations of resource scarcity. Then, the concept of sustainable development and the precautionary principle are reconsidered as ethical frameworks for responsibility. The discussion offers arguments for industrial designers and engineers to embrace material scarcity as a challenge to their profession.

The Material Base of Modern Technology

Mineral resources are extracted from the earth's lithosphere to produce and operate technological artefacts. Common base metals, including ferrous metals as well as aluminium, copper, zinc and several alloying metals (e.g. tin, nickel and chromium) play a dominant role in traditional technologies. Meanwhile, the so-called 'technology metals' have attained a prominent role in industry. Once considered of only marginal technological usefulness, these elements have proven their paramount importance in the progress in science and technology (Angerer et al. 2009; Buchert et al. 2009). Almost every metal or metalloid in the periodic table of elements (PTE) now has technical applications.

The heterogeneous group of materials (Fig. 1) is referred to in a variety of ways: 'strategic metals', 'specialty metals', 'technology metals', 'green minor metals' or 'trace metals'. In contrast to bulk metals, comparatively small quantities of high-tech metals are needed to provide the desired material properties. Nevertheless, the demand for technology metals has grown tremendously. Technological innovation is one reason for the growing demand. Another reason is the mass consumption of short-lived high-tech products, from which the technology metals are difficult to be recycled.

Technology metals and metalloids are used to produce high-performance components (strong permanent magnets, high-density data storage devices, lasers, etc.). Rare earth elements, for example, are indispensable in the creation of

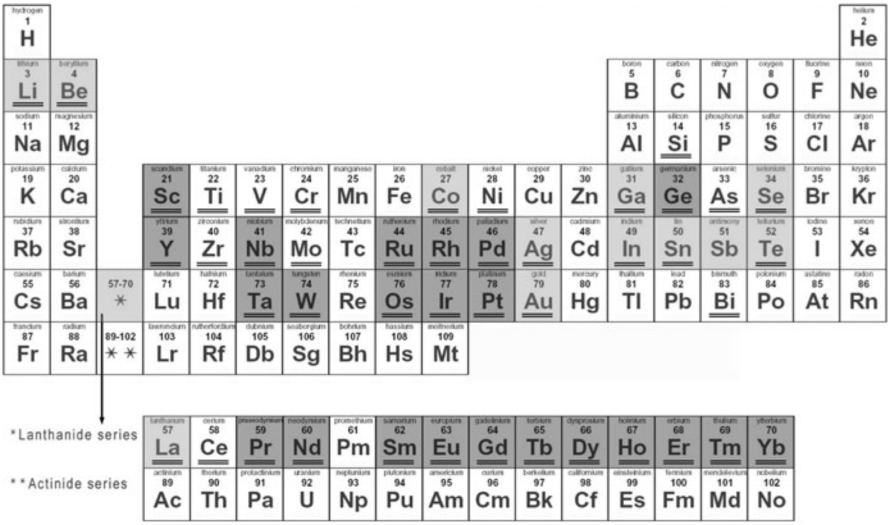

Fig. 1 Overview of critical elements (*grey*). A *darker shade* represents higher criticality. *Underlined* technology metals that are used in clean technology and high-performance applications

electronic high-tech products and infrastructure. An overview of their technical applications is provided in the supplementary information to this article (Case Study 1). The electronics, aerospace and automotive industries depend on a reliable supply of technology metals, as does the clean technologies sector. Low-carbon energy technologies, such as thin-film solar cells, wind turbines, fuel cells and batteries for electric vehicles, contribute to the growing demand for technology metals. Without these elements, clean technology would perform less efficiently and would have a less competitive cost-benefit ratio.

The impending scarcity of critical materials could slow down the necessary transition towards a low-carbon economy. The European Commission (2010) has warned of a high supply risk for fourteen critical raw materials that play an essential role in the EU economy. Material scarcity, in particular the scarcity of critical metals, constitutes a “subtle, but further reaching” risk (Bleischwitz et al. 2008). The US Department of Energy (DOE 2011) has identified a high supply risk for five REE metals that are key materials in clean energy technologies. In addition, shortages in the supply of PGM and various metalloids could “significantly inhibit the adoption of otherwise game-changing energy technologies” (APS and MRS 2011). Hence, the issue poses a strategic risk for sustainable development strategies that build on high-tech solutions.

Another aspect that is worth considering is the fate of critical elements when high-tech products reach the end of their useful lives. These artefacts typically consist of bulk materials, which contain small amounts of critical elements. The future trends in smart electronics and ICT foresee myriads of tiny, short-lived devices that will pervade the consumer mass markets (Köhler and Erdmann 2004). As a consequence, critical elements are expected to be dispersed within large waste streams, which will make it very difficult to recycle them (Köhler et al. 2011). It is assumed that a substantial amount of critical elements is lost in waste streams because the recycling rates for electronic waste are very low in most countries (Schluep et al. 2009). With no effective recycling schemes in place, the demand for technology metals is satisfied solely through the extraction of virgin minerals from non-renewable natural deposits, which are continuously depleted as a result. Any further growth in demand will have to be accommodated either by exploration of new mineral deposits or by extracting technology metals from lower-grade resources (Kooroshy et al. 2010).

Review of Different Interpretations of the Material Scarcity Problem

Over the last 50 years, more resources have been consumed by humans than ever before (EPA 2009). There are two main reasons for the rapid increase in the demand for raw materials. The first is economic and population growth, and the second the growing consumption of goods and services. Technological innovation has a strong influence on resource consumption in that it facilitates the resource-intensive mass production of high-tech products. Modern technology has led to a substantial increase in resource productivity (e.g. due to the miniaturisation of products) but not to an overall decrease in resource consumption. The bottom line is that the global industrialised economy has caused an unprecedented surge in the consumption of natural resources.

According to Bleischwitz et al. (2008), "for various commodities, the peak of extraction has already been reached or is currently about to be reached." The remaining mineral resources tend to be of a lower grade, which means that their extraction requires more energy and causes higher environmental impacts per unit of raw material (Giurco et al. 2010). The depletion of high-grade mineral deposits coincides with the depletion of accessible mineral oil reserves. The United Nations Environment Programme (UNEP) underpins that 'peak oil', the point in time at which the maximum rate of global oil is reached, is rapidly approaching or may have already become reality (UNEP 2011). Energy prices are expected to increase in the post-peak oil era. This could exacerbate the material scarcity problem as the extraction of low-grade resources may become prohibitively expensive.

The primary production process of most technology metals is energy intensive and causes large greenhouse gas emissions per mass unit produced (Norgate and Haque 2010). Mineral mining is known for its immense social and environmental impacts (Mudd 2010). While the easily accessible mineral deposits are being rapidly depleted, the exploration of remaining deposits is increasingly shifting to remote sites, such as the deep sea and the Arctic. Mineral mining is likely to add to the disruption and pollution of these vulnerable ecosystems (Glaister and Mudd 2010; MMSD 2002; Richards 2006; Mason et al. 2011; Yellishetty et al. 2011). The environmental side effects of increased mining on critical resources can impair important ecological functions (e.g. the marine food chains). A further increase in resource extraction rates will lead to serious reactions by the ecosphere as the impacts of mankind's global economy have already surpassed the environment's safety thresholds (WRF 2009).

The current debate on impending material scarcity reflects a recurring scientific dispute as to whether the exploitation of mineral reserves causes depletion of resources or not. Numerous scholars have repeatedly warned about the scarcity of resources (Meadows et al. 1972; Simpson et al. 2004; inter alia). Communities of environmental experts and economists disagree on how to interpret the phenomenon of material scarcity. The two main positions are summarised below (Tilton 2003; Gordon et al. 2006; Kooroshy et al. 2010).

Fixed stock paradigm The accelerated depletion of known mineral reserves has repeatedly given rise to concerns over the possible exhaustion of the limited mineral stocks in the earth's crust. The fixed stock paradigm assumes that the total stock of highly concentrated mineral reserves is limited, and that this stock is progressively depleted. The metals are consumed and finally degraded (e.g. due to wear and tear, corrosion and as waste). Moreover, population and economic growth are causing resource depletion to accelerate. If the depletion of non-renewable resources continues, mankind will 1 day run out of materials in useful concentrations

Opportunity cost paradigm The opportunity cost paradigm assumes that the total stock of mineral resources on earth far exceeds human needs. Scientific progress and technological innovations will offset the depletion of high-grade mineral reserves, as new technology will enable access to previously inaccessible/uneconomical reserves. Free market mechanisms balance supply and demand, which keeps the growing demand in check. The only limiting factor is society's willingness to accept the opportunity costs of resource extraction

Experts have expressed numerous arguments in favour of or in disapproval of these respective doctrines. Proponents of the opportunity cost paradigm refer to historical experiences in which new technologies combined with free market mechanisms have mostly offset the depletion of available mineral reserves. Past long-term trends have shown no dramatic increase in the prices of most mineral commodities (Bretschger et al. 2010).

The historical perspective on raw material availability is often used as an argument for resource optimism (Tilton 2003). On the other hand, some experts warn that we cannot continue in the future as we have done in the past. It seems possible that business-as-usual approaches to dealing with material scarcity may fail in the future (Meadows 2009). The arguments are summarised below.

- Supply shortages for several critical raw materials are likely to occur simultaneously. This limits the possibility of finding substitutes for scarce materials. Furthermore, the erratic occurrence of supply shortages can constrain technological innovation.
- Free market mechanisms may fail due to the high vendor power of countries in which the deposits of critical elements are located. In the long run, material scarcity may result in increasing raw material prices.
- The energy consumption of mining and refining processes increases exponentially as the grade (concentration) of ores declines (APS and MRS 2011). Extracting critical metals from low-grade minerals requires high-grade energy, which is usually taken from fossil fuels. Low-grade mineral resources may be

out of reach for future mining due to energy constraints. The peak oil problem amplifies energy constraints (Kooroshy et al. 2010; Tilton 2003).

- From an environmental perspective, the extraction of mineral resources is becoming increasingly expensive (Mudd 2010). These eco-costs comprise environmental pollution, public health impacts, ecosystem and food chain disruption and the displacement of people. Life-supporting functions of nature can be regarded as "new scarcities" (Simpson et al. 2004) and must be included in the calculation of the opportunity costs of resource extraction.

One of the fundamental problems in anticipating the future availability of raw materials is the uncertainty regarding emergent phenomena in technological and economic systems. Numerous aspects of modern society, notably population size, climate change and peak oil, are without historical precedent. The significance of forecasts on the possible consequences of resource scarcity is also limited (Peck et al. 2010). Thus, knowledge of the possible consequences of material criticality is limited. The range of uncertainty extends to different aspects, each influencing the risk of raw material scarcity in a different manner:

1. Geological uncertainty: although the total amount of mineral resources on earth is unknown, we know that extraction of known mineral reserves leads to the depletion of these deposits. The peak oil problem also implies uncertainty with regard to future energy costs.
2. Socioeconomic uncertainty: the capability of future technology to access the remaining resources may be under or overestimated. Furthermore, shifts in societal priorities may influence the societal willingness to accept the opportunity costs of resource extraction. This can change as a result of global environmental and social pressures. Political and environmental circumstances can cause market failure (e.g. trade barriers, export restrictions, etc.).

Set against the background of modern technology's increasing dependency on critical elements, and taking into account the uncertainty that exists, the question arises of whether it is fair to proceed with the depletion high-grade resources. This ethical question is closely related to the significance of sustainable development.

Sustainability as a Framework of Responsible Innovation

Sustainable development (SD) has been defined as a policy goal in the report Our Common Future as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987: 43). SD is regarded as a socioeconomic concept that helps to maintain an equitable level of needs satisfaction for the whole of mankind today and for the human generations of the future (Langhelle 1999: 129–149). The Brundtland Commission emphasised the right of development and improvement of living standards for the world's poor. Thus, the concept of SD acknowledges mankind's right to make use of non-renewable resources as a basis for prosperity. Furthermore, the idea imposes limitations with regard to contemporary needs satisfaction: development today must not impair development in the future.

The essence of this idea is the combination of intragenerational and intergenerational justice. Thus, the ethical principle underlying the concept of SD is the idea of the universal equality of all human beings. Equality in this context is seen as a fair entitlement of all people living throughout the world today (intragenerational justice) to satisfy their essential human needs without this being—to the detriment of people living in the future (intergenerational justice). Strictly interpreted, intergenerational justice is a concept of altruistic human behaviour. It would be revolutionary if implemented at a global level. However, even intragenerational justice, which is the fair global distribution of costs and benefits from resource extraction, has not yet been achieved (Richards 2006: 324–333). To that end, the selfish interests of the people living today may be a stronger driver of sustainability, because material scarcity is already likely to limit prosperity within the lifespan of present generations (WRF 2009).

Since the definition of sustainable development was coined in 1987, there has been debate on the extent of natural resource exploitation to which current generations can rightfully commit without compromising the developmental abilities of future generations. This dilemma has led to the emergence of two extreme interpretations of sustainability:

- *Strong sustainability* The total natural capital of the earth must be preserved. The depletion of non-renewable resources would therefore be ruled out, and renewable resources could be used only within the scope of their regeneration rate. This interpretation refers to the above-mentioned finite stock paradigm
- *Weak sustainability* The total anthropogenic and natural capital of the earth must be preserved. This means that natural capital can be reduced at will if, in return, human-created capital of the same economic value is substituted for it. This interpretation refers to the opportunity cost paradigm

It has become apparent that a possible consensus between the two extreme interpretations of SD must be sought as a political goal. The following arguments may be taken into account when searching for a moderate interpretation of SD in the context of material scarcity:

Minerals and metals do not physically vanish when they are used. They are incorporated in the technosphere. This can be seen as a process of substituting human-created capital for natural capital, adding economic value in the sense of ‘weak sustainability’. However, usage inevitably leads to a degradation of the quality of materials, due to corrosion, wear and tear, contamination and dispersion in waste. Future generations cannot utilise the same materials in useful concentrations and qualities (Richards 2006). The contemporary depletion of mineral resources must be offset by exploration and acquisition of virgin mineral deposits, which tend to be of a lower grade. It is therefore possible that the energy costs of raw material production will increase to a prohibitive level, thus hindering the ability of future generations to satisfy their needs. This consideration suggests ‘strong sustainability’, i.e. abstemious use of natural resources in order to preserve them as well as possible.

Future generations have no influence on today's decisions, which will determine the availability of resources in the future. The concept of sustainability imposes a moral obligation on the present generation to act in advance of the future generation's interests. A fundamental difficulty in doing so comes with the fact that we act under conditions of uncertainty and do not know the precise effects of today's decisions. As we do not possess sufficient knowledge about the total amount of resources on earth, how can we then make prudent decisions in technology development? How can we determine the extent of resource consumption that is acceptable in terms of sustainable development?

The precautionary principle (PP) may complement SD as a guide in decision-making under conditions of uncertainty. The PP helps society to make conscious decisions for or against entering into developments that may pose potentially severe or irreversible risks in the long term. According to the maxim of precaution, technology-induced risks should be counteracted before having any adverse impacts on subjects requiring protection (nature and human health). The PP emphasises avoidance of irreversible developments and technological lock-in effects in the innovation process. Preserving a margin of freedom for the decisions and activities of future generations is referred to as the free-space theory of the PP (Beyer 1992). The latter is founded on the two basic ethical principles of justice (intergenerational) and self-determination (autonomy). Thus, the ethical basis of the PP is consistent with SD and leads to the same conclusions: "…present generations may be obligated by considerations of justice not to pursue policies that create benefits for themselves but impose costs on those who will live in the future" (Meyer 2003).

Sustainable Management of Critical Materials

Applying the ethical propositions of both concepts—sustainable development (SD) and the precautionary principle (PP)—helps to answer the first question posed in this article: 'Should preventive actions be taken today in order to mitigate resource scarcity in future?'

The PP leaves no doubt that risks must be counteracted before adverse impacts occur. Material scarcity can have far-reaching consequences because materials are indispensable in the production and maintenance of the technological base of our modern civilisation. On the flipside, intensifying extraction of the remaining natural resources entails environmental impacts in the form of pollution and damage to the ecosystem. Therefore, resource depletion can arguably be considered a severe risk for people and the environment.

Uncertainty regarding the determinants of the material scarcity problem gives reason to choose the PP as a guiding maxim of judgment: a potentially severe and irreversible risk should be prevented even if there is incomplete knowledge about the risk. According to the "priority of the bad forecast" (Jonas 1979), it is better to overestimate a risk (e.g. to assume a small stock of remaining resources) than to underestimate it (e.g. false confidence in future discoveries of new resources). Tilton (2003) stresses that signs of impending scarcity are likely to become visible long before depletion becomes a serious problem. The recent disruptions in the supply of rare earth elements can be interpreted as a warning sign in that sense. A prudent strategy would be to heed early warnings because the depletion of non-renewable resources is irreversible. A precautionary response involves creating awareness of such impending signs before supply shortages become a roadblock for innovation. On the other hand, the stockpiling of raw materials is not a precautionary strategy because, at best, it can only buffer short-term disruptions in supply.

One question remains: why should we reduce resource consumption rates right now? Why not continue to trust in the ability of future technologies to offset the depletion of mineral reserves? The PP suggests an answer: a margin of safety must be preserved in case future technologies fail to offset exhausted resources. A precautionary strategy means increasing the resilience of modern technologies and business concepts against material scarcity. That requires more than technical solutions alone; it necessitates a paradigm shift in the ways we design, produce, consume and dispose of products.

The Responsibility of Technology Developers for Sustainable Material Management

'Should technology developers feel responsible for taking actions towards sustainable material management?'

In their self-understanding, the majority of industrial design engineers may agree with the following statement: "Technological progress is good and developing new technology products is therefore 'doing good'." Society as a whole tends to share this point of view as consumers usually cherish the market introduction of new innovative high-tech products. On the other hand, it has become clear that technical innovation often creates new risks. The term 'risk society', coined by Beck (1986/1992), stands for modern society's solicitude in the face of adverse side effects that can emanate from technology. It also stands for society's expectations that technology developers will 'do no harm', meaning that they will minimise possible adverse side effects.

The moral obligations are beneficence (do good) and non-malfeasance (do no harm). Both obligations are interdependent: someone who is of—good intent is responsible for acting in such a way that no harm is created. Hence, the responsibility borne by industrial designers is twofold. Firstly, in terms of beneficence, they ought to convert natural capital into "more valuable and durable forms of social capital" than short-lived high-tech goods, affordable only for an affluent minority (Richards 2006: 326). Secondly, when they create new technology, their mission must include the minimisation of adverse side effects. Acting responsibly in order to prevent future risks can be regarded as one of the provisions of the PP. This concerns an active form of responsibility where the central question is "what is to be done?" (Bovens 1998). With regard to material scarcity, the people best able to answer to this question are those who have a causal connection to the potential source of risks: scientists, engineers and designers are the ones who conceive new technology and create demand for critical materials.

Industrial designers, for example, exert a substantial influence on the demand for critical technology metals. Designers give physical shape to ideas and technological visions as they transform abstract technical phenomena (e.g. new materials) into functions that are meaningful to users. Together with other protagonists in the technological innovation system, such as mechanical and electronics engineers, they create new areas of application for scarce materials when they conceptualise new products. Thus, they determine the amount and the fate of the critical elements incorporated in their products. They also determine how consumers use products, e.g. how long products are used before being disposed of (Wahl and Baxter 2008: 72–83). Hence, the designer's influence on the demand and the fate of materials extends well beyond the design phase. The supplementary information to this article, available online, illustrate this in two cases studies: the design of smart textiles and energy-efficient lighting.

Society's perception of the designers' role indeed goes beyond the creation of socially responsible products. They act as "facilitators of a system of value co-production" (Morelli 2007: 3–21). By virtue of their profession, industrial design engineers are qualified to 'do good' and have a notable degree of self-determination (autonomy). With the multidisciplinary modality of their work, they are in a good position to contribute actively to the development of sustainable solution strategies (Wahl and Baxter 2008). This implies a collective obligation on the part of designers to prevent the material scarcity risk. They therefore have a form of a virtue-responsibility (Kermisch 2010). Someone who develops new technologies or products bears an active responsibility to consider the consequences of his or her actions (Leerberg et al. 2010). Technology developers should take this role seriously and develop an attitude for sustainable management of critical materials.

What Can Technology Developers do in Practice?

A broad discourse among industrial design engineers on resource-preserving innovation strategies is overdue. Although they can by no means solve the material scarcity problem single-handedly, they can work out strategies for sustainable material management. This requires a good understanding of the energy and materials that underlie modern technology. Lifecycle thinking is an important tool that helps technology developers understand the interrelationships between the design of products, consumption patterns and end-of-life treatment of products and the sustainability impacts. This includes a grasp of cause and effect relationships regarding the impacts of design decisions on sustainability. Some of the ideas of what industrial designers and engineers can do to mitigate material scarcity are summarised below:

- Analysing the influence of design decisions on resource consumption and anticipate the fate of critical elements throughout product lifecycles. Engineers possess first-hand information on the material composition of new technologies. By making this knowledge available, they can help to make the scarcity phenomenon more tangible.

- Conceive viable concepts for the sustainable management of critical materials. For example, exploring ways to design out technology metals from short-lived and low value-added products. This would help to preserve critical resources for applications that are essential for the fulfilment of human needs in the long term.
- Designers can inspire decision makers in politics and industry as they create visions about resource-saving innovation pathways. One possibility is to search for ways to satisfy consumer needs in less material and energy-intensive ways (e.g. dematerialisation).
- Implementing eco-design principles (e.g. design for repair, refurbishment and recycling) in the product development process helps to retain critical elements in a useful embodiment for a longer period of time.
- Taking an active stand for a paradigm shift in industrial design, away from planned obsolescence. By making designs for durable products, they can reduce the wastage of critical elements in difficult-to-recycle high-tech waste.

Design engineering practitioners need knowledge support to respond to the new challenges in an effective and timely manner (Davidson et al. 2010). Multidisciplinary knowledge collaboration with other expert communities can help them to work out sustainable solutions. Particular attention should be paid to the further development of professional skills and qualifications. It is important to train future design engineering professionals to enable them to thrive under circumstances of limited material choices. Thus, sustainable material management should be addressed in education courses for industrial design engineering students (Köhler et al. 2012).

Conclusions

In following the ethical premises of sustainable development, there is reason to regard material scarcity as a serious risk. The impending scarcity of technology metals can limit the freedom of development and impart innovations in low-carbon technologies in particular. The conclusion reached by the examination of ethical arguments is that material scarcity should be mitigated in the course of the development of new technologies. Uncertainty or ambiguous information regarding the determinants of the phenomenon must not be a reason to ignore a potentially severe and irreversible risk. The precautionary principle offers a framework of orientation for decision-making against the background of this ‘wicked problem’. It suggests keeping the increasing demand for critical elements in check so as to prevent the depletion of non-renewable resources. This means, for example, that critical elements should not be squandered in mass-produced applications that have a short service life and that are hard to recycle. To that end, the business model of planned product obsolescence must be renounced.

The discussion elaborated arguments explaining why technology developers should feel responsible for counteracting the increasing demand for critical materials. Technology developers have a profound influence on the demand side (the possibility to act). Moreover, society expects them to consider the consequences of their innovations so as to avoid undesired side effects (collective role obligation). Innovators can and should create viable strategies for resource-aware technology development. They may champion the transition towards more resource-efficient generations of technology. That is, they must not shift the responsibility on someone else, such as the mining industry, the recycling sector or government authorities.

Designers, who have high social reputations, may play a leading role in the sustainable management of critical materials. They can explore technical as well as non-technical options. One possibility is to design out critical elements from products that are not essential for sustainable development. Lifecycle thinking, for example, lends a long-term perspective to the product development process. Eco-design principles can serve as a maxim of action that aims to retain materials in a useful form for a longer period of time.

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