MATERIALS SCARCITY: A NEW AGENDA FOR INDUSTRIAL DESIGN ENGINEERING

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Abstract

Societal stakeholders are expressing concerns over the increasing scarcity of critical elements on which high-tech industries rely. Geochemical rare elements are indispensable in producing high-tech products such as electronic gadgets and renewable energy technologies. The surge in demand for critical elements presents a risk of exhaustion of available mineral resources. The consequences appear severe and may include high price volatility, supply disruptions and geopolitical conflicts. Materials scarcity can affect the transition towards a sustainable society if supply shortages of critical elements curb the proliferation of green technologies.

This situation presents the world with a range of multidimensional complex problems, sometimes termed 'wicked' problems. Industrial design engineers, with their multidisciplinary design approach, are well equipped to be able to thrive in such a period of change. Industrial design can contribute to more efficient use of scarce materials by exploring design options to eliminate or substitute them. Designing products for longer life spans, and facilitating predicted reuse as well as high intensity recycling can be part of possible solution strategies.

This scoping paper reviews important aspects of material scarcity and aims to define and delineate the topic for the industrial design engineering community. The risk of material scarcity poses a challenge in finding innovative approaches and methods that will help to counteract the depletion of scarce materials. This prompts us to re-examine and reframe the curriculum of higher education in industrial design and to outline elements of a new agenda for resource-aware industrial design.

Keywords

Critical elements, Higher education, Green technologies, Rare earths, Resource depletion, Sustainable design,

1. Introduction

Very recently, concern over shortages in raw materials supply was fuelled when China capped its foreign shipments of rare-earths commodities to 30,258 tons metric tons in 2010 (Yu 2010). Today, China controls 97% of supply of the world market for these commodities (Corfield 2010). This confronts the high-tech industry with a 40% reduction in available raw materials of that group of elements, underpinning the vulnerability of high-tech economies against acute supply disruption (Kooroshy et al. 2010). For the industry there is a risk that supply disruptions constrain technological progress in the near future (Hilty 2007), and it is because of this strategic relevance that scarce materials, such as rare-earths, are often referred to as critical materials.

The ICT, aerospace, automotive and electronics industries rely on a constant supply of critical materials, as does the sustainable technologies industry (Angerer et al. 2009). In the long run shortages of certain critical materials may constrain action plans for a widespread adoption of sustainable technologies such as solar cells, wind turbines, and fuel cells. These materials are of vital importance for green technologies, allowing for the design of highly effective components (i.e. strong permanent magnets, catalysts). Without these critical materials, green-tech apparatus would perform inefficiently and would suffer from less competitive cost-benefit ratios. Materials scarcity could even impede further innovations in this sector entirely (Andersson 2001; Buchert et al. 2009).

On the other hand, the sustainability supremacy of green technologies is diminished due to the enormous environmental footprint of critical materials production. Mineral mining is known for its immense environmental impacts including disruption and pollution of vulnerable eco-systems, such as the deep sea and the Arctic (MMSD 2002; Kitula 2006; Glaister et al. 2010). Primary production of metal commodities is energy intensive and causes large CO_2 emissions per mass unit produced (Norgate et al. 2010). Continuing demand growth will have to be accommodated by mining minerals at more remote sites and extracting metals from lower-grade minerals (Kooroshy et al. 2010). The lower the grade of minerals the higher the energy demand of mining and extraction processes, there is a exponential increase of the impact (Diederen 2009). That way the embodied energy of critical elements is expected to increase in future, putting an extra burden on the lifecycle wide eco-performance of products containing these elements. And if the products are not properly recycled at the end of their useful lives the critical elements are lost in waste and can even cause human health hazards and ecosystem pollution.

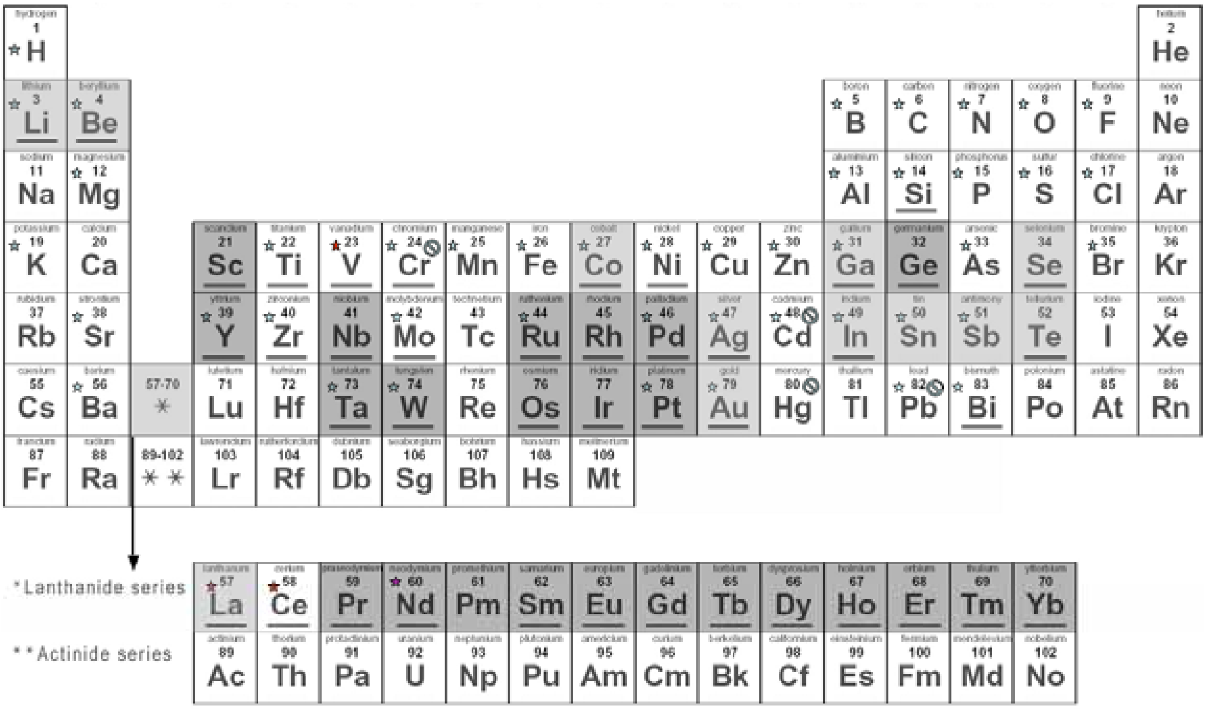
The issue of material scarcity has been poorly addressed in the process of developing new technologies and products. While some scientists and economists have debated concerns of finite resources over and over throughout the past four decades (Simpson et al. 2004), the debate has been rather inconsequential for the ways in which products are designed, produced, consumed and disposed of. Innovators and designers seem to have underrated the risk of resource depletion in the pursuit of more sophisticated products. A debate on resource preserving strategies for technological innovation is overdue (World Resources Forum 2009). The recent supply shortage with rare-earth elements should be taken as a wake up-call for the industrial design profession. In this paper we explore the ways in which industrial designers can contribute to better resource management for critical raw materials.

The objective of this paper is exploring the question how the industrial design community can respond to the materials scarcity challenge. As a starting point, a review of the various uses of critical elements in technology is given. A case study on the electro and electronic sector illustrates how dependent the high-tech industry is on supply with critical metals. It follows a review summarising the extensive literature on the problem of materials scarcity. The review allows us to define and delineate the topic of material scarcity from a design scholar perspective and to examine the challenges for the industrial design engineering community. The paper concludes by outlining elements of a new agenda for resource-aware product design and recommends revisions in the curriculum of higher industrial design engineering education.

2. The material base of technology

Mineral resources are extracted from the earth’s lithosphere to build and operate the technologies and infrastructures our civilisation is founded upon. The availability or scarcity of raw materials has determined the ways of production and consumption in each society throughout history. Names of materials are used to characterise different epochs of history: the stone age, the bronze age, the iron age, and, most recently, the “silicon era” (Krimmel et al. 2004). Materials are attributes for the perceived state-of-the-art technology of that respective era. In recent years, the attention has shifted away from base metals such as steel, aluminium and copper towards semiconductor materials, that symbolise the dominant material base of the high-tech industry (Weil et al. 2009). Silicon is the substrate of which the vast majority of products in information and communication technologies (ICT) are made.

In near future, the so-called minor metals may represent the frontier of innovation. They are about to eclipse silicon as a symbol of high-tech materials. Once being considered of only marginal technological usefulness, these elements have proven their paramount importance for progress in science and technology (see Figure 1) (Angerer et al. 2009; Buchert et al. 2009). Almost each metal and semimetal populating the periodic table of elements (PSE) has technical applications nowadays. The heterogeneous group of minor metals has been named in a variety of ways, depending of the respective point of view: “strategic metals” (Bell 2010), “technology metals” (Lifton 2009), “green minor metals” (Buchert et al. 2009), or “specialty metals”, “Gewürzmetalle” (Reller 2008). A generic overview of terminology of metal commodities is shown in Table 1.



☆ Elements contained in mobile phones. Source: (Meskers at al 2009), ★ in PCs (Soneji 2009) + WEEE (Dimitrakakis 2009)

⃠ RHOS Elements (use in electronic appliances is restricted)

Figure 1: Overview of critical metals and semimetals in the periodic table of elements (highlighted grey). A darker shade represents acute criticality (e.g. low supply security and high technical importance). Minor metals (underlined). Elements that used in commoditised electronic products (indicated by an asterisk).

Table 1: Frequently used terminology of metal commodities

Ferrous metals	Iron and its alloys (steel, cast iron, stainless steel). Some authors class minor metals used for steel alloying in this group *	Fe (Mn, V, Nb, Cr, Ni, Mo, Si, Bi)
Non ferrous metals	All industrial metals other than iron and its alloys.	Al, Co, Cu. Pb, Mg, Sn, Ti, Zn,
Base metals	Industrial non-ferrous metals traded on the London Metal Exchange (LME) except of precious metals. Used as industrial bulk metals and alloying metals.	Ni, Pb, Cu, Zn, Al, Sn, Co, Mo,
Minor metals (Speciality metals) (Gewürzmetalle -German)	Metal commodities that are not traded on the London Metal Exchange (LME). Characteristics: Relatively small global production as compared to base metals. They are usually extracted as by-products in the production of base metals.	Sb, As, Be, Bi, Cd, Ce, Cr, Co, Gd, Ga, Ge, Hf, In, Li, Mg, Mn, Hg, Mo, Nd, Nb, Ir, Os, Pr, Re, Rh, Ru, Sm, Se, Si, Ta, Te, Ti, W, V, Zr
Noble metals	Noble refers to the chemical properties i.e. resistant to corrosion and oxidation.	Ru, Rh, Pd, Ag, Os, Ir, Pt, Au
Precious metals	The name refers to the economic value of certain naturally rare metals[1], Properties: lower chemical reactivity than most elements (corrosion resistant)	Ru, Rh, Pd, Ag Re, Os, Ir, Pt, Au, Hg
Platinum Group Metals (PGM)	Subcategory of precious metals comprising the metals of groups 8, 9, and 10, and periods 5 and 6 in the PSE; They occur in the same minerals and have exquisite physical and chemical properties (corrosion resistant, catalytic).	Ru, Rh, Pd Os, Ir, Pt
Rare earth elements (REE)	Metals of the group 3 in the PSE including the 15 metals of the lanthanide group. Most rare earth elements are not rare in lithosphere but their concentration in common rock is low. 'Rare' refers to the scarcity of minable ores with sufficient concentration.	Sc, Y, Lu, & [La … Yb]
Halfmetals or Metalloids	Chemical elements that have allotropes of merely metallic and non-metallic properties. Metallic allotropes are typically semiconductors; non-metallic allotropes are insulators.	B, Si, Ge, As, (Se), Sb, Te, Po, At
Semiconductors	Materials (elements, alloys, compounds) having semiconductive electrical properties.	Metalloids, Compounds (GaAs, InP, GaN etc.)

* (Graedel 2010)

2.1 Case study: critical elements in electronic products and ICT

This section of the paper takes a closer look at typical applications of critical materials in electronic products and ICT in order to provide a basis for the discussion of future material demands of the high tech sector.

Modern industrial technologies are composed of a variety of speciality and precious metals (Hagelüken et al. 2010). Mobile phones, small as they are, contain considerable amounts of valuable materials (Meskers et al. 2009). Their printed circuit boards, with microchips mounted on it, contain various metals such as copper, silver, and gold, which are used for electrical interconnections, heat dispersion and corrosion prevention. Ceramic capacitors contain the scarce metal tantalum. Ferrite cores of high frequency coils can contain ceramic compounds of rare earth metal oxides. Figure 1 provides an overview of elements that used in common electronic products.

Many of these scarce elements are used in minute amounts per product but they are indispensable for the electronic hardware to perform as required. Fine-tuning the semiconductive properties of silicon, for instance, is requisite for building p-type and n-type transistors and diodes. This is possible by introducing tiny amounts of doping elements into the crystal lattice of silicon (Kooroshy et al. 2010). The doping concentration is usually very low and rages between 0,1 to 100 ppm. Common dopants deployed for silicon-based electronics are comprised of aluminium, boron, and gallium (acceptor atoms for p-type semiconductor), and of antimony, arsenic, and phosphorus (donors atoms for n-type semiconductor).

Optoelectronic components such as light emitting diodes (LEDs), microwave generators, and thin film solar cells make use of doped gallium arsenide (GaAs) as substrate material. For such components, doping elements are essential to achieve the desired function. Common dopant elements for GaAs are:

- cadmium, magnesium, silicon, zinc (acceptor atoms for p-type semiconductor)
- selenium, silicon, sulfur, tellurium (donors atoms for n-type semiconductor)

Optical glass fibres are doped with rare-earth elements such as dysprosium, erbium, neodymium, praseodymium, thulium and ytterbium. Table 2 provides an overview of application areas of rare earth elements (the lanthanide group of the PTE) in electronic and electro sector. Many functional components referred to in table 2 play an important role in the ICT infrastructure (e.g. the Internet, server farms, optical and wireless networks etc.).

Table 2: Rare earth elements used in electronic and electric appliances

Scandium Sc	Gas discharge lamps, high performance aluminium-scandium alloys
Yttrium Y	Phosphors in cathode ray tubes (CRT), oxygen sensors in car exhaust systems, YAG laser rods, component of oxide superconductor materials
Lanthanum La	Camera lenses, high refractive index glass for optical fibres, anodic material of nickel-metal hydride batteries.
Cerium Ce	TV screens and fluorescent lamps.
Praseodymium Pr	Permanent magnets, optoelectronics: optical switch, optical amplifier
Neodymium Nd	Permanent magnets used in [electric motors & generators, microphones, loudspeakers, hard disks], ceramic capacitor (dielectric layer), solid-state lasers (Nd-YAG laser rods).
Promethium Pm	Beta radiation source, used in nuclear batteries
Samarium Sm	SmCo permanent magnets, solid-state lasers, infrared light absorbing optical glass
Europium Eu	Red phosphors in CRT and fluorescent lamps
Gadolinium Gd	Permanent magnets, magneto–optical films, microwave technology, green phosphors for CRT and Radar screens, rewritable media CD-RW
Terbium Tb	Solid-state devices, e.g. crystal stabilizer of fuel cells, sensors, flat panel speaker, green phosphors in CRT
Dysprosium Dy	Permanent magnets, laser materials, hard disks, drive motors for hybrid electric vehicles
Holmium Ho	Fluorescent lamps, high-strength magnets, solid-state lasers, microwave equipment, optical glass fibres
Erbium Er	Optoelectronics: optical glass fibres, erbium-doped fibre amplifiers, fibre lasers
Thulium Tm	YAG laser rods, high temperature superconductors, ceramic magnetic materials
Ytterbium Yb	Fibre lasers, optical fibres, solid state lasers

The examples above can provide only a rough glimpse on the inventory of rare and critical elements, which modern high-tech products contain. In spite of the small quantities of substances found in a single device the global demand for these is rapidly increasing as a result of mass production in the high-tech sector. For instance, the rapid growth of the mobile telecommunication sector and the widespread application of mobile phones in consumer markets have result in a growing demand for such elements (Soneji 2009). Table 3 shows the material composition of cell phone handsets found in samples of electronic waste. Newer generations of smart phones are thought to contain higher relative amounts of certain critical elements because of their design features (e.g. large touch screen displays containing indium in form of transparent ITO-electrodes (indium-tin oxide).

Table 3: Material composition of cell phones produced around 2003 according to: (Huisman 2004)

Material	g per kg	Material	g per kg
Ag	1.4157	Hg	0.0000
Al	18.9633	Liquid Crystals	2.0000
As	0.0068	Ni	8.7567
Au	0.3261	Other	0.0000
Be	0.0219	Pb	3.4952
Bi	0.0489	Pd	0.1178
Br	9.4099	Plastics	634.4918
Cd	0.0004	Plastics FR	0.0000
Ceramics	0.0000	Pt/ Ta	0.0542
Cl	0.1253	PVC	0.0000
Cr	6.2697	Sb	0.7703
Cu	116.2145	Silic.plast.	0.0000
Epoxy	0.0000	Sn	5.3234
Fe	82.8234	Zn	3.4275
Glass	105.9372		

The example above illustrates the complex materials composition of contemporary electronic products. Valuable materials are often blended with hazardous substances in the same product. Once they are discarded as e-waste it is difficult to separate valuable and hazardous substances. That, among other reasons, makes recycling of post consumer e-waste insufficient in most countries. As a result, a big share of valuable materials contained in e-waste is disposed of without appropriate recycling. In particular the content of minor metals in e-waste is mostly lost even if the end-of-life products undergo crude recycling schemes for copper and gold recovery (Chancerel et al. 2009).

Future generations of information and communication technologies are envisioned as miniaturised electronic gadgets being embedded in objects of daily life (smart objects). The vision of pervasive computing implies that myriads of tiny devices are used simultaneously and they might have a relatively short service live (Hilty 2005). Pervasive computing devices will contain critical elements materials just like contemporary electronics (Köhler & Erdmann 2004). The valuable materials will be dispersed within innumerable items that may be embedded in bulk materials such as textiles or concrete (Köhler 2008). As a consequence, scarce materials would be diluted within waste streams, rendering recycling and recovery of materials infeasible in practice. Hence, there is a risk that material depletion would be accelerated. On the other hand, the innovation process of the electronics industry offers opportunities to design out the functional use of scarce materials. Avoiding the use of critical elements for short living consumer products remains a design challenge for electronic engineers and industrial designers.

2.2. Future demand perspectives for critical elements

Contemporary innovation in the high-tech sector has become highly dependent on these metals, in spite of the fact that high-tech products usually contain only small amounts or even traces of them. In the near future, the demand for technology metals is expected to increase considerably for the following reasons:

- Innovations in the high-tech sector and green technologies push the demand for technology metals. As a result, there is an increasing competition for these critical elements among different emerging technologies (Angerer 2009).
- Economy-of-scale principles ruling the high-tech sector stimulate mass consumption of electric and electronic products. At the same time, market size inflates due to population growth and economic upturn in newly industrialized countries (e.g. India, China, Brazil).
- Consumers tend to use products for ever-shorter service time. Many products are replaced by newer ones long before the old ones cease to fulfil their function physically, an obsolescence effect that is known as virtual wear and tear (Cooper 2004; Köhler et al. 2004).

The increasing demand for critical metals meets a rather inelastic supply system at the global metal commodity market. For reasons explained in the following chapter, the supply of critical metals cannot be increased easily so as to satisfy the increasing demand. The consequence for industry is scarcity of raw materials. Materials scarcity may result in a roadblock for industries following business-as-usual avenues of technological innovations (creating more function by using more sophisticated materials). This situation will not be resolved without having consequences for engineers and industrial designers.

3. Review of materials scarcity

3.1. Interpretation of materials scarcity

Global economic and population growth plus the widespread adoption of modern technologies have resulted in an unprecedented surge in resource consumption of human society (Krausmann et al. 2009). During the past five decades, more resources have been consumed by humans than ever before in history (US EPA 2009). Extracting minerals from deposits in the lithosphere inevitably results in depletion of the known mineral reserves. The remaining geologic reserves are immense for certain minerals such as iron and coal, giving prospect for maintaining supply security for many decades into the future. Certain elements however are geologically scarce and deposits of minerals containing them are either few or located in single countries (e.g. China) (Kooroshy et al. 2010). This applies for most of the technology metals. Known geologic deposits of such minerals, being accessible for profitable mining, are limited in capacity or of low grade. They are difficult to acquire due to energy, technological or geo-political barriers (Diederen 2009).

The accelerated depletion of known mineral reserves has repeatedly given raise to concerns over the possible exhaustion of the limited mineral stock containing critical elements. The ongoing debate amongst experts sequels a scientific dispute, lasting for many generations, as to whether non-renewable resources are finite or not. Moreover it has been disputed whether the progressing depletion of accessible mineral resources can be offset by technological progress at all times. Current thinking about materials scarcity is ambiguous at best. Expert communities seem to disagree fundamentally on how to interpret the problem of materials scarcity. The two major doctrines are the finite stocks and opportunity cost paradigms (Tilton 2003; Wäger et al. 2006):

- <u>Finite stock paradigm:</u> Assumption that non-renewable minerals resources on earth are limited. These stocks are progressively depleted due to extraction of mineral commodities. The commodities (e.g. metals) are consumed and finally degraded (e.g. as waste). In conclusion: Humankind is proceeding with resource depletion and is going to run out of useful materials in the course of time. Moreover, population growth and economic growth cause resources depletion to accelerate.

- <u>Opportunity cost paradigm:</u> Assumption that the existing stock of non-renewable minerals on earth exceeds the human needs by far. Extraction is limited only by human ignorance of their existence and by economic factors (such as production costs). Free market mechanisms are thought to always balance the supply-demand dynamics. Rising commodity prices would keep growing demand in check thus slowing down resource depletion. Importantly, technological know-how is thought to compensate future generations for exploited reserves as they extend the human capabilities to get hold of previously undiscovered resource deposits.

Experts have expressed numerous arguments in favour or contra these respective doctrines (Tilton 2003; Simpson et al. 2004). Proponents of the opportunity cost paradigm refer to historical evidence when supporting their argument that new technology in combination with free market mechanisms can always offset the depletion of available resources. Historical trends of most mineral commodities prices seem to show no massive upturn on the long term (see Figure 2).

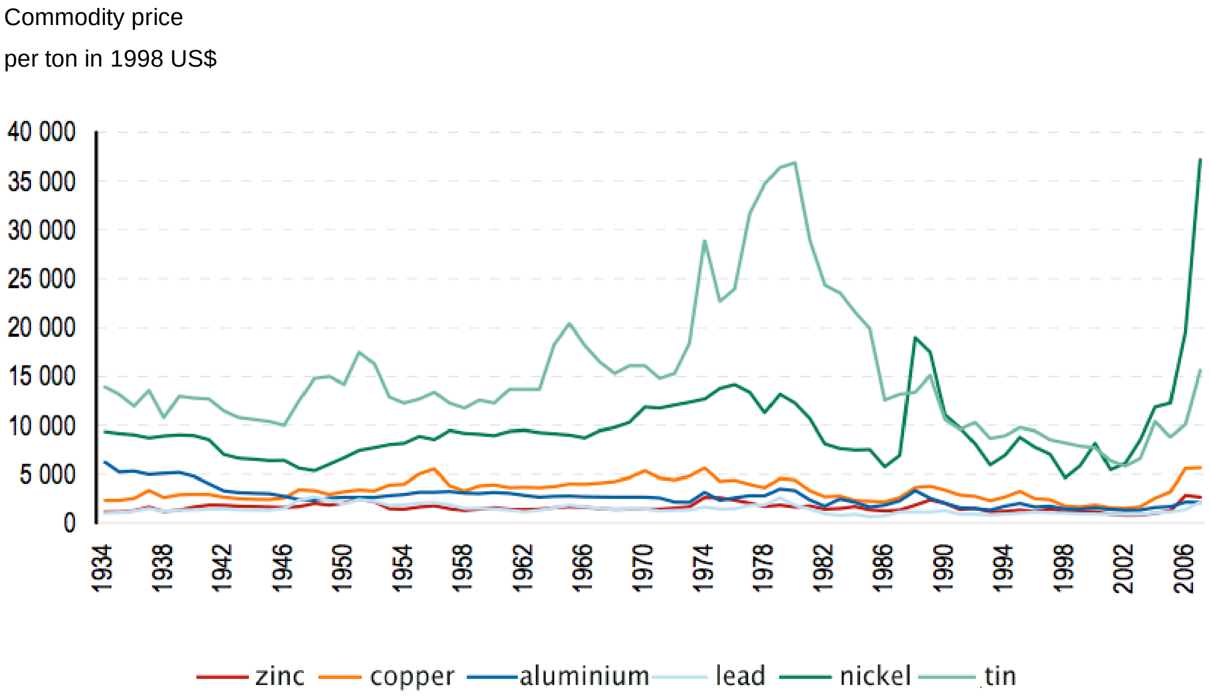


Figure 2: Historical price trends for several base metals. Source: (Bretschger et al. 2010)

However, some experts warn of the false confidence created by extrapolation of trends from the past, arguing that it seems possible that business-as-usual approaches of dealing with materials scarcity may fail in future (Meadows 2009). Their arguments are summarised as follows:

- Contemporary materials scarcity affects simultaneously a large variety of geochemical rare elements. The supply side (mining and extraction) is an inelastic system incapable of smoothly following an erratic increase in demand for certain minor metals. This is due to the long lead-time of geologic explorations and the large investments needed.
- Critical metal commodities are traded in comparatively low tonnage at the world market. Vendors are located in few (or even single) countries that have power to control the market supply for speculative, political or geo-strategic reason. Thus, free market mechanism may no longer be applicable to balance supply-demand dynamics.
- The energy consumption of mining and refining processes increases exponentially as the ore grades decline. Extracting critical metals from low-grade minerals requires high grade energy (exergy), which is usually taken from fossil fuels (such as mineral oil). The latter represents a scarce resource itself. The re-emerging concern over peak-oil fortifies concerns that remaining low-grade mineral resources will be out of reach for future mining due to energy constraints (Kooroshy et al. 2010; Tilton 2003).
- Climate change can push the opportunity costs of mineral mining beyond societal acceptance.
- Supply shortages for several critical metals substances are likely to occur within the same period of time so that they cannot easily be relinquished or substituted for each other.

It appears that resource scarcity is a serious risk that should be given more attention. Whereas the historical perspective on resource scarcity is indeed reason for a resource-optimist stance there is a gathering concern suggesting a more cautious attitude. One of the fundamental problems in anticipating the future supply security based on experiences drawn from the past is the uncertainty regarding emergent phenomena in technological and economic systems. There are no historical experiences for various modalities of modern society, notably population size, climate change and peak-oil. Thus, knowledge of the possible consequences of resource scarcity is limited. The range of uncertainty extends over different aspects each influencing the material scarcity risk in a different manner:

1) Geologic uncertainty: we cannot know the total amount of non-renewable mineral resources on earth but we know that extraction of high-grade deposits depletes the

remaining exploitable reserves. Whereas it is certain that more mineral resources exist than we currently know it is uncertain whether they can ever be exploited in a profitable manner taking the increasing energy demand for mining operations into account.

2) Socioeconomic uncertainty: Climate change and future political situations might push the opportunity costs of mineral mining beyond societal willingness to pay. Future shifts in societal priorities may also influence the supply side of the mineral commodity market, e.g. the conditions to grant political and militarily aid to mining industry. Future innovations on the demand side may become distorted by market failure, e.g. trade barriers etc.

3) Procedural uncertainty: resource scarcity comprises a range of multidimensional complex problems, which are sometimes termed ‘wicked’ problems. Uncertainty prevails due to the fragmentation of the intelligence regarding the various aspects of scarcity. While relevant information might actually exist somewhere in society or industry it is hardly possible for practitioners to retrieve all relevant knowledge. From a single practitioners’ perspective these matters are simply too complicated and cannot be scrutinised ad infinitum. The situation can be interpreted as a sign of insufficient knowledge exchange.

Uncertainty or incomplete knowledge regarding the determinants of material scarcity must not be reason for ignoring a potentially severe and irreversible risk. Tilton (2003) stresses that signs of impending scarcity are likely to become visible long before depletion becomes a serious problem. A prudent strategy in face of a serious risk would be to heeding early warnings even if there is currently no alarm of acute physical exhaustion of mineral resources. Short and long-term supply disruptions due to a combination of factors discussed above (inelasticity, non-substitutability, energy issues, geopolitical issues) can be interpreted as call for a precautionary response. According to that maxim of action, a potentially severe and irreversible risk should be counteracted even under conditions of uncertainty regarding the probability of occurrence of adverse effects (Som et al. 2009). A precautionary perspective can serve as a framework to constructively set the course for innovations and helps to avert irreversible pathways and lock-ins in the innovation process (Rammel 2003).

3.2. Stakeholder perspectives on material scarcity

A growing number of governmental bodies, civil society interest groups and other stakeholders have warned of the adverse implications of shortfalls in raw material supply. This section of the paper presents an overview of a number of recent reports and summaries the recommendations suggested to mitigate the problem.

The European Parliament considers eco-innovation a salient pathway for accomplishing a resource and energy efficient economy (Bleischwitz et al. 2008). The report recognises that “the EU is the world region that outsources the biggest part of resource extraction” (ibid p.6). European industry is becoming increasingly dependent on raw materials from other regions of the world. Material scarcity, in particular scarcity of critical metals, is understood as a “subtle, but further reaching“ risk for the European economy. Moreover, the report notes that, “for various commodities, the peak of extraction has already been reached or is currently about to be reached” and that “peak oil” as a widely accepted reality.

Innovations in the high-tech sector and eco-technologies could be slowed down by resource scarcity. The authors of the report emphasise that a significant reduction of the resource use will be necessary. Policy interventions in six strategy areas outline possible steps to be taken by the public sector to enhance Europe’s competitive position on future world markets:

- Creating and satisfying demand for green and fair products.
- Communicating for low impact product use.
- Innovative after sales services.
- Product and service innovations.
- Service-oriented business models.
- Leadership for social change and socially responsible business.

It appears to be in the private sectors own interest to support proactively the implementation of these strategies on a EU, national and regional level. Technology developers should critically reflect upon the proposed strategies for eco-innovation and contribute with their know-how to the implementation into practice.

The European Commission acknowledges that raw materials play an essential role for the EU economy (European Commission 2010) and warns of a high supply risk for 14 critical raw materials:

Critical raw material:	**Use for emerging technologies:**
• Antimony	ATO, micro capacitors
• Cobalt	Lithium-ion batteries, synthetic fuels
• Gallium	Thin layer photovoltaics, IC, WLED
• Germanium	Fibre optic cable, IR optical technologies
• Indium	Displays, thin layer photovoltaics
• Platinum (PGM)	Fuel cells, catalysts
• Palladium (PGM)	Catalysts, seawater desalination
• Niobium	Micro capacitors, ferroalloys
• Neodymium (rare earth)	Permanent magnets, laser technology
• Tantalum	Micro capacitors, medical technology

Other critical materials include: beryllium, fluorspar, graphite, magnesium, platinum group metals (comprising 6 metals), rare earth elements (comprising 17 metals), and tungsten. The criticality of these materials is characterized by their high relative economic importance and their high relative supply risk (Figure 3).

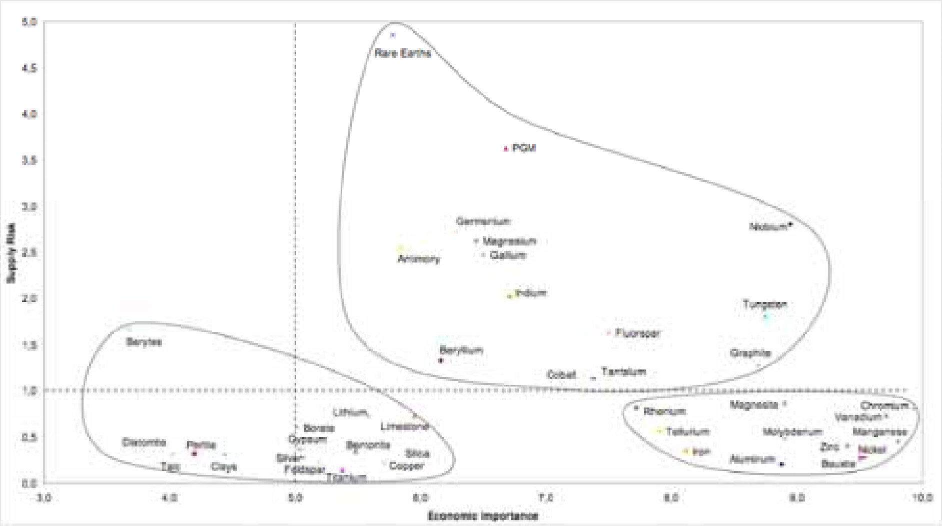


Figure 3: Criticality of raw materials as a function of their relative economic importance

and their relative supply risk. Source: (European Commission 2010)

The criticality of the supply side is mainly determined by the fact that, according to the European Commission, only a few countries (China, Russia, Congo, and Brazil) produce these commodities, thus controlling the global supply situation. Additionally, technological change and widespread market diffusion of new products are expected to substantially increase the demand for certain critical raw materials. Recommendations fall within two major domains of action: 1) steps for improving the knowledge base and 2) policy-oriented actions aimed at improving access to primary resources. Below we quote from (European Commission 2010) those recommendations being relevant for engineers and industrial designers:

- “Improve the availability of reliable, consistent statistical information in relation to raw materials”; and “promote the dissemination of this information,”
- “Encourage more research into life-cycle assessments for raw materials and their products on a “cradle-to-grave” basis”;
- “Analyse the impact of emerging technologies on demand of raw materials”
- “Improve the overall material efficiency of critical raw materials,” by “minimising the raw material used to obtain a specific product function” and “substitution of potentially critical raw materials by less critical ones”.
- ”Reduce losses of raw material into non-recyclable residues by means of smart production.”
- Overall, recycling of critical materials from end-of-life products must become more efficient. This can be achieved by “promoting research on system optimisation and recycling of technically-challenging products and substances”. That is clearly to be understood as an assignment for industrial designers to create recyclable products so as to make subsequent steps of recycling chains more effective.

The US EPA calls attention to the necessity to commence sustainable management of materials (US EPA 2009). EPA stresses that “business as usual cannot continue” because the „rapid rise in material use has led to serious environmental effects such as habitat destruction, biodiversity loss, overly stressed fisheries, and desertification“ (ibid, p.ii). The EPA report analyses the flows of materials through the technosphere from a material life cycle perspective (see Figure 3). The assessment of the material intensity of the US economy suggests that the human ecological footprint has exceeded the Earth’s biocapacity in the late 1980s.

The environmental pressures caused by the current patterns of resource extraction can be expressed as societal opportunity costs. These societal costs are usually externalized from commodity prices. The report underpins that, although the price system leads to economically efficient allocation of material resources, it does not encourage sustainable materials management. Conclusions drawn from the analysis predict environmental pressures to increase rapidly if economic growth cannot be decoupled from resource use and waste generation. Thus, opportunity costs can increase up to a point where economic growth cannot be sustained any longer.

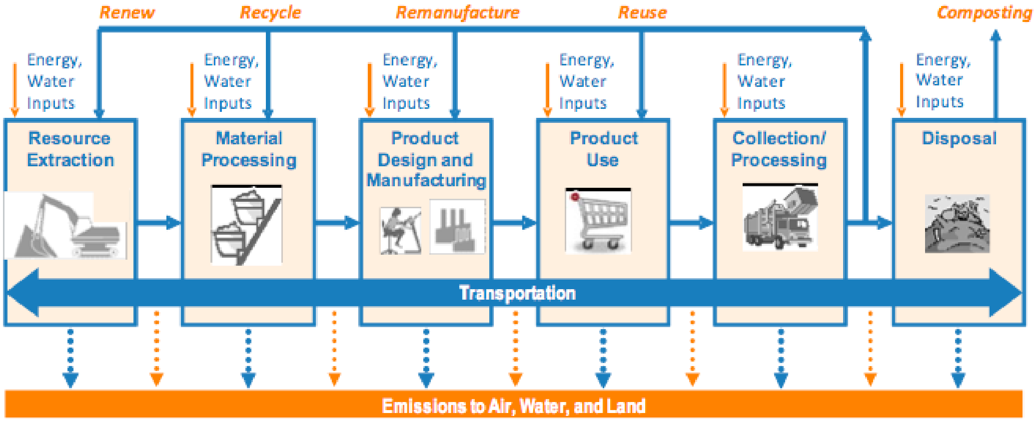


Figure 4: The Flow of Materials. Source: (US EPA 2009)

EPA recommends careful industrial and product design as a strategy to reduce the consumption of virgin materials. Sustainable life-cycle management and reuse of materials can help “to fulfil our human needs and prosper while using less material, reducing toxics and recovering more” (US EPA 2009). The following lists recommendations that industrial designers could pick up and put into practice:

- „Initiate demonstration projects on a few well-chosen materials and products to show the value of integrated materials management strategies“. “Recognize and support champions“ of sustainable materials management approaches.
- Build capacity to support life-cycle materials management (e.g. data and decision tools) including necessary research.
- Engage in a broad public dialogue on life-cycle materials management to “create public awareness of the environmental consequences of material and product choices”.
- Promote greener products, product stewardship, and product-to-service transformations.

UNEP, the United Nations Environment Programme, has placed the resource scarcity problem on a priority position of its agenda. Two recent reports, (Buchert et al. 2009) and (Graedel 2010), investigate the implications of critical elements scarcity on sustainable development. Future sustainable technologies are found to be critically dependent on “green minor metals”, a range of elements comprising indium, germanium, tantalum, PGM, tellurium, cobalt, lithium, gallium, and rare earths. Buchert et al. (2009) prioritize the general criticality of “green minor metals”[2] based on the three indicators “supply risk”, “demand growth” and “recycling restrictions”.

The authors of the report conclude that a short-term scarcity risk exists for the elements gallium, tellurium, and indium. These critical metals deserve a special focus in innovation strategies and policies in the short term. Single metals of the rare earth elements will see increasing demand whereas supply is expected to decline. The report suggests profound research and development efforts to be taken in regard to recycling of these critical elements. Serious technical recycling problems will need to be overcome to recover metals like tantalum from dissipative applications. Moreover, research and development for sector specific recycling technologies is recommended. Therein lies the challenge for the industrial design community. Efforts for establishing recycling schemes should be taken before end-of-life high-tech products such solar cells and fuel cells as appear in waste streams in large amounts. Finally, the report underscores the importance of enhanced know-how transfer and international knowledge cooperation. That is considered crucial „in order to avoid serious supply restrictions regarding valuable critical metals for future sustainable technologies“.

4. Discussion

The potential consequences of supply disruptions are severe since our modern civilization has become so dependent from critical elements. Without them, numerous innovative technology developments could suffer serious setbacks. Hence, the risks are high and it is time for government and industry to take a long view and establish policies of scarce resource management.

In the review it was observed that most scholars and professionals from the industrial design engineering discipline are not well aware of the materials scarcity problem. The whole problem area appears difficult to comprehend from a practitioner’s perspective. The matter is complex and multidimensional (comprising geological, technical, economic and environmental aspects) and is therefore sometimes termed a ‘wicked’ problem. From the viewpoint of industrial designers these issues appear rather far-fetched and insignificant to

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[2] Indium (In), germanium (Ge), tantalum (Ta), PGM [platinum group metals, such as ruthenium (Ru), platinum, (Pt) and palladium (Pd)], tellurium (Te), cobalt (Co), lithium (Li), gallium (Ga) and RE (rare earths).

their core business. In addition to uncertainty, the ambiguity of information is often bewildering: there is a prevailing dissent among expert communities on how to interpret the problem of material scarcity (see section 3.1).

Although industrial design engineers are not to the facilitators in resolving the expert dispute they should be aware that neglecting the problem of material scarcity is a risk for their profession. Shortages in supply with critical elements can affect the freedom of design and can even render certain technological innovations infeasible. Against this backdrop, a discourse is overdue how to tackle the scarcity risk. This paper argues that the industrial design engineering profession needs to develop an awareness of the problem of materials scarcity, and should investigate the potential impacts and opportunities this brings. The view of this paper states that the limited scope of action that a single actor has in face of 'wicked' problems is no excuse for inactivity but a call for proactive cooperation along the whole innovation chain. This paper recommends implementing the precautionary principle as a useful approach for sustainable resource management. It offers a framework of orientation for decision-making under conditions of uncertainty and helps preserve the potential for future developments (Som et al. 2009).

Industrial design engineers exert influence upon the demand for critical elements. Together with other protagonists in the technological innovation process such as mechanical engineers and electronics engineers, they create new application areas for scarce materials when they conceptualise new products. Designers are the professionals who 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. They also determine the ways consumers use products, i.e. for how long, before they are disposed of and recycled. Thus, the designer's influence on the demand and fate of critical elements that are incorporated in products extends well beyond the design phase.

By nature of their profession design engineers must have good perception and understanding in both directions of the innovation process: the upstream perspective (what novel technologies are in the research & development pipeline) and the downstream perspective (what needs consumers have and what trends govern the market). Few other actors in the innovation process seem to have a similar universal mindset. Presented below are some examples of what industrial design engineers can do to alleviate the problem of materials scarcity:

- Designing successful products that demonstrate the feasibility of sustainable design approaches that work well without the use of critical elements.
- Searching actively for alternative (non-material) ways to fulfil user demands or to influence user’s needs.
- Creating realistic visions and scenarios of possible technological futures in order to inspire decision makers and stakeholders to rule out innovation pathways that could fail due to material scarcity.
- Taking an active stand against the prevailing trend of planned obsolescence of high-tech gadgets. By making emotionally durable designs for long lasting products they can prevent wastage of critical elements in difficult-to-recycle waste streams.

Although industrial design engineers can by no means single-handedly solve the emerging issue of materials scarcity they hold key abilities to counteract the risk of material scarcity. The community of industrial design scholars can and should adopt a proactive attitude and play a leading role in developing and implementing a precautionary solution framework. A first step is commencing a stakeholder discourse over strategies to prevent material scarcity from becoming a roadblock for sustainable innovations. Designers, working in industry, may seek dialogue with marketing strategists, technology developers, material suppliers, material scientists and customers. As food for thought this paper proposes several elements to consider in such a discourse:

4.1 Launching multidisciplinary knowledge collaboration

We interpret the prevailing state of unawareness regarding the scarcity risk as a consequence of a lack of in-depth knowledge. It appears key to overcome the current state of unawareness. A multidisciplinary discourse can function as a starting point for mutual learning and knowledge collaboration with the aim of bringing the scarcity problem to the attention of scholars and practitioners alike. Moreover, gathering and bundling knowledge that is fragmented among scholarly disciplines is the basis for building up comprehensive intelligence of the different facets of the issue at hand.

The discourse should bring together knowledge from various disciplines of the innovation process, including engineers (industrial design, mechanics, electronics, chemistry), material scientists, technologists, and entrepreneurs. Moreover, it seems useful to consult various interest groups and share the podium with clients and stakeholders such as supply chain managers, marketing managers of companies, technology assessment experts, and of course recycling specialists. We think that industrial design scholars can greatly facilitate the commencement of a discourse for they have professional dealings with many of the above-mentioned disciplines.

The following outlines agenda items for a multidisciplinary discourse:

- Creating awareness regarding material scarcity.
- Engender a sense of responsibility and commitment to scope out the problem.
- Setting priorities for action and outlining a framework for viable solution strategies from a design engineering perspective.
- Involving the various protagonists of the innovation system and engaging with them in knowledge exchange, learning (skills & methods), and planning for solution strategies.
- Engaging in stakeholder dialogues and adjusting the agendas of innovation policies; Intervention in the innovation process of new technologies in order to avert innovation pathways that could result in accelerated resource depletion.
- Building up designers' and engineers' capacity to implement solution strategies into practice.
- Creating showcases of successful mitigation of material scarcity can greatly inspire the discourse.

Supporting research activities should facilitate the discourse with up-to-date knowledge regarding material scarcity:

- Assessing the criticality of scarce elements from a design research perspective taking the functions of materials in products into account. Making that design knowledge available to practitioners.
- Increasing the transparency of the material flows from a life cycle perspective: Tracing the use of critical elements in production processes along the whole the value chain (e.g. as auxiliary materials, intermediates and residues). Compiling existing information on the incorporation of critical elements in goods, and their fate during the disposal of waste products.
- Mapping past experiences with material scarcity and evaluating the success of existing solution strategies in the design context (e.g. heuristics such as 'design for recyclability' should be re-evaluated as to what they mean for critical metals).
- Researching substitution potentials for critical metals at various levels: substituting one material for another, looking for alternative ways to achieve a product function (designing

out scarce materials), substitution potential on the level of product use (durability, sufficiency, changes in user behaviour, marketing strategies etc.).

- Evaluating prospects of success for the proposed solution strategies in a forward looking perspective by means of trend extrapolation, scenario techniques, and modelling.
- Finally, design engineers should be supported in anticipating future challenges. Knowledge cooperation with scholars in technology assessment and methodological support from experts in future studies should be actively sought.

It should be noted that multidisciplinary knowledge collaboration is an ongoing process rather than a single event. It may be kick-started however at the occasion of the ERSCP 2010 conference and this paper invites interested parties to introduce their points of view in the discussion.

4.2 Capacity building for the implementation of solution strategies in practice

While knowledge cooperation is a necessary means of a solution framework for material scarcity it is even more important implementing applied proposals for solution into the daily business of industrial design engineers working in industry and SMEs. Developing professional skills and qualification of design practitioners is important for the implementation process of policies for sustainable use of critical metals. This paper regards capacity building a crucial aspect of a solution framework. The following outlines ideas on how to support design engineering practitioners with appropriate methods and tools.

It can be seen that innovators and design engineers working for enterprises face difficulties in taking informed decisions in favour of sustainable design because:

- They usually lack knowledge on what substances are contained in intermediate materials and sub-assemblies, which are usually procured from suppliers. It is also unknown to them in which quantities critical elements are to be found in semi-products or materials.
- They lack a holistic overview over the fate of critical elements that are incorporated into products throughout all stages of the product life cycle. Whereas the general assumption prevails that valuable materials are recyclable somehow they neglect that recycling rates are rather low in general and almost non-existent when it comes to critical elements.
- They are not aware of possible alternative technical solutions that would fulfil the same function in a more sustainable manner, i.e. using less critical materials.

From these observations we infer that setting up an open knowledge database can greatly support design engineering practitioners in their ability to make informed design decisions. A basic cast of a knowledge database would preferably host information regarding:

- Application areas of critical elements and their functions,
- Inventory of products and product components and technologies that rely on critical elements.
- Information on recyclability and actual recycling rates of critical elements from waste, referring to the technical components they are contained in.
- Compendium of substitution potentials, e.g. alternative materials or components that can serve the same purpose and are less dependent on critical elements.
- Basic design guidelines for dealing with trade-offs that result from substitution or elimination of critical elements.

In practice, industrial design engineers do often access databases to retrieve a variety of engineering and material related data. Upgrading established engineering databases such as the Granta Cambridge Engineering Selector (CES) with material scarcity related data would greatly support the profession of industrial design engineers as a whole.

Moreover, there is a need for building capacities in form of appropriate methods and tools. While an abundance of sustainable and green design paradigms (DfS) have been developed, evaluated and disseminated they mostly suffer from inadequate implementation in industry. DfS-methods can be used as a building block for creating a resource-aware design framework but they need to be customized to the emerging problem of resource scarcity. Furthermore, DfS methods should be refined in such a way that they become applicable to sustainability challenges of the future.

4.3 Reviewing the curriculum for education industrial designers, engineers and material scientists

A matter of particular attention in the context of capacity building is the education of future design professionals. Today’s students of industrial design engineering are likely to encounter the impacts of resource scarcity sooner or later in their subsequent careers. Thus far, sustainability aspects have played a relatively marginal role in the education of designers. In particular the problem of resource scarcity has hardly been addressed in the course of instruction and has seldom been brought to the attention of the teachers.

This paper proposes that the time is right to scrutinize the curriculum of industrial design engineering education, readjusting the priorities on the most pressing challenges of the near and medium future. In an anticipated post peak-oil economy of the near future there will be fierce competition over energy and mineral resources, most of which are basically non-existent in the European economic zone. If the European economy is meant to remain competitive in an international arena then it will be only be as a result of the innovative aptitude of its citizens. It is argued that it is imperative to lay the intellectual foundations in the minds of future professionals to prepare them for the challenges ahead. Future material scientists, engineers and industrial designers will be the ones who, inter alia, will have to work out a cure for our highly resource dependent and technology shaped economy. For this reason they must be made aware of and familiar with the resource scarcity problem so as to enable them to respond adequately in their future professional lives. The following aspects should be included in the curriculum for higher education:

Forming awareness and comprehension:

- Understanding the energy and material base of modern technology from a life-cycle perspective.
- Understanding the contemporary impacts of growing resource consumption and future implications.
- Developing a sense of responsibility for the problem of material scarcity and forming attitudes of approaching future problems in a proactive manner.
- Developing a mindset to commit to the aim of sustainable development.
- Debunking myths and oversimplified imagination: e.g. the belief in recycling as a first-rate solution to the material scarcity problem.
- The ability and mindset to make deliberate design decisions under conditions of incomplete knowledge.

Developing cognitive capacities and applicable skills:

- Learning to understand causal interrelation between design of products, consumption patterns, and product end-of-life treatment. Ability to analyse and comprehend complex interrelations between technology innovation and resource consumption.
- Training the ability to think of technical and functional alternatives.
- Taking a long view: design engineers should learn to take the future availability of materials into account when designing future products.

- Training how to engage in knowledge collaboration across disciplinary boundaries. That includes also interaction with suppliers and stakeholders (e.g. recycling sector).
- Learning of and training in skills and methods, which enable the identification and implementation of material substitution potentials.
- Introducing the concept of life-cycle thinking. Creating comprehension of cause-effect relations regarding sustainability impacts of design decisions.
- Scenario thinking and reality check. Learn to heed early warnings of future risks.

We expect the implementation of the aforementioned recommendations to be an interminable process, which in itself needs constant re-adjustment and updating. Moreover, industrial design scholars and teachers need to familiarise themselves with the topic area in order to be able conveying the seriousness of the challenge.

Conclusion

This paper has reviewed the contemporary state of debate regarding materials scarcity. There are warning signs that scarcity of critical elements is emerging as a risk for innovations in the high-tech sector. Possible future shortages of critical metals can jeopardise sustainable innovation policies that rely on green technologies. The depletion of critical elements must therefore be taken seriously. It has been argued that the precautionary principle could serve as a maxim of action for responding to impending signs of scarcity before resource depletion becomes a serious problem.

Industrial design engineers can play a central role in finding prudent strategies to counteract the problem. This paper outlined elements of a new agenda for resource-aware product design. Multidisciplinary knowledge collaboration can serve as a means to overcome the prevailing state of unawareness regarding the material scarcity risk. This work recommended enabling future design professionals with skills and methods to tackle the problem. For that purpose, revisions in the curriculum of higher industrial design engineering education appear advisable.

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