Journal of Cleaner Production 108 (2015) 281–288

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Some pervasive challenges to sustainability by design of electronic products – a conceptual discussion

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ARTICLE INFO

Article history:
Received 4 February 2014
Received in revised form
4 August 2015
Accepted 12 August 2015
Available online 20 August 2015

Keywords:
Sustainability
Design
Challenges
Unintended consequences
Electronic products
Rebound effects

ABSTRACT

Sustainability should encompass responsibility for unintended environmental consequences of modern developments. This study examined some pervasive challenges to sustainability by design of electronic products, namely: (i) product and consumption redundancies; (i) embodied environmental and social impacts occurring distant in time and space from the point of consumption; and (iii) production and consumption dynamics. This analysis identified essential developments in certain areas that can assist design practice in preventing unintended environmental consequences. These were: (1) complementing life cycle assessment studies with analyses of unintended environmental consequences; and (2) exploiting the vital role of product design in fostering a circular economy. Indicators that provide information about (a) the increasing spatial and decreasing temporal separation of production, consumption and waste management, (b) constraints in raw materials supply and (c) marginal changes in money and time spent should be available to product designers and consumers. Furthermore, information technology, namely computer-aided design (CAD) tools, should be refined to assist product designers in designing for effective circularity and end-of-waste and limiting hibernation of resources in the use phase.

1. Introduction

Much of the increased human well-being that modern society is experiencing is the result of scientific and technological developments. However, these developments have also had severe environmental consequences. In an attempt to respond to this dilemma, the concept of sustainability has emerged.

According to Swilling and Annecke (2012), there are three main schools of thought within the domain of sustainability: (1) 'Doom and gloom' environmentalism; (2) 'ecological modernisation'; and (3) acknowledgement of unintended environmental consequences. Within the 'doom and gloom' school, environmentalists have basically given up on technological development, blaming it for the 'mess' in which they perceive society to be engulfed. They claim that Earth has already passed its tipping point in terms of the environment's carrying capacity and resilience and that future efforts should be devoted to adapting society to the negative consequences to come (Lovelock, 2009).

The other extreme is the 'ecological modernisation' school of thought. It believes that technological fixes can mitigate environmental improvements through economic growth (OECD, 2010). Within this paradigm, product designers and engineers have been directing their product innovation efforts towards massively reducing the purchase cost per unit of functionality (Bovea and Pérez-Belis, 2012). From an industrial perspective, great progress has been made in achieving environmental gains that yield parallel economic benefits, e.g. refrigerators, washing machines, cars, computers, mobile phones and other industrial appliances now consume much less material and energy during their life cycle than previous generations.

However, rather less attention has been paid to the unintended consequences (e.g. rebound effects) of incremental improvements, which occur separated in time and geographical location from the point of consumption. Thus incremental improvements may be acting in a counterproductive manner from a long-term sustainability perspective, posing many challenges to design practice.

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http://dx.doi.org/10.1016/j.jclepro.2015.08.041
0959-6526/

The third school of thought within the domain of sustainability involves acknowledgement that with modern developments comes responsibility for unintended environmental consequences. Most of these unintended consequences are defined during the product design phase by design specifications. Therefore, the aim of this study was to identify some pervasive challenges to design for sustainability, with the focus on electronic products. The sustainability challenges to design practices examined were:

i) Product and consumption redundancies.
ii) Embodied environmental and social impacts occurring distant in time and space from the point of consumption.
iii) Production and consumption dynamics.

Based on examination of these challenges, attempts were made to highlight directions for further developments in the field.

2. General concepts

2.1. Unintended environmental consequences

Although the term unintended consequences may seem self-explanatory, the setting in which this term is used requires further explanation. In the first place, unintended consequences are not direct outcomes of purposive action, since the intended and anticipated outcomes of purposive action are always relatively desirable from the perspective of the actor of the action (Merton, 1936). However, those intended and anticipated outcomes may later cause negative and undesirable effects from the perspective of an outside observer. These later effects not addressed by the actor of the purposive action are treated in this paper as unintended consequences.

Examples of pervasive unintended environmental consequences occurring at different times and geographical locations are:

- Increasing use of scarce minerals in smart phones, tablets, laptops, hybrid cars, LED light bulbs, etc., which have contributed to resource wars in developing countries (Christopher, 2012; Kumah, 2006; Prior et al., 2012; Stamp et al., 2012; Whitmore, 2006).
- Rapid technological advances in consumer goods, which have contributed to shortening the life span of products and increasingly rapid replacement of product generations (Laurenti et al., 2015).
- Growing amounts of discarded electronic products not accompanied by growing installed capacity for properly managing this large waste stream, which have led to illegal exports of electronic waste (e-waste) to low-income countries for poor informal e-waste recycling (recovery of some precious metals present in electronic products) in those countries (Dwivedy and Mittal, 2012; Nnorom and Osibanjo, 2008; Ongondo et al., 2011; Widmer et al., 2005).
- The crude processes of informal e-waste recycling in low-income countries, which add toxins to the environment and negatively affect the health of workers (Ekener-Petersen and Finnveden, 2012; Umair et al., 2013).
- Population growth, improved standard of living and the associated increasing demand for material goods, which have been rapidly depleting the stocks of high-grade resources for producing consumer goods (Hall et al., 2014; Jowsey, 2009; Northey et al., 2014). Consequently, raw materials have become more difficult to extract and production of goods more expensive (Prior et al., 2012; Yellishetty and Mudd, 2014).

2.2. Sustainability

Sustainability is both a vague and politicised term (Lant, 2004). It has different meanings for different people (Graedel and Klee, 2002), ranging from short- to long-term visions, from individual to community perspectives and from technological innovations to changes in people's attitudes, behaviours and preferences (Partidario et al., 2010). It has been estimated that some three hundred definitions of 'sustainability' exist within the domain of environmental management and associated disciplines linked directly or indirectly to that domain (Johnston et al., 2007). Due to this lack of objectiveness, sustainability can be defined sufficiently narrowly or broadly to suit particular interests.

Like other fields, Industrial Ecology has struggled with practical application of the concept of sustainability. Ehrenfeld (2007) states that sustainability is not merely the opposite face of unsustainability and that "*[…] reducing unsustainability, the objective that is the driving force behind dematerialization, efficiency improvements, and other strategies associated with sustainable development, will not automatically produce sustainability […]*". Similarly, Swilling and Annecke (2012) suggest that sustainability will not result from causing less damage over time, but rather by finding ways of living that restore those ecosystems upon which we depend. This is the meaning of sustainability adopted in the present study.

2.3. Product design

Product design involves conceiving and giving form to artefacts that solve problems (Ulrich and Eppinger, 2008). In this sense, design is part of an overall problem-solving process beginning with perception of a gap in user experience, leading to a plan for a new artefact and resulting in the production of that artefact. In addition, product design determines most of the environmental impacts that a product will potentially have during its life cycle. Design choices such as type of materials and manufacturing processes strongly influence the rate of material or energy input per unit of the service offered by the product (see Fig. 1).

3. Unintended environmental consequences of design

3.1. Technological obsolescence and redundancy by design

Capitalist economies work by a combined strategy comprising a continuous innovation process which brings new product models that render previous products more or less obsolete; and a complex social logic leading to consumption redundancy. This combined strategy involves a self-perpetuating cycle of innovation, production, consumption, innovation, marketing of quality enhancement in emerging product models, a perpetual desire for novelty and redundancy in consumption. The health of all modern economies depends on this cycle (Jackson, 2009; Partidario et al., 2010). However, it is important to stress that the process of growth in terms of profits is also partly achieved by increased labour and capital productivity. If there is no net economic growth, then any productivity increase will result in fewer people being employed.

Consumers replace their products for the latest launched on the market, rather than because of technical failure in their existing product, for a variety of reasons, including (Khetriwal and First, 2012):

- Style preferences
- Product feature and technology advances
- Marketing campaigns with emphasis on price decreases and sales promotions
- Changed family circumstances

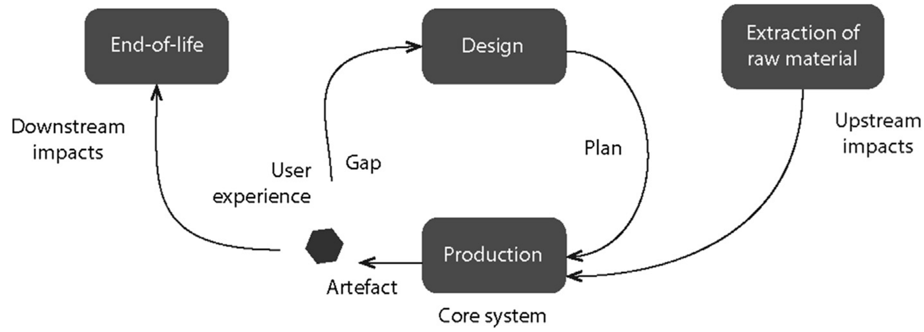

Fig. 1. Design and production as the two activities that deliver artefacts to address gaps in the user experience. Upstream and downstream impacts of a core system are defined at the point of design.

- Improved financial circumstances.

In these cases, product replacement can be seen as redundant consumption. Consumption can be redundant for:

i. A specific type of product – when a product that still has good technical usability is perceived as obsolete due to a new model being launched on the market (Herat and Agamuthu, 2012; Tischner and Hora, 2012).
ii. Products that carry the same function but do not completely replace one another. This is particularly evident for some electronic products such as smart phones, tablets, pocket cameras and computers with overlapping functions. Smart phones, tablets and pocket cameras can all take photos with reasonably good quality, but a user may still possess all three types of products. Examining the activity of taking photos further, in recent years there has been a proliferation in cameras for sport and yet consumers of sport camera still also have a normal type of camera. In the case of smart phones, tablet and computer manufacturers have used the strategy of offering different screen sizes, weights and performance to instigate redundant consumption.

Within the consumer electronic products sector, mobile phones represent an acute example of unsustainability. Mobile phones are one of the fastest growing consumer products worldwide and the number of subscribers has increased dramatically in the past 20 years (Basel Convention, 2008; ITU, 2013). As Fig. 2a shows, there has been an exponential growth trend for developing countries since the year 2000, while in industrialised countries there has been a linear growth rate followed by a plateau in 2012 at about 1.5 billon subscribers. In 2012, the number of phones per 100 people reached around 127 and 95 phones in industrialised and developing countries, respectively (Fig. 2b). Redundant consumption (market saturation) has been occurring since around 2006 in industrialised countries.

Rapid technological innovation, with better functions and models, impels consumers to change their mobile phones more frequently. This leads to a short lifetime of mobile phones and rapid generation of retired mobile phones that are still in good operating condition (Li et al., 2015).

Redundant consumption of mobile phones may be of benefit in developing countries. If replaced phones are not stored in drawers but properly collected, a secondary market can be created. This market would allow low-income consumers to afford second-hand phones (Sinha, 2014). However, in industrialised countries, where e.g. the perceived price utility ratio of a second-hand phone is lower than that of a new phone, redundant consumption leads to stockpiling of unwanted goods (Ongondo and Williams, 2011). In this sense, product and consumption redundancies are both important and under-reported challenges to sustainability by design.

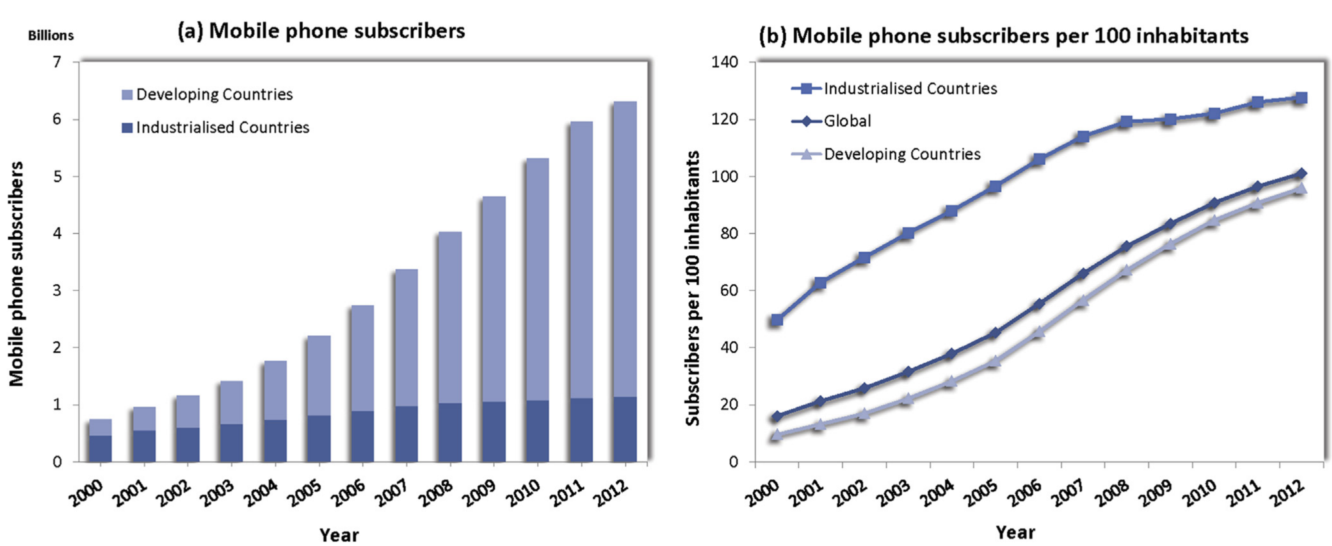

Fig. 2. Mobile phone subscribers in developed and developing countries. Charts developed by the authors based on ITU (2013).

3.2. Embodied impacts by design

In a life cycle perspective, each choice of materials for a product involves downstream impacts from the point of design. Since in a globalised world materials are produced, shipped and consumed all across the world, embodied impacts go mostly unnoticed at the point of consumption. Accordingly, it can be claimed that design embodies and international trade 'telecouples' consumption of goods and services to pervasive environmental and social impacts such as greenhouse gas emissions (Peters and Hertwich, 2008), energy use (Bordigoni et al., 2012), water use (Hoekstra, 2014), 'bad labour' (Simas et al., 2014a,b), land use (Schaffartzik et al., 2015) and biodiversity loss (Ståhls et al., 2010) (see Fig. 3).

During the Industrial Revolution, raw materials were characterised as easy to obtain and production as cheap (Barbiroli, 2011; Prior et al., 2012). Raw materials continued to be relatively cheap because relatively high-grade deposits could be found in nature, e.g. metal ores and oil reserves (Barbiroli and Focacci, 2009; Mohr et al., 2015). Commodities and industrial products have now also become relatively cheap due to e.g. economies of scale[1] and due to social and environmental externalities (waste and pollution) not being accounted for in their price (Daly and Farley, 2010). These economies of scale and the (unintentional) externalisation of social and environmental costs have made it possible to produce artefacts at relatively low cost in a linear economy model of extract-produce-use-dispose (Mathews and Tan, 2011; Van den Bergh, 2010).

In post-industrialisation times, population growth and improvements in the standard of living of people world-wide have increased the demand for material products, which has been rapidly depleting the stocks of high-grade resources (Hall et al., 2014; Jowsey, 2009; Northey et al., 2014). Raw materials have become more difficult to extract and production more expensive (Prior et al., 2012; Yellishetty and Mudd, 2014). These pervasive unintended environmental consequences have recently imposed resource constraints on the business of industrial enterprises, e.g. peak oil, peak energy, peak fishing.

As an example, over 40 elements in the periodic table are present in a mobile phone (Kuehr, 2012; Schluep et al., 2009). Among these elements, on average 23% are metals (Schluep et al., 2009), mostly copper and a small amount of precious metals, e.g. gold, silver and palladium. According to Williams et al. (2013), mobile phone circuit boards contain a higher economic value of metals than other types of circuit boards in electronic products, such as video cameras, LED TVs, etc. Table 1 shows the range and abundance (natural reserves) of materials used in mobile phones and the recovery potential from mobile phones relative to global production of virgin materials in 2012. Around 8% of the gold and 16% of the silver produced world-wide were used in mobile phones in that year. This growing demand poses severe resource supply risks. Indeed, gold and silver are rare materials and global reserves may be depleted in less than 25 years at the current consumption rate (Graedel and Allenby, 2003).

Consumption patterns in industrialised and developing countries differ significantly. In the industrialised countries, the number of discarded phones is continually increasing (Panambunan-Ferse and Breiter, 2013), but less than 20% of the phones discarded are properly managed (Bollinger et al., 2012). This has created growing interest in electronic waste (e-waste) for reuse and informal recycling in developing countries, e.g. Ghana and Pakistan (Umair et al., 2013).

A large e-waste flow from developed to developing countries, mostly illegal exports, has been reported (Umair et al., 2013). Severe environmental and social negative impacts related to informal recycling have been documented in those developing countries (Bollinger, 2010; Herat and Agamuthu, 2012; Umair et al., 2013). Informal recycling consists e.g. of manual dismantling (often with bare hands) or open burning (Panambunan-Ferse and Breiter, 2013). The crude processes of informal e-waste recycling in low-income countries add toxins to the environment and negatively affect the health of workers (Ekener-Petersen and Finnveden, 2012; Umair et al., 2013). Furthermore, these informal recycling processes recover extremely low fractions of the valuable elements present in the discarded phones (Bollinger et al., 2012; Herat and Agamuthu, 2012). Consequently, large fractions of valuable resources end up in illegal open dumps or landfill.

3.3. Production and consumption dynamics by design

Technological improvements are a key driver for the development and marketing of successive product generations. There are multiple examples, e.g. the first generation of mobile phones was relatively heavy and was only capable of performing calling, but following generations incrementally not only decreased weight but also added new and enhanced features such as cameras, media players, power capacity, screen size and resolution, etc. The newest generation, smart phones, allows users to access internet browsers, check emails, communicate via Facebook and Instant Messenger, share pictures and run more sophisticated applications.

The diffusion dynamics of multiple product generations have been used in the core strategy of the modern business. The theoretical model of adoption and diffusion of technological improvements leading to empirical support for the existence of an S-shaped pattern to represent the first-purchase growth (cumulative distribution of adoption over time) for new products in marketing was first presented by Frank M. Bass in 1969 (Bass, 2004).

However, sustainability by design must adopt a much wider perspective to account for unintended changes in production and consumption dynamics. Technological improvements in material and energy efficiencies (purposive action by a company) lead to associated cost and price reductions and increased consumption and profit for the company (intended and anticipated outcomes of the purposive action). However, when these products are provided more efficiently in terms of natural resources and cost this also saves money for consumers, who can then buy a larger number of the same product or other types (Mont, 2000). This increasing consumption may, in turn, result in increasing raw material extraction, production, waste/pollution and environmental impacts (later undesirable effects from the perspective of an outside observer). Accordingly, the question of the excess of current production and consumption due to efficiency improvements still remains.

This problematic issue of the consumption rebound effect was first identified in the middle of the 19th century, during the Industrial Revolution, by the British economist William Stanley Jevons (Freeman et al., 2015; Polimeni et al., 2008). Jevons showed that technological improvements, such as increasing the efficiency of coal use in engines doing mechanical work, were actually increasing the overall consumption of coal, iron and other resources, rather than saving them as many claimed (Alcott, 2005).

An interesting and more comprehensive understanding of rebound effects in production and consumption is provided by Weidema (2008), who defines rebound effects as "*derived changes in production and consumption when the implementation of an improvement option liberates or binds a scarce production or consumption factor*". According to Weidema (2008), these factors are:

[1] Various factors such as assembly lines, interchangeable parts and monopolies act as reinforcing synergies.

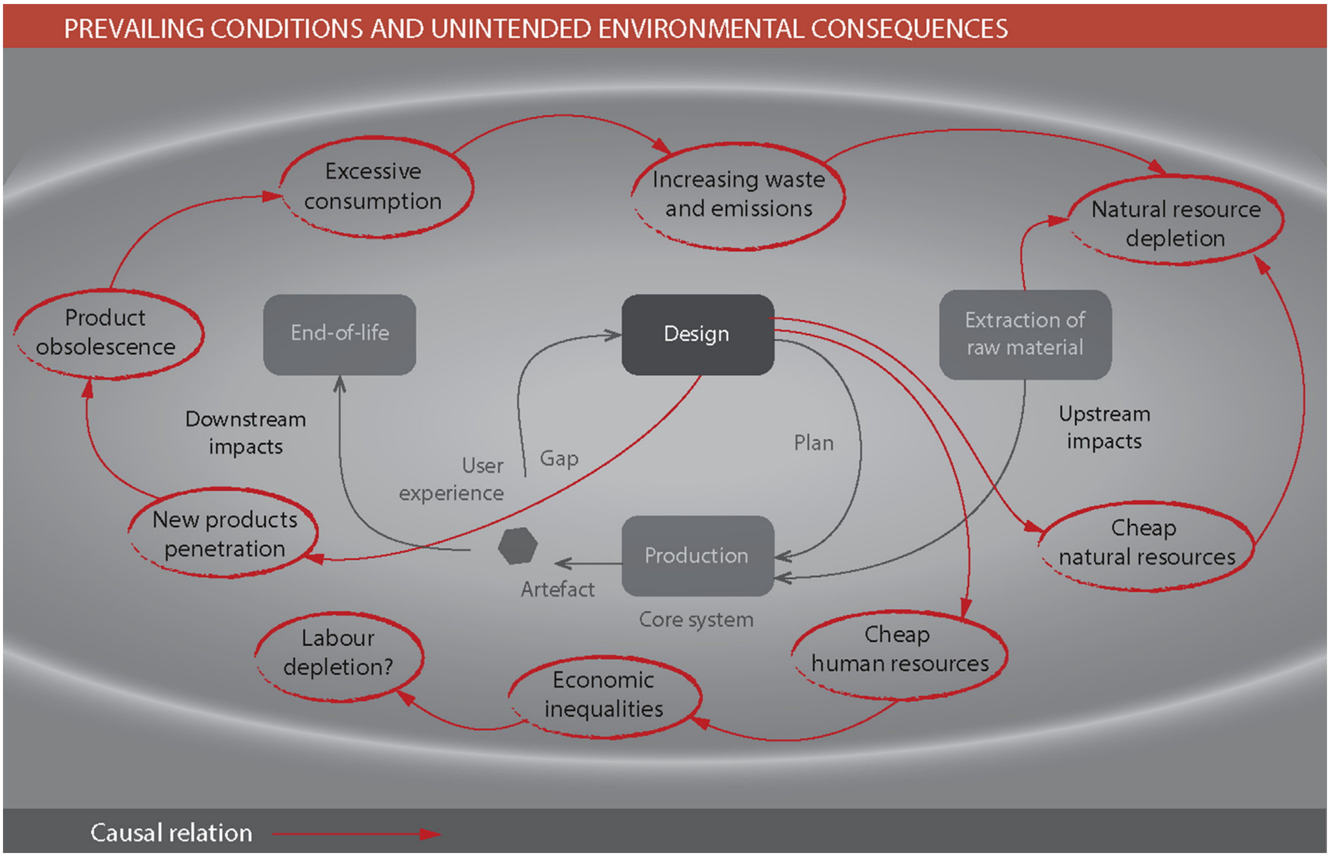

Fig. 3. Examples of prevailing conditions and unintended environmental consequences connected to product life cycle stages that can occur at multiple temporal and spatial scales. The arrows represent cause and effect chains.

- Money. Price rebounds occur when the improvement is more or less costly than the current option, affecting the specific product in question (specific price rebound) and/or the general consumer expenditure (general price rebound, also known as the income effect)
- Time. Time rebounds occur when the improvement is more or less time-consuming than the current option, affecting the time available for other activities (shopping, leisure time, business and private travels, eating, etc.)
- Space. Space rebounds occur when the improvement requires more or less space consuming than the current option, i.e. land use change
- Technology. Technology rebounds occur when the improvement affects the availability of other specific options or raw materials, resulting in wider applications than originally foreseen and/or reducing the demand for other current technologies.

4. Discussion

Efforts directed towards improving sustainability have been concerned with lessening the environmental impacts of industrial and consumer activities by using traditional methods for providing decision-making support. The material and energy requirements of physical consumer goods — household appliances, vehicles, computers, mobile phones, etc. — have decreased as new product models and generations are launched into the market. In addition, highly toxic materials have been replaced by less toxic alternatives.

Nonetheless, from the perspective of an outsider, these improvements have been causing unintended environmental consequences to occur, namely consumption rebound effects, increased waste, pollution, negative externalities, economic inequalities and other environmental and social negative impacts. These issues influence one another and interact by cause-effect linkages and

Table 1
Recovery potential of various materials from mobile phones compared with world production of virgin raw materials. Annual production and abundance based on Basel Convention (2008) and Graedel and Allenby (2003).

Material	Annual production (tons)	Material used in phones (tons)[a]	% Used for mobile phones[b]	Abundance[c]
Steel, iron	1,300,000,000	53,000	0.00	Abundant ($t_D > 100$ yr)
Aluminium	22,000,000	52,000	0.23	Abundant ($t_D > 100$ yr)
Copper	16,000,000	95,000	0.59	Constrained ($t_D = 25$–50 yr)
Tin	270,000	5700	2.2	Plentiful ($t_D = 50$–100 yr)
Silver	20,000	3200	16	Rare ($t_D < 25$ yr)
Gold	2500	190	7.6	Rare ($t_D < 25$ yr)
Palladium	220	130–280	60–130	Plentiful ($t_D = 50$–100 yr)

[a] Material used in phones = Phone subscriptions in 2012*material content in a phone.
[b] % Used for mobile phones = Material used in phones*100/Annual production.
[c] t_D represents the depletion of resources under the constant current use rate.

reinforcing feedback loops. This counterintuitive system behaviour helps explain why efficiency measures alone will never be sufficient to achieve the level of decoupling of economic growth from consumption required for sustainability.

Accordingly, in order to address these challenges, there is an urgent need to: (i) complement life cycle assessment studies with analysis of unintended environmental consequences; and (ii) foster a circular economy.

4.1. Complementing life cycle assessment with analysis of unintended environmental consequences

Within the design phase, several methods and tools can be applied to evaluate the environmental performance of the product from a life cycle perspective. One of the most commonly used is Life Cycle Assessment (LCA).

Analysis of the sustainability challenges to design discussed in this paper – redundancy, embodied impacts and production and consumption dynamics – reveals that marginal negative burdens on society and the environment depend essentially on two dynamics: consumption and investment.

The consumption dynamic concerns how new product generations encourage consumers to spend their money and time. If these are spent on new products and activities that carry higher impact intensities, the overall burdens are clearly increased. Alternatively, if money and time are spent on products and activities that carry lower impact intensities, then environmental gains are obtained.

The investment dynamic concerns how those providing the new products (companies) reinvest the profits from sales. Revenues should be reinvested to foster societal welfare (increasing equality) and restoration of ecosystem services (doing good instead of less bad). Due to these consumption and investment dynamics, directing consumers to buy more expensive products in order to restrict their availability of money and avoid increased consumption will not necessarily decrease the total negative burden of consumption.

There has been an enduring phase of economic and population growth at global and national level. Hence, the process of wealth expansion accompanying population expansion may be the underlying reason for the greater negative consequences observed. Sustainability by design(ers) should therefore be highly concerned with potential marginal changes in money and time use by the unit of service provided. As it is desirable to maintain affluence (GDP growth) and as people always spend the time available to them in some activity, it is thus necessary to direct consumers away from products and activities with high impact intensity and towards products and activities with low impact intensity.

In this respect, useful frameworks to optimise product design and resolve business dilemmas can be applied. For instance, the Eco-costs/Value Ratio (EVR), an LCA-based decision support tool for designers, business, managers and governments, can be used to internalise external costs (such as costs of pollution prevention and material depletion costs) while improving the perceived added value of a product (service system) (Vogtländer, 2001; Vogtländer et al., 2002). This tool thus addresses unintended environmental consequences by design (Mestre and Vogtlander, 2013).

4.2. Circularity by design

Natural resource management has entered into a transition from 'cheap and easy' to 'expensive and difficult' (Mason et al., 2011). The transformation from a linear 'extract-produce-use-discard' system to a circular economy model is seen as a promising pathway for coping with resource constraints and pervasive environmental pressures (Webster, 2013). A circular economy runs by means of closing material loops (Ellen MacArthur Foundation, 2014). 'Closed material loops' implies that materials are reused, either as bulk material, products or components, or recycled (Mentink, 2014), thus avoiding the extraction of raw materials from the environment.

Product design has a significant role in fostering a circular economy, which relies on creating man-made capita (such as employment and economic benefits) by efficiently circulating the same natural capital (e.g. metals in electronic products). Material streams should be kept clean so that materials can be recycled cost-efficiently. Furthermore, hibernation of resources (stock in use) should be minimised, collection should be facilitated and the cost of primary material should reflect externalities, so that the price of secondary (recycled) material is kept lower than that of primary (virgin) material.

Information technology should develop in the direction of helping product designers to design products suited to a circular economy or for end-of-waste. For instance, computer-aided design (CAD) software should include features to help designers:

a) Guide user behaviour towards increased product lifetime and reuse (including consumer trust in refurbished products), e.g. modular design of products for longer life.
b) Design in a way that decreases hibernation (stock in the use phase), e.g. a user benefit when they recycle the product at the end of its life.
c) Consider material and design concept choices so that material flows are kept clean, allowing recycling to provide high-quality recycled material to manufacturers.

5. Conclusion

This paper examined some pervasive challenges to sustainability by design, namely: (i) product and consumption redundancies; (ii) embodied environmental and social impacts occurring distant in time and space from the point of consumption; and (iii) liberation of scarce production or consumption factors – such as money, time, space, technology – that can encourage increasing consumption.

Addressing unintended environmental consequences is not, in any sense, a simple challenge, nor one that a single discipline can solve. It requires more than engineering and technological solutions, since it involves rather complex socio-economic environmental issues which require integration of various knowledge domains and interventions at multiple levels. Product design is obviously a powerful leverage point at which to intervene in production and consumption systems and the design community can respond to these complex challenges through their creativity. In order to assist this endeavour, some directions for improvements in the field are suggested:

- Analyses of unintended environmental consequences should accompany LCA studies. Frameworks such as the Eco-costs/Value Ratio (EVR) could help in such analyses
- Indicators that take into account (i) the increasing spatial and decreasing temporal separations of production, consumption and waste management and (ii) resource limitations should be delivered to product designers and consumers
- Indicators that provide information about marginal changes in money and time spent should be delivered to product designers
- Designers should design to limit the hibernation of resources in the use phase
- All the above could be embedded in modules of CAD tools to assist users in designing to improve circularity and end-of-waste.

Acknowledgements

The authors would like to thank the European Commission for funding this research project under the Erasmus Mundus External Cooperation Windows 'EU-Brazil STARTUP' and 'India4EU' programmes. Suggestions from anonymous reviewers to improve this paper are greatly acknowledged.

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