Available online at www.sciencedirect.com
ScienceDirect
Journal of Cleaner Production 15 (2007) 1337–1348
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design

Michael Braungart [a,b,c,*], William McDonough [b,d], Andrew Bollinger [c]

[a] University of Lüneburg, Suderburg, Germany
[b] McDonough Braungart Design Chemistry, Charlottesville, VA, USA
[c] EPEA Internationale Umweltforschung GmbH, Hamburg, Germany
[d] William McDonough and Partners Architecture and Community Design, Charlottesville, VA, USA
Available online 9 November 2006

Abstract

Eco-effectiveness and cradle-to-cradle design present an alternative design and production concept to the strategies of zero emission and eco-efficiency. Where eco-efficiency and zero emission seek to reduce the unintended negative consequences of processes of production and consumption, eco-effectiveness is a positive agenda for the conception and production of goods and services that incorporate social, economic, and environmental benefit, enabling triple top line growth.

Eco-effectiveness moves beyond zero emission approaches by focusing on the development of products and industrial systems that maintain or enhance the quality and productivity of materials through subsequent life cycles. The concept of eco-effectiveness also addresses the major shortcomings of eco-efficiency approaches: their inability to address the necessity for fundamental redesign of material flows, their inherent antagonism towards long-term economic growth and innovation, and their insufficiency in addressing toxicity issues.

A central component of the eco-effectiveness concept, cradle-to-cradle design provides a practical design framework for creating products and industrial systems in a positive relationship with ecological health and abundance, and long-term economic growth. Against this background, the transition to eco-effective industrial systems is a five-step process beginning with an elimination of undesirable substances and ultimately calling for a reinvention of products by reconsidering how they may optimally fulfill the need or needs for which they are actually intended while simultaneously being supportive of ecological and social systems.

This process necessitates the creation of an eco-effective system of ''nutrient'' management to coordinate the material flows amongst actors in the product system. The concept of intelligent materials pooling illustrates how such a system might take shape, in reality.

Keywords: Eco-effectiveness; Cradle-to-cradle design; Intelligent materials pooling; Triple top line

The concept of *eco-effectiveness* offers a positive alternative to traditional eco-efficiency approaches for the development of healthy and environmentally benign products and product systems. Eco-efficiency strategies focus on maintaining or increasing the value of economic output while simultaneously decreasing the impact of economic activity upon ecological systems [1]. Zero emission, as the ultimate extension of eco-efficiency, aims to provide maximal economic value with zero adverse ecological impact—a true decoupling of the relationship between economy and ecology.

Eco-efficiency begins with the assumption of a one-way, linear flow of materials through industrial systems: raw materials are extracted from the environment, transformed into products and eventually disposed of. In this system, eco-efficient techniques seek only to minimize the volume, velocity and toxicity of the material flow system, but are incapable of altering its linear progression. Some materials are recycled, but often as an end-of-pipe solution since these materials are not designed to be recycled. Instead of true recycling, this process is actually

* Corresponding author. Braungart Consulting, Osterstrasse 58, 20259 Hamburg, Germany. Tel.: +49 40 87 97 620; fax: +49 40 87 97 62 26.
E-mail address: braungart@braungart.com (M. Braungart).

0959-6526/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.jclepro.2006.08.003

downcycling, a downgrade in material quality, which limits usability and maintains the linear, cradle-to-grave dynamic of the material flow system.

In contrast to this approach of *minimization* and *dematerialization*, the concept of *eco-effectiveness* proposes the transformation of products and their associated material flows such that they form a supportive relationship with ecological systems and future economic growth. The goal is not to minimize the cradle-to-grave flow of materials, but to generate cyclical, *cradle-to-cradle* ''metabolisms'' that enable materials to maintain their status as resources and accumulate intelligence over time (*upcycling*). This inherently generates a *synergistic relationship* between ecological and economic systems—a positive *recoupling* of the relationship between economy and ecology.

1. Eco-effectiveness and zero waste

The eco-effective approach contrasts with zero emission strategies in that it deals directly with the issue of maintaining (or upgrading) resource quality and productivity through many cycles of use, rather than seeking to eliminate waste. The characteristic of zero waste (no production of negative side-products) arises as a natural side-effect of efforts to maintain the status of materials as resources, but is not the focus of eco-effective strategies. The maintenance of a high level of quality and productivity of resources is, by contrast, not necessarily a side effect of zero waste approaches.

This difference in focus between the concepts of zero waste and eco-effectiveness is reflected in the array of strategies which they employ. The zero waste concept encompasses a broad range of strategies including volume minimization, reduced consumption, design for repair and durability and design for recycling and reduced toxicity [2–4]. Whether changes are made in product design, manufacturing processes, consumer behavior or material flow logistics, reduction and minimization remain a central component of the zero waste concept.

In contrast to this, eco-effectiveness emphasizes strategies such as cradle-to-cradle design and intelligent materials pooling, which deal directly with the question of maintaining or upgrading the quality and productivity of material resources. Eco-effectiveness does not call for minimization of material use or prolonged product lifespan. In fact, it celebrates the creative and extravagant application of materials and allows for short product lifespans under the condition that all materials retain their status as productive resources. Even the application of toxic materials is acceptable as long as it takes place in the context of a closed system of material flows and the quality of the material is maintained. In the context of eco-effectiveness, strategies of reduction and minimization are not even steps in the right direction unless they contribute to the ultimate aim of achieving cyclical material flow systems that maintain material quality and productivity over time.

2. Eco-efficiency: less bad is no good

Eco-efficiency is a broad concept that has been supplied with various definitions by a number of groups since its inception in 1989. The World Business Council for Sustainable Development originally defined eco-efficiency as ''being achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's carrying capacity'' [5].

The Wuppertal Institute defines eco-efficiency as a ''social action strategy'' seeking to ''reduce the use of materials in the economy in order to reduce undesirable environmental impacts … and produce a relatively higher degree of economic affluence which is more fairly distributed'' [6]. This more material-based and socially-oriented approach reflects the multitude of slightly varying definitions for the term ''eco-efficiency''. Table 1 provides a sampling of these variations.

Despite various definitions, the core of the eco-efficiency concept can generally be understood as *to get more from less*: more product or service value with less waste, less resource use or less toxicity. In this context: eco-efficiency can be said (in the material realm) to encompass the concepts of:

- Dematerialization
- Increased resource productivity
- Reduced toxicity
- Increased recyclability (downcycling)
- Extended product lifespan

Each of these strategies starts with an assumption of the linear, cradle-to-grave flow of materials through industrial systems. They presuppose a system of production and consumption that inevitably transforms resources into waste and the Earth into a graveyard. Strategies of dematerialization and increased resource productivity seek to achieve a similar or greater level of product or service value with less material input [3,7].

With cradle-to-grave material flows as a background, strategies for generating increased recyclability and extended product lifespan seek to prolong the period until resources acquire the status of waste, for instance by increasing product durability or reprocessing post-use material for use in lower value applications. Though recycling strategies begin to approach eco-effectiveness, the large majority of recycling actually constitutes ''downcycling'' because the recycling process reduces the quality of the materials, making them suitable for use only in lower value applications. Some materials still end up in landfills or incinerators. Their lifespan has been prolonged, but their status as resources has not been maintained.

Though some have commented that zero emissions cannot be achieved through the practice of eco-efficiency [8], parallels certainly exist between eco-efficiency strategies and the zero emission concept. Both strategies concern themselves directly and primarily with the reduction of waste, and neither focuses directly on the maintenance of resource quality and productivity. This, however, is a necessary characteristic of eco-effective industrial systems.

The mode of action of eco-efficiency strategies—reductions in the quantities, velocities, and toxicities of the waste

Table 1
Definitions of eco-efficiency from different sources

Source	Definition
Australian Government	Eco-efficiency is a management process that is designed to "produce more from less". Eco-efficiency can be achieved by increasing mineral recovery, using fewer inputs such as energy and water, recycling more and reducing emissions[a]
European Environmental Agency	Eco-efficiency is the amount of "environment" used per unit of "economic activity"[b]
Global Development Research Center	The relationship between economic output (product, service, activity) and environmental impact added caused by production, consumption and disposal[c]
Joseph Fiksel	The ability of a managed entity to simultaneously meet cost, quality, and performance goals, reduce environmental impacts, and conserve valuable resources[d]
Klaus North	Eco-efficiency, cleaner production and lean production are based on a common philosophy: to reduce "waste" in all steps of a production process. Eliminating waste will lead to improvements in eco-efficiency and thus contributes to: less energy consumption, less waste material, less materials handling, and less intermediate storage[e]
Laurent Grimal	This strategy induces the integration of cleaner production technology into the production process, aiming at a reduction in materials and energy consumption and thus at a decrease in pollution[f]
LEAN Advisors	The means by which more and better goods and services are created using fewer resources and minimizing waste and pollution. In practice, eco-efficiency has three core objectives: increasing product or service values, optimizing the use of resources, and reducing environmental impact[g]
Nokia	Eco-efficiency means producing better results from less material and energy. For us this means: minimizing energy intensity, minimizing the material intensity of goods and services, extending product durability, increasing the efficiency of processes, minimizing toxic dispersion, promoting recycling, and maximizing the use of renewable resources[h]
PrintNet	Eco-efficiency is a concept that links environmental and financial performance. It does this by focusing on the development, production and delivery of products and services that meet human needs while progressively reducing their environmental impact throughout their lifecycles. Eco-efficiency essentially means doing more with less-using environmental resources more efficiently in economic processes. The application of eco-efficiency is undertaken, but not limited, by approaches and tools such as cleaner production and environmental management systems[i]
Toshiba Group	Eco-efficiency is calculated by dividing the "value" of a product by the product's "environmental impact". The smaller the environmental impact and the higher the value of the product, the greater is the eco-efficiency. The value of a product is calculated based on its functions and performance, taking the voice of customer into consideration. The environmental impact of a product is calculated, taking into consideration various environmental impacts throughout its life cycle[j]
WMC Resources Ltd.	Maximizing efficiency of production processes while minimizing impact on the environment. Eco-efficiency can be achieved by using new technology, using fewer inputs per unit of product such as energy and water, recycling more and reducing toxic emissions. In summary doing more with less[k]

[a] Australian Government website: erin.gov.au/industry/finance/glossary.html.
[b] European Environmental Agency website: http://reports.eea.eu.int/.
[c] Global Development Research Center website: www.gdrc.org/uem/ait-terms.html.
[d] Fiksel J, editor. Design for environment: creating eco-efficient products and processes. McGraw-Hill; 1996.
[e] North K. Environmental business management. 2nd revised ed. Geneva: International Labour Organisation; 1997.
[f] Grimal L. The adoption of cleaner production technology and the emergence of industrial ecology activity: consequences for employment. In: Bourg D, Erkman S, editors. Perspectives on industrial ecology. Alsace, France; 2003.
[g] LEAN Advisors website: http://www.leanadvisors.com.
[h] Nokia website: http://www.nokia.com.
[i] PrintNet website: http://www.printnet.com.au.
[j] Toshiba Group website: http://www.toshiba.co.jp.
[k] WMC Resources Ltd. website: http://www.wmc.com.au/sustain/envrep97/glossary.htm.

stream—are not adequate solutions. Less bad is no good—to destroy less is not positive, as has been stated by the authors before [19]. By extension of this point, with zero emissions as the ultimate though unattainable target of eco-efficiency, "no bad" is not good either, when compared to eco-effective systems where the products and outputs are inherently positive.

In the short-term, eco-efficiency strategies present the potential for tangible reductions in the ecological impact of a business's activities and an opportunity for (sometimes significantly) reduced costs. In the long-term, however, they are insufficient for achieving economic and environmental objectives on several accounts:

1. Eco-efficiency is a reactionary approach that does not address the need for fundamental redesign of industrial material flows.

2. Eco-efficiency is inherently at odds with long-term economic growth and innovation
3. Eco-efficiency does not effectively address the issue of toxicity.

2.1. Eco-efficiency is a reactionary approach that does not address the need for fundamental redesign of industrial material flows

Eco-efficiency is principally a strategy for *damage management and guilt reduction*. It begins with an assumption that industry is *100% bad*, and proceeds with the goal of attempting to make it *less bad* (Fig. 1). While being eco-efficient may indeed reduce resource consumption and pollution, and provide temporary economic advantage in the short-term, it lacks a long-term vision for establishing a truly positive relationship between industry and nature. Eco-efficiency strategies do not address the deep design flaws of contemporary industry. They address problems instead of the source, setting goals and using practices that sustain a fundamentally flawed system. The ultimate result is an unappealing compromise that takes for granted, even institutionalizes, the antagonism between nature and industry.

This tendency can be seen in resource use patterns over recent decades, where the absolute quantities of materials extracted from, and wastes and pollution disposed into, the natural environment have continued to grow despite significant efficiency improvements. For instance, on a global level, the amount of energy used in metallurgical aluminum production per tonne of product dropped by 10% in the period between 1991 and 2000 [9]. During the same period, however, total global production of metallurgical aluminum increased by over 40%, causing the total energy used for aluminum production to increase as well [8]. Rebound effects like this unavoidably connect increased efficiency with a greater total rate of destruction. Because of its largely inefficient industry, for instance, the former East Germany did a much better job of ‘‘protecting’’ the environment than did the West. Its greater level of efficiency allowed industry in West Germany to much more successfully and completely destroy the local ecology.

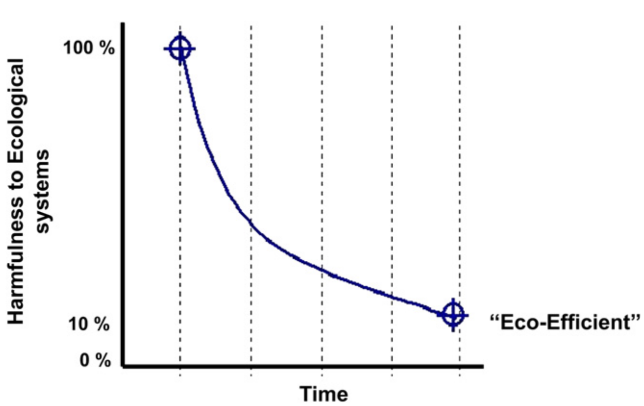

Fig. 1. Eco-efficiency strives to minimize damage to ecological systems.

Recycling is hardly a magic bullet solution. As previously noted, the large majority of recycling done today is actually *downcycling* where materials lose value as they circulate through industrial systems. When plastics are recycled into countertops, for example, valuable materials are mixed and cannot be recycled again. Their trip to the landfill has only been slowed down and the linearity of the material flow system has been maintained. From this same perspective, mixing metals dilutes their value and increases the impact of the materials. When rare and valuable metals like copper, nickel and manganese are blended in the recycling process, their discrete value is lost forever. Creating new stockpiles is extremely costly, both economically and ecologically.

Recycled paper offers another example of the difficulty in recycling products that were not designed for this purpose. The range of materials—often including plastics, dyes, inks and various chemical additives—that are included in modern papers make recycling a highly awkward process necessitating the use of even more toxic chemicals and in a product of inevitably lower quality. In ‘‘Recycling is Garbage’’, John Tierney claims that recycling newsprint produces 5000 gallons more polluted water than creating newspaper from virgin wood [10].

2.2. Eco-efficiency is inherently at odds with long-term economic growth and innovation

The ultimate aim of eco-efficiency approaches is to achieve a state of *zero:zero* waste emission, *zero* resource use and *zero* toxicity. Within the context of a system of cradle-to-grave material flows, however, the goal of *zero* is inherently unreachable. Despite the immense dematerialization possibilities of the digital era, it will never be possible to provide the vast majority of goods and services without the use of any material resources. The digital realm will always require the hardware to keep it running, and humans will always need food to nourish them, clothes to cover them, physical shelters to protect them and a transportation infrastructure to move them.

Eco-efficiency promotes incremental reductions in the ecological impact of industrial processes and products. While this type of incremental change has been a worthwhile (and maybe necessary) initial step with regards to laying a groundwork and getting hold of the ‘‘the low-hanging fruits’’, it cannot be regarded as an end in itself or even a feasible long-term strategy. While such improvement can lead to cost savings in the short-term, opportunities for marginal improvement inevitably decrease as dematerialization limits are reached. The subsequent maintenance of this dematerialized system limits possibilities for innovation and growth. Innovation is impossible because the priority for dematerialization suffocates creative approaches to the use of materials while simultaneously directing funding towards the generation of decreasingly beneficial incremental improvements. Growth becomes a problem because it threatens to result in increased resource use and waste emissions.

The constant pursuit of the goal of zero—*zero* waste, *zero* resources, *zero* impact—results in an uneasy marriage between financial and ecological objectives reflected for instance in the concept of the *triple bottom line*. In reality, triple bottom line strategies do not result in a balance amongst economic, environmental and social aims, because economic objectives remain paramount. The goal with regard to environment is to be *less bad*. This approach is reflected amongst others in the vision statements of major corporations committed to a triple bottom line approach:

> Philanthropy is important to Hewlett-Packard, but we at HP want our contribution and involvement in global citizenship initiatives to have a far greater impact than simply writing a check would…. On the environmental front, we have an explicit goal of designing new products so as to minimize their ecological impact, from production through disposal [11].

Despite a positively-stated vision within the social realm, the implicit goal in the environmental realm is to achieve a state of *zero* impact.

2.3. Eco-efficiency does not effectively address the issue of toxicity

Whether a telephone, an electric razor, athletic shoes, a newspaper or a mobile phone, all products emit chemicals. The concentration of these emitted chemicals is generally so small that they do not acutely sicken the user, but rather present an additional chemical load with an undefined long-term effect. The increasing contamination, especially of interior air, can lead to a multiplicity of health problems, including allergies, chronic fatigue syndrome and multiple chemical sensitivity [12].

Statistics over the past several decades indicate two- to three-fold increases in various types of allergies in Europe, including allergic asthma, atopic dermatitis and others [13]. The increasingly ubiquitous application of certain chemicals in everyday products is highly suspect as a contributing factor. Common plastics, for instance, contain a wide spectrum of additives, including antioxidants, lubricants, antistatic agents, blowing agents, mineral fillers, pigments, plasticizers, flame retardants, heat stabilizers, impact modifiers, UV absorbers, longer life additives and others. The toxicological and ecotoxicological profiles of some of these substances are often not well defined. A recent study led by the Swedish National Testing and Research Institute, for instance, found a link between phthalates, a common plasticizer in PVC plastics, and allergic symptoms in children [14].

Global sourcing and lean production have resulted in products with undefined material and chemical compositions. A product assembled in Germany, for instance, may be made up of components produced in India and sub-components produced in China. The result is that companies often are unfamiliar with the material composition of their products, which may be wholly unsuitable for the purpose for which the products are intended. Fig. 2 shows the off-gassing diagram of a brand-name children's toy sold in the United States and produced in China. Each peak in the diagram indicates a chemical emitted from the product into the air around it. Some of these peaks indicate the presence of a spectrum of aromatic hydrocarbons and other potentially toxic components, clearly unsuitable for application in a product intended for young children.

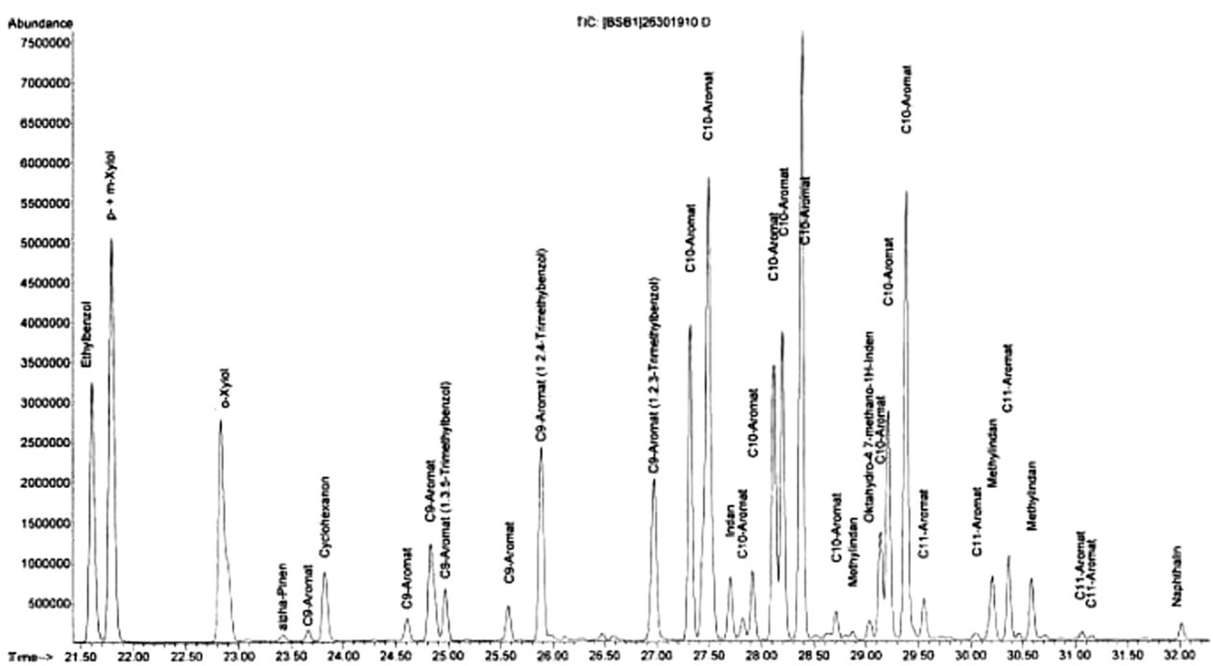

Fig. 2. Off-gassing of a brand name children's toy sold in the United States.

When dealing with toxic chemicals, a minimization approach is insufficient. Even very small amounts of some toxic chemicals pose a significant risk because of their extreme bioaccumulation or eco-/toxic potential. Even more, existing knowledge about the toxicity of substances is for the most part limited to the toxicity of single substances. Studies show that significant allergenic potential also exists in synergies amongst multiple chemicals [15]. This presents an especially increased risk in the context of products that employ a larger set of chemicals and chemical combinations. Penetration enhancers used in cosmetics, for instance, can increase the ability of certain toxic chemicals to enter the body through the skin, enabling small amounts to have a multiplied effect.

As the levels of chemicals present in indoor air climbs, eco-efficient building construction guidelines call for more heavily insulated and tightly sealed interior spaces. While this helps to reduce energy requirements for maintaining constant interior temperatures, it also traps chemicals released into interior spaces, potentially leading to an acute incidence of indoor air pollution known as the *sick building syndrome* [16].

One approach to reducing the issues associated with toxic chemicals in products is to replace known toxic substances. If a toxic substance is replaced with another substance that has a better eco-/toxicological profile, then this is certainly a step in the right direction. Such *free of* strategies may be problematic, however, because known toxic substances are sometimes replaced by others with similar, or even worse, toxicological characteristics. This may occur, for instance, if the toxicological profile of the replacement substance is unknown, or if inconsistent regulations call for the elimination of a particular high-profile substance while leaving open the possibility for the application of potential replacement substances with similar toxicological characteristics. A 1989 ban of the wood preservative pentachlorophenol in Germany, for instance, did not automatically result in the banning of tetrachlorophenol, despite their comparable toxicological properties.

The zero emissions concept contradicts thermodynamics: existence creates emissions. By striving to eliminate emissions from their activities, people are attempting to sever the link between themselves and their environment. An eco-effective approach takes the position that the quantity of the emissions is not the problem, it is the quality of the outputs that must be addressed by making the emissions healthy. To illustrate this, consider that the biomass of ants on the planet is greater than that of humans, yet the Earth suffers no ill effect from ants' emissions, rather it is continually nourished by them [32]. Eco-effectiveness designates all outputs from human activity as positive—healthy waste is good—and make people native to the planet once more by re-establishing a positive link between human activity and natural systems. In this, eco-effectiveness eliminates the need to associate guilt with human activity, and celebrates the relationship between man and nature as mutually beneficial.

3. Eco-effectiveness and cradle-to-cradle design

In contrast to eco-efficiency that begins against an assumption of linear, cradle-to-grave material flows, eco-effectiveness encompasses a set of strategies for generating healthy, cradle-to-cradle material flow *metabolisms*. Use of the term metabolism in this case is indicative of a similarity between cradle-to-cradle material flow systems and the internal processes of a living organism. Ayres and Simonis [17] note the similarities between biological organisms and industrial activities on multiple levels. Just as the metabolic systems of biological organisms include the synthesis and breaking down of substances for the maintenance of life, the metabolic systems of eco-effective material flow systems include the synthesis and breaking down of products for the maintenance of a healthy economy and provision for human needs.

Eco-effectiveness is modelled on the successful interdependence and regenerative productivity of natural systems. In nature, all outputs from one process become inputs for another. The concept of waste does not exist. The blossoms of a cherry tree bring forth a new generation of cherry trees while also providing food for microorganisms, which in turn nourish the soil and support the growth of future plant-life.

Each element within a natural system may also be highly inefficient. The growth and release of thousands of cherry blossoms, only a few of which may become new cherry trees, is a travesty of material intensity per service unit. When the cherry tree is viewed in the context of the interdependent natural system of which it is a part, however, the overall effectiveness of the system becomes clear.

In eco-effective industrial systems, the material intensity per service unit of each individual element is irrelevant to the effectiveness of the whole. As long as those materials that enter industrial systems are perpetually maintained at the status of resources, the system is perfectly effective and no waste is produced. If the trimmings from the production of a textile system are composed in such a way that they become nutrients for ecological systems, then it is ecologically irrelevant when they are not included in the saleable product. Even if the material intensity per service unit of the textile mill were astronomically high, the system as a whole would be highly eco-effective because the trimmings would become productive resources for natural systems.

Efficiency and effectiveness can be complementary strategies. If efficiency is defined as "doing things the right way", effectiveness means "doing the right things" [18]. The concept of efficiency in itself has no value; it can be either good or bad. If industry is driven by systems that are inherently destructive, making them more efficient will not solve the problem, and may even aggravate it (e.g. the rebound effect) [19]. The slimming down of material flows per product or service unit (eco-efficiency) is only beneficial in the long-term if the goal of closing material flows (eco-effectiveness) has first been achieved. Once effectiveness has been achieved, efficiency improvements are not an environmental necessity, but a matter of equity. They are necessary to ensure the fair distribution of goods and services.

Where eco-efficiency begins with an assumption of industry that is 100% bad, Eco-effectiveness starts with a vision of industry that is 100% good (Fig. 3), that supports and regenerates ecological systems and enables long-term economic

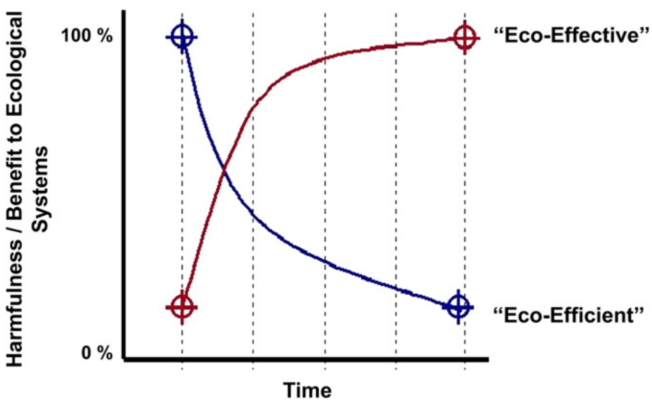

Fig. 3. Eco-effectiveness strives to generate an entirely (100%) beneficial impact upon ecological systems.

prosperity. This perspective is the basis for the concept of the *triple top line* [20]. Pursuit of triple bottom line objectives promotes awareness within companies of the environmental and social impacts of their activities and a drive to minimize ecological footprint. In contrast to this, pursuit of triple top line growth begins with recognition of the inherent business value of natural and social capital, and promotes a celebration of the potential synergies amongst economic, environmental and social business aims.

3.1. Cradle-to-cradle design

Cradle-to-cradle design enables the creation of wholly beneficial industrial systems driven by the synergistic pursuit of positive economic, environmental and social goals. The practical, strategic expression of the eco-effective philosophy, *cradle-to-cradle design* defines a framework for designing products and industrial processes that turn materials into *nutrients* by enabling their perpetual flow within one of two distinct *metabolisms*: the *biological metabolism* and the *technical metabolism*.

Materials that flow optimally through the biological metabolism are called biological nutrients. As defined for cradle-to-cradle products, biological nutrients are biodegradable materials (or the result of biodegradation processes) posing no immediate or eventual hazard to living systems that can be used for human purposes and be safely returned to the environment to feed biological processes. Biological nutrients can be natural or plant-based materials, but include also materials like biopolymers and other potentially synthetic substances that are safe for humans and natural systems. The biological metabolism includes processes of resource extraction, manufacturing and customer use, as well as the eventual return of these materials to natural systems where they can again be transformed into resources for human activity.

Products conceived as biological nutrients are called *products of consumption*. This, for instance, includes products that may actually be *consumed* (e.g. through physical degradation or abrasion) during the duration of their lifespan, such as textiles, brake pads, shoe soles, etc. Because they are designed as nutrients for living systems, products of consumption can be returned to the natural environment after use to become nutrients for living systems. A biological nutrient textile, for example, can be used as garden mulch after its useful life as an upholstery fabric. An ice cream wrapper can be designed to contain seeds and liquefy at room temperature so that when thrown away, it not only dissolves safely into the ground but also supports the growth of plant-life.

A technical nutrient, on the other hand, may be defined as a material, frequently synthetic or mineral, that has the potential to remain safely in a closed-loop system of manufacture, recovery, and reuse (the technical metabolism), maintaining its highest value through many product life cycles. Technical nutrients are used as *products of service*, which are durable goods that render a service to customers. The product is used by the customer but owned by the manufacturer, either formally or in effect. The product of service strategy is mutually beneficial to the manufacturer and the customer. The manufacturer maintains ownership of valuable material assets for continual reuse while the customers receive the service of the product without assuming its material liability. The manufacturer or commercial representative of the product also fosters long-term relationships with returning customers through many product life cycles. Consider, for instance, a television or a washing machine that is leased to a customer for a defined period, and then afterwards returned to the company so that the materials can be recovered and used again in the creation of new products (either by the same or a different company, but at an equivalent or higher level of quality).

4. From efficiency to effectiveness

The shift from efficiency to effectiveness necessitates a fundamental redesign of products and the system of industrial material flows within which they circulate. Cradle-to-cradle design defines a broad framework for creating eco-effective industrial systems, but for businesses to put this framework into practice they need both the right technologies and the right strategies.

Standard life cycle assessment (LCA) is an unsuitable approach for generating eco-effective products and processes because its linear nature does not allow for optimization in the context of cradle-to-cradle design. Braungart and McDonough [21–25] have defined a stepwise strategy for businesses to realize the transition from eco-efficiency to eco-effectiveness on the level of product design:

Step 1: Free of …
Step 2: Personal preferences
Step 3: The passive positive list
Step 4: The active positive list
Step 5: Reinvention

This five-step process begins with an elimination of undesirable substances and moves towards the positive definition of desirable substances (Step 4). Ultimately, Step 5 calls for a *reinvention* of products by reconsidering how they may optimally fulfill the need or needs for which they are actually intended while simultaneously being supportive of ecological and social systems.

4.1. Step 1: Free of …

Most companies today have a very limited knowledge of the toxicological and eco-toxicological characteristics of the substances that make up their products. An automobile, for instance, may contain thousands of different materials and chemicals. Gaining an understanding of the impact that each of these materials may have on the natural environment and human health is an immense undertaking, and something that the large majority of businesses have not done and do not immediately have the capacity to do.

Most companies, however, have a general knowledge of the most dangerous substances in their products (referred to as X-substances in the context of eco-effectiveness). For companies like this, a first step in moving towards eco-effectiveness is to find replacements for the X-substances in their products. This includes substances like mercury, cadmium and lead that are known or suspected carcinogens, teratogens, mutagens or endocrine disruptors. Removal of X-substances is almost always a step in the right direction, but as noted previously, such a *free of* approach has to be applied carefully to ensure that replacement substances are indeed better than those that are replaced.

4.2. Step 2: Personal preferences

Once the most undesirable substances have been removed from a product, the next step is to begin to make educated choices about those substances that should be included in the product. Though the best way to do this is to have a detailed knowledge about the impacts of a particular substance on ecological and human systems throughout its life cycle, this is often impractical or even impossible. Furthermore, different substances have different types of impacts. Should a company prefer a substance which is potentially sensitizing or one which is persistent in the environment; a substance that may contribute to global warming or one that might end up harming marine life?

Without a detailed scientific knowledge of a substance's toxicological profile and its fate throughout the life cycle of a product, these decisions can be difficult to make. At the same time, design decisions have to be made and products have to be brought to the market. With incomplete knowledge, the best way to make decisions about which chemicals and materials to include in a product comes down to *personal preferences* based upon the best available information. Though decisions guided by personal preferences may not always result in the most eco-effective design choices, they generally will result in a product that is at least *less bad* than its predecessors.

4.3. Step 3: The passive positive list

Step 3 includes a systematic assessment of each ingredient in a product to classify them according to their toxicological and eco-toxicological characteristics, especially their capability to flow within biological and technical metabolisms. For products of consumption, criteria to examine should include for instance: toxicity to humans (acute, delayed, developmental, reproductive), aquatic toxicity, persistence and bioaccumulation in nature, sensitization potential, mutagenicity, carcinogenicity and endocrine disruption potential. Based upon the assessment of a material or chemical according to these criteria, a *passive positive list* can be generated which classifies each substance according to its suitability for the biological metabolism. This list can be used to determine the degree of additional optimization necessary for a particular product to be a true product of consumption.

This same process applies for products of service as well, though the criteria are somewhat different. Cadmium, for instance, is a highly toxic heavy metal, and is often applied in photovoltaics in the form of cadmium telluride. Though cadmium telluride is far from an ideal substance from an ecological perspective, its careful application in photovoltaics in the context of a product of service concept may be considered acceptable until a suitable replacement is found. As part of a defined material flow metabolism that ensures the safe handling and recapture of the material after use, the risk of the cadmium coming into contact with natural systems is minimal.

4.4. Step 4: The active positive list

Step 4 includes the optimization of the passive positive list to the point until each ingredient in the product is positively defined as a biological or technical nutrient. Whereas step 3 establishes knowledge of the degree to which each component in a product needs to be optimized, step 4 implements this optimization to the fullest degree.

Climatex® Lifecycle™ upholstery fabric is an example of a product whose constituent materials are positively defined as biological nutrients. Created in a collaboration amongst EPEA Internationale Umweltforschung GmbH, McDonough Braungart Design Chemistry and Rohner Textil, Climatex® Lifecycle™ is a completely biodegradable and compostable fabric. Each component was selected according to EPEA's positive listing methodology for its positive environmental and human health characteristics and its suitability as a biological nutrient.

The fabric is made from natural fibers, including wool from free-ranging, humanely sheared New Zealand sheep, and Ramie, a tall, fibrous plant grown in Asia. To identify suitable dyes for the fabric, 60 major dye producers were asked to provide the necessary information on their best dyes to enable an assessment of their suitability as biological nutrients. From a selection of 1600 dye formulations, EPEA utilized their methodology to identify 16 that met both the desired technical and environmental specifications [26].

The optimization of the materials and dyes used in the product also has an impact upon the environmental profile of the production process. Before eco-effective optimization of the product, trimmings from the mill were classified as hazardous waste requiring special (and expensive) disposal. After optimization, waste material from the mill could be made into felt to be used as garden mulch, and in the cultivation of strawberries, cucumbers and a wide range of other plants.

Step 4 also applies for products of service. An automobile, for instance, might be designed so all of the materials and components it contains are biological or technical nutrients. Brake pads, tires and interior upholstery might be designed as biological nutrients because these are components that will likely degrade over the period of use of the car. The frame and body, on the other hand, might optimally be designed as technical nutrients like steel and polypropylene so they can be regained and upcycled into new automobile components or other products after the use period of the car.

The Ford Model U concept car reflects an initial effort to put this concept into practice. It contains a number of biological and technical nutrient materials, including a polyester upholstery fabric optimized for flow in closed-loop cycles and a car top made from polylactic acid, a potential biological nutrient. From packaging [27] and textiles [28] to buildings [29] and furniture [30], the practicality of this approach has been illustrated again and again. Once a product's material components have been positively defined as biological or technical nutrients, Step 4 has been achieved.

4.5. Step 5: Reinvention

Where step 4 stops at the level of redefining the substances in a product, step 5 involves a *reinvention* of the relationship of the product with the customer. The concept of reinvention addresses the interconnected nature of ecological, social and economic systems by pushing the idea of the biological and technical metabolisms beyond the confines of existing product and service forms. Strategies for reinvention view products from the perspective of the services they provide and the needs they fulfill for customers and for the broader context of social and ecological systems.

The product of service concept offers an ideal strategy for this. One might think about a washing machine, for instance, in terms of the service it provides: a convenient cleansing system for clothes. When customers purchase a washing machine, they are not paying for ownership of the materials it contains but for this service that it provides. If companies began to sell the service of a convenient cleansing system for clothes instead of the material object of the washing machine, a new set of immediate benefits becomes apparent. A company could potentially still provide a washing machine to customers, but perhaps under the form of a time-limited lease, or 3000 cycles of washing including service and possibly even detergent and water. Ownership of the washing machine itself would not change hands.

One benefit of such a system is that customers are no longer confronted with the liability associated with owning a product which contains potentially hazardous materials, connected with the dilemma of what to do with them at the end of the product's useful life. Another benefit for customers is that their interests are now aligned with those of their service provider. Under a traditional situation of ownership transfer, it is at least partially in the interest of the company to provide a product that fails as quickly as possible because this enables them an opportunity to sell yet another washing machine to their customer. This system encourages the production of cheap, low-quality goods. When products are provided in the form of a service scheme, however, companies are interested in producing the best product possible, because the better the needs of customers are fulfilled the more likely they are to remain customers after the end of the service period. Furthermore, when products are constructed using biological and technical nutrient materials, companies have the added benefit of getting these valuable nutrients back after the product's defined use period. This enables the application, for instance, of high quality technical nutrient materials like polysulfonic polymers, which are too expensive for application in most products when they are not regained after use. The result is higher quality and less expensive products.

Going back to the example of the automobile, reinvention means considering how the services that an automobile provides may be fulfilled with broader ecological and social benefits. This might mean, for instance, designing a *nutrivehicle* that not only releases no negative emissions, but releases positive emissions that have a nourishing effect on the environment. Instead of making the catalytic converter as small as possible, methods could be developed so that the nitrogen could be used as a fertilizer. Cars could be constructed so that as much nitrogen as possible is produced and collected during use. Likewise, perhaps using fluid mechanics, tires could be designed to attract and capture harmful particles, thus cleaning air instead of further dirtying it.

If in twenty years there are three times as many cars on the streets, then their relationship with ecological systems will only be a part of the issue. The amount of resources (both land and material) required to sustain such widespread use of the automobile would have a significantly detrimental social effect by placing severe limits on resource availability. In this case, reinvention means considering how systems of mobility might be redesigned to have a beneficial impact on social conditions while better fulfilling the need for mobility.

The concept of the *community car* [24] addresses these issues. As part of a local or regional transportation plan, the community car could automatically respond to electronic calls to provide door-to-door transportation service twenty-four hours a day. Operating within a smaller area, the cars could eventually even be driven automatically, providing the service of transportation amongst others to children, the elderly, the handicapped, and a broad spectrum of others who are often excluded from current forms of transportation, while at the same time reducing the number of cars on the road.

5. Eco-effective nutrient management

Products designed as biological or technical nutrients need to be embedded in an eco-effective system of *nutrient flows*. The effective management of nutrient flows associated with the biological and technical metabolism necessitates the formation of collaborative business structures with the role of coordinating the flow of materials and information throughout the product life cycle.

Individual businesses generally have control only over a small portion of material flow system of which their product is a part, and are incapable of directing the flow of materials or exchanging intelligence with other actors throughout the product's life cycle. Manufacturers may be able to positively define the materials in their products as biological or technical nutrients, but once the product has been passed on to customers they have little control over the fate of its constituent materials.

Extended producer responsibility legislation like the EU's End-of-Life Vehicles (ELV) Directive requires manufacturers to begin to ensure the safe handling of their product's materials after the customer use phase. The ELV Directive has stimulated the formation of automobile industry collaborations for the safe take-back and recycling of automobiles within the EU. In this case, the producer links the upstream (supplier) and downstream (collector, dismantler, and shredder) portions of the vehicle's life cycle through coordinated collaboration with actors on both ends as well as with other vehicle manufacturers. Though the ELV Directive and other similar legislative initiatives have generally not spurred the development of true cradle-to-cradle metabolisms, they have resulted in the beginnings of collaborative mechanisms for handling the flow of materials throughout the product life cycle.

The shift to eco-effective industrial systems and the enabling of upcycling requires not only a redirection of material flows, but also the establishment of new forms of supportive information and finance flow networks. Manufacturers require information from suppliers concerning the exact composition of their intermediate products and disassembly capabilities at recovery sites; customers need information on how to deal with the product after its use period; recyclers need information on appropriate dismantling processes and material composition. The exact structure of the network that supplies this information and the manner in which information is shared may vary amongst situations. Kamejima and Ejiri [31] suggest the use of automized computer-based systems for the sharing of information between suppliers/manufacturers and recyclers in the context of achieving cyclical material flow systems.

As an initial move in the direction of cyclical material flows for automobiles, the ELV Directive has given rise to a new network of information flows amongst relevant actors. Original equipment manufacturers (OEMs) are required to release dismantling information within 6 months of the release of a new vehicle, and to provide information to prospective buyers about design changes that increase vehicle recyclability. Likewise, the International Material Data System (IMDS) was developed in collaboration amongst automobile OEMs as a tool to integrate and share supplier data relating to the constituent substances of varying tiers of an automobile construction.

The ELV Directive establishes the OEM in a central role as a coordinator of information and material flows, but structures for realizing cradle-to-cradle metabolisms may take many different forms. Regardless of their configuration, the central role of these structures remains the same*: to optimize or ensure the integrity of cyclical nutrient flow metabolisms and the maintenance of the status of materials as resources*. In addition to coordinating the flow of materials the structure also plays a key role in managing the exchange of information and intelligence amongst actors.

In some cases, this role may best be fulfilled by an entity (an organization or group of organizations) external to the network of material flows. Such an entity could ensure that all actors within the material flow metabolism have access to the information that they need, while also ensuring that proprietary information remains proprietary. A chemical company producing a particular dye formulation, for instance, may wish to keep the specifics of their formulations confidential to ensure that they are not copied by competitors. At the same time, a fabric manufacturer wishing to dye their products with the chemical company's product may want to be able to ensure the compatibility of the dye formulation with the criteria for a product of consumption. A third party external to the material flow system may be in an ideal position to mediate the exchange of information in this situation by analyzing and certifying the formulation as a biological nutrient while ensuring the safe handling of proprietary information. In other contexts as well, this external entity could provide each actor throughout the material flow metabolism with the necessary information to ensure the eco-effective integrity of the system as a whole.

6. Intelligent materials pooling

Another type of structure for the management of eco-effective nutrient flow metabolisms is intelligent materials pooling [32]. Intelligent materials pooling is a framework for the collaboration of economic actors within the technical metabolism which allows companies to pool material resources, specialized knowledge and purchasing power relating to the acquisition, transformation and sale of technical nutrients and their associated products. The result is a mutually beneficial system of cooperation amongst actors along the supply chain that supports the formation of coherent technical metabolisms and the enabling of product-service strategies.

The heart of an intelligent materials pooling community is a *materials bank*, which maintains ownership of technical nutrient chemicals and materials. The materials bank leases these substances to participating companies, who in turn transform them into products and provide them to consumers in the form of a service scheme. After a defined use period, the materials are recovered and returned to the materials bank. The materials bank also manages the information associated with these materials, integrating and sharing related information amongst relevant actors. In this manner, it ensures the accumulation of intelligence relating to a particular material over time, and a true *upcycling* of the material.

As illustrated in Fig. 4, the duties of a materials bank are ideally performed by the product chain actor responsible for post-use reprocessing of the material (e.g. a polymer or steel producer). This actor is responsible for reprocessing and

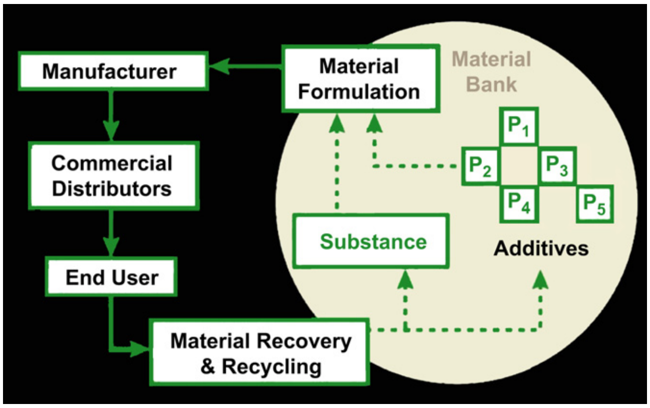

Fig. 4. Material flows in the context of an Intelligent Materials Pooling community.

intermediate storage of the material, as well as for leasing it to others for transformation into products.

The formation of an intelligent materials pooling community is a four-step process:

- Phase 1. Creating community: identification of willing industrial partners with a common interest in replacing hazardous chemicals with technical nutrients, targeting of toxic chemicals for replacement;
- Phase 2. Utilizing market strength: sharing lists of materials targeted for elimination, development of a positive purchasing and procurement list of preferred intelligent chemicals;
- Phase 3. Defining material flows: development of specifications and designs for preferred materials, creation of a common materials bank, design of a technical metabolism for preferred materials;
- Phase 4. Ongoing support: preferred business partner agreements amongst community members, sharing of information gained from research and material use, co-branding strategies.

The formation of intelligent materials pooling communities has the potential to result in economic advantage for all actors involved. By establishing a framework for materials to be regained after use, intelligent materials pooling enables the application of higher quality materials at lower cost. This in turn results in the potential for higher quality, safer and less expensive products. The prospects for realization of this potential depend upon the specific material metabolism in question, namely the relationship between the costs of material recovery and recycling and those associated with disposal and raw material acquisition.

In the steel industry, for instance, value is often lost when a range of grades is mixed in the recycling process. A materials pool could preserve the value of steel over many life cycles by specifying the separation of different grades. Rare, valuable constituent elements such as chromium, nickel, cobalt and copper could also be preserved and reused at the highest level of quality. With cooperation between steel producers (the materials banks) and the manufacturers of a wide variety of products, from automobiles to trains to refrigerators, the steel loop could begin to be closed and the value of its nutrients preserved over time. The aim is not just zero waste, but the maintenance or upgrading of the quality and productivity of materials through subsequent cycles of production and use.

7. Conclusions

Eco-effectiveness is a concept for the production and consumption of goods and services that goes beyond the reduction of negative consequences implied in eco-efficiency and zero emission. Eco-effectiveness positively defines the beneficial environmental, social, and economic traits of goods and services, thereby eliminating the fundamental problems (material flow quality limitations, antagonism to economic growth and innovation, and toxicity) that arise in eco-efficiency strategies.

Eco-effectiveness encompasses a set of strategies—cradle-to-cradle design, positive lists, intelligent materials pooling, etc.—that enable the formation of cyclical material flow metabolisms. Eco-effective material flow systems not only empower materials to maintain their status as resources, but by establishing a coherent network of information flows amongst actors in the material flow chain, they enable a continual accumulation of knowledge that forms the basis for true *upcycling*. This continuously accumulating intelligence becomes a perpetually source of added value to products and services, and provides for a supportive relationship between eco-effective industrial systems and long-term economic prosperity. The aim is not only to achieve zero emissions, but to utilize materials in a way that maintains or increases their value and productivity over time.

Coherent biological and technical metabolisms ensure the availability of raw materials for industrial processes. In the technical metabolism, material reprocessing is conducted by industry and generates added employment and further economic activity. Within the biological metabolism, material reprocessing is carried out by ecological processes, and results in the regeneration and replenishment of natural systems. This supportive relationship between the biological metabolism and the health of natural systems is the basis for a *positive recoupling* of the relationship between ecology and economy.

References

[1] Verfaillie HA, Bidwell R. Measuring eco-efficiency: a guide to reporting company performance. World Business Council for Sustainable Development; June 2000.
[2] Zero Waste International Alliance. Standards [web page]. http://www.zwia.org/standards.html [accessed February 2006].
[3] Martin DJ. Zero waste: useful target or dangerous delusion? http://www.productpolicy.org/assets/resources/DuncanMartin2004ZW.pdf [accessed February 2006].
[4] Zero Waste New Zealand Trust. The end of waste. http://www.zerowaste.co.nz/assets/Reports/TheEndof Waste.pdf [accessed February 2006].
[5] World Business Council for Sustainable Development, editor. Eco-efficiency [web page]. http://www.wbcsd.ch/templates/TemplateWBCSD5/layout.asp?type=p&;MenuId=NzA&doOpen=1&ClickMenu=LeftMenu [accessed January 2005].

[6] Schütz H, Welfens MJ. Sustainable development by dematerialization in production and consumption – strategy for the new environmental policy in Poland. In: Wuppertal Institute, No. 103; June 2000.
[7] Schmidt-Bleek F. Das MIPS-Konzept – Faktor 10. Munich: Droemer; 1998.
[8] Pirker U, Pschernig G, Gwehenberger G, Schnitzer H. Implementation of zero emissions waste technologies. 8th European Roundtable on Cleaner Production Conference, Oct. 9–11, 2002, Cork, Ireland. http://zeria.tugraz.at/pics/zeria_round_table.pdf [accessed January 2006].
[9] UNIDO. Industry and environment: the need for a new industrial revolution. UNIDO position paper. 30 September, 2003.
[10] Tierney J. Recycling is garbage. The New York Times Magazine June 1996;30:2–8.
[11] Dunn D, Yamashita K. Microcapitalism and the megacorporation. Harvard Business Review August 2003;1–9.
[12] Braungart M, Soth J. Allergieprävention Durch Intelligentes Produkt-Design. Medizin und Umwelt 1999;12:54–8.
[13] Watson R. Europe urged to tackle rise in allergies. BMJ 1997;314:1641.
[14] Bornehag CG, Sundell J, Weschler CJ, Sigsgaard T, Lundgren B, Hasselgren M, et al. The association between asthma and allergic symptoms in children and phthalates in house dust: a nested case-control study. Environmental Health Perspectives 2004;112(14):1393–7.
[15] Bashir S, Maibach HI. Compound allergy. An overview. Contact Dermatitis 1997;36:179–83.
[16] Brinke JT, Selvin S, Hodgson AT, Fisk WJ, Mendell MJ, Koshland CP, et al. Development of new volatile organic compound (VOC) exposure metrics and their relationship to "sick building syndrome" symptoms. Indoor Air 1999;8(3):140.
[17] Ayres RU, Simonis UE. Industrial metabolism: restructuring for sustainable development. Tokyo: United Nations University Press; 1994.
[18] Drucker FE. The effective executive. 4th ed. New York: HarperCollins; 2002.
[19] Berkhout P, Muskens HG, Jos C, Velthuijsen JW. Defining the rebound effect. Energy Policy 2000;28(6–7):425–32.
[20] McDonough W, Braungart M. Design for the triple top line: new tools for sustainable commerce. Corporate Environmental Strategy 2002;9(3): 251–8.
[21] McDonough W, Braungart M. Reinventing the world, Green@Work. 2001;8:43–5.
[22] McDonough W, Braungart M. Reinventing the world: step two, Green@Work. 2001;9:37–40.
[23] McDonough W, Braungart M. Reinventing the world: step three, Green@Work. 2001;10:33–5.
[24] McDonough W, Braungart M. Reinventing the world: step four, Green@Work. 2001;11:29–32.
[25] McDonough W, Braungart M. Reinventing the world: step five, Green@Work. 2001;12:32–5.
[26] Kälin A. Positive definierter Chemikalieneinsatz als Voaussetzung für die Schliessung von Material- und Wasserkreislaufen: Das Beispiel des Möbelbezugstoffes Climatex Lifecycle der Rohner Textil AG. In: von Weizsäcker EU, Stigson B, Seiler-Hausmann JD, editors. Von Ökoeffizienz zu nahhaltiger Entwicklung in Unternehmen. Wuppertal: Wuppertal Institute; 2001.
[27] Newcorn D. Cradle-to-cradle: the next packaging paradigm? Packaging World. http://www.packworld.com/articles/Features/16105.html; May 2003 [accessed February 2006].
[28] Rodie JB. Survival tactics. Textile World. http://www.textileworld.com/News.htm?CD=1371&;ID=3533; March 2003 [accessed February 2006].
[29] Gissen D, editor. Big & green: toward sustainable architecture in the 21st century. Princeton Architectural Press; 2002.
[30] Smith R. Beyond recycling: manufacturers embrace 'C2C' design. The Wall Street Journal Mar 2005;3:B1–2.
[31] Kamejima K, Ejiri M. Recycling on network: an information-control architecture for ecologically-conscious industry. In: Proceedings of the 1993 International Conference on Advanced Robotics, Tokyo, 1993.
[32] McDonough W, Braungart M. Intelligent materials pooling: evolving a profitable technical metabolism through a supportive business community. Green@Work 2003;20:50–4.