Materials selection and design for development of sustainable products

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Abstract

How can we develop and produce more sustainable products? The author reviews current methods as well as presents models on how to develop sustainable products. Different methods for achieving products with as low environmental impact as possible are shown as well as principles for product development with special regards to materials selection, design, the product in use and recycling are given.

Definition of a sustainable product, triple bottom line, dematerialisation, recycling, design considerations, ISO 14001 standard and the EMAS (Eco Management and Audit Scheme) regulation are examples of areas, which are reviewed in this article. Life cycle assessment, environmental impact, eco-efficiency, environmental space, market contacts, cultural aspects, fashion and trends are also reviewed.

Guidelines for sustainable product development are presented with special regard to material, design and ecology. A description of materials selection and models for design based on a sustainable society is also presented.

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1. Background

In a world with limited resources and serious environmental impacts, it is obvious that a more sustainable life style will be more and more important. Material products, like paperclips, telephones or cars, are examples of products, which can consist of one single or up to many thousands of different materials. Estimations tell us that we have to deal with probably over 100.000 commercial materials on the market with respect to the great amount of variants. Extraction, refinement, transports, product use phase, recycling or deposition are examples of complex areas, which can give different types of impacts on the environment.

During the last century, environmental problems were often seen as local problems due to the impact from a certain product. However, today it becomes more obvious that the problems are much more complex and related to all the phases in a product’s life cycle from extraction of material to waste or deposition of the used product [1].

The fact that even in the Bible man was seen as having dominion over the living things and subdues the earth (Genesis 1:28) has been neglected in various areas in the world. Rapid technical developments, during the last centuries, have for example caused serious environmental impact, which can be regarded as an un-sustainable life style. Unsustainability is mainly caused by the current global situation.

There are today at least four basic problems, which are more or less unsolved:

- Over-consumption.
- Resource utilisation.
- Pollution.
- Over-population.

Over-consumption. The use of material today for energy, packaging and the products themselves has increased at least 20-fold per capita in many highly industrialised countries from the end of the 19th century until today [2,3]. More components and more mixed materials in various products, which demand transportation, in combination with generally higher energy consumption around the
world, are only examples of over-consumption. The nature cannot sustain today’s growth rate of up to about 5% in some countries, without serious impact in the long run [4].

Resource utilisation. The human productivity has not been able to co-operate with the nature regarding sustainability. Only a few percent of the material and energy theoretically required for producing products today is used for the product itself. A lot of energy and material is for example lost during production and transportation, which includes waste material and emissions, especially for non-recycled products [2].

Pollution. Even if all companies reach zero emissions right now, the earth would still be seriously affected by the emissions so far [5].

Over-population. The world could have more than ten billions inhabitants by 2025. It is clear as to how this situation will lead to less sustainability with more and more environmental impact. Even if many products like, e.g., cars, have become more environmental friendly over the last decades, they cannot obviously reduce the total amount of materials and energy used due to the population increase.

However, there are no possibilities to reduce all environmental impacts to zero. The increase of the entropy on the earth is a fact, which has been proven by thermodynamic laws. It is clear that the earth is populated by its inhabitants and this causes a situation which is “non-sustainable by itself”.

2. Sustainable product development

There is no simple way of how to develop ‘sustainable products’. The complexity of the situation has already been presented above and according to the thermodynamic laws, total sustainable products are not possible to develop in general. However, there are many different approaches and definitions of how to develop sustainable products, which will be studied and analysed in this article. The main problem is still unsolved which is the fact that the world is not sustainable by itself. Life on the earth cannot go on forever in a way that the nature can be brought back to some sort of an initial condition without drastic influences from systems outside the earth causing a reduction of the entropy in our earthly system. Most definitions of sustainable products among researchers in this area have shown the lack of understanding the fact that our planet is not a sustainable system by itself! However, the following definition will be applied in this paper:

2.1. Example of a simple definition of a sustainable product

- A sustainable product is a product, which will give as little impact on the environment as possible during its life cycle.

The life cycle in this simple definition includes extraction of raw material, production, use and final recycling (or deposition). The material in the product as well as the material (or element) used for producing energy is also included here. This definition is in fact not totally defined according to the amount of impact on the environment or the nature. Hence the impact cannot be zero, it must be ‘reasonably minimised’. This opens up the fact that there will be similar products, which are more or less ‘sustainable’ when they are compared side by side!

As can be understood from above, there are many different aspects and details related to this definition. This paper will elucidate the product development of sustainable products by presenting some important aspects and then discuss ways to measure the ‘sustainability’.

2.2. A sustainable product must be a successful product

A good sustainable product must give as much satisfaction as possible for the user. If not, it will be unsuccessful on the market and an economic failure. There are estimations, which tell us that nearly 90% of all technically good products will not be a success on the market for various reasons [6]. When releasing sustainable products on the market, it is reasonable to believe that the risk for failure is not less. It is also important to inform people as to what basis a certain product is considered to be sustainable or not and why they should buy it.

2.3. Environmental marking or labelling of products

To inform customers whether a certain product is environmentally friendly, different kinds of environmental marking systems have been developed. Examples of these are the EU sign (a flower with 12 stars), the Energy Star (Emidast) Environmental Protection Agency in the USA, the TCO sign (Tjänstemännens Centralorganisation) in Sweden, Svanen (Standardiseringskommissionen i Sverige), Umweltzeichen (in Germany) or Environmental choice (in Australia). These kinds of markings are voluntary for the companies and can be used when a product fulfils certain requirements from the specific organisation [7]. However, the demands for producing environmentally friendly products are not clear and easy to understand for a general customer. Even for an expert it is problematic or impossible to determine which product of many similar ones is the best choice.

Other examples of marking are the Panda (WWF, World Wildlife Foundation) and the recycling mark with “three arrows”. The Panda mark only tells us that money has been donated to WWF and the three arrows only indicate that the producing company is working with recyclable products.

2.4. Sustainable development

The following areas are examples of important issues connected to sustainable development [8]:

- Resource utilisation
- Over-population
- Pollution
- Environmental marking or labelling of products
• **Environment.** The eco-system in the world must be treated in order to protect plants and animals. The environment must be seen as a part of the development process and not be taken for free to use.

• **Equity.** The issue of poverty and equal distribution and use of natural sources must be solved in order to maintain stable societies and equal value of people.

• **Futurity.** The impact from development must be seen in a long perspective in order to minimise the impact for future generations.

Another, rather new approach to meet the demand for measuring the sustainability of a product is to use the conception **Tri**ple **Bottom Line** (TBL). The TBL term was first coined by John Elkington and according to him: “...the term triple bottom line is used as a framework for measuring and reporting corporate performance against economic, social and environmental parameters”. The TBL concept involves the traditional economic bottom line together with the society and the environment. This triad can simply be drawn as a triangle with the following corners: [9].

- Ecology (environmental protection).
- Equity (social equity).
- Economy (economic growth).

When developing a new product, it is illustrative to move between the three corners Ecology, Equity and Economy in order to obtain a suitable balance so that each category can be fulfilled in the best way. The ecological side emphasises, e.g., clean landscapes, pure air and water, while the equity side, e.g., can tell us if a certain product can lead to social welfare regardless of people's background and if it promotes fair compensation as well as health, safety, etc. The economy side tells us if it is possible to make profit on a product.

Another example of sustainable product development, which is based on TBL, but more product orientated, is the SPSD (Sustainable Product and Service Development). The SPSD method is designed to give more practical guidance to the industry and can be simplified with four stages: (1) Question the functionality already at the concept stage. (2) Determine all the life cycle stages. (3) Determine all the supply chain companies. (4) Optimise the sustainability impacts. The criteria for optimising the sustainability in products and services are mainly: functionality, environmental impacts, social impacts, economic impacts, market demand, quality, customer requirements, technical feasibility, compliance with legislation and different specifications [10].

2.5. Environmental management systems, EMS, EMAS and ISO 14001

Earlier sustainable production with environmental issues was often seen as a problem for most companies. Today many companies can see the benefits of environmental production. Good reputation and even better economy by using recycled material, etc. in the production are examples of advantages. During the last decades, we have also seen that many companies have found that pollution prevention has become economically beneficial [5,11].

A way to create a systematic environmental plan for a producing company is to use international standardised Environmental Management Systems (EMSs). This has become more and more important for different companies all over the world [12].

EMSs can normally be described as a voluntary system. It can be seen as a tool for management that can be used to steer and control environmental efforts by computer controlling or performed by a special organisation. Any company that has taken steps towards environmental issues has in fact implemented an EMS [13]. EMS can simply be defined as “the part of the overall management system that includes the organisational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, achieving, reviewing and maintaining the environmental policy” [14].

In the early 1990s, the World Business Council for Sustainable Development (WBCSD) issued a declaration about the connection between environmental protection, economic growth and satisfaction of human needs [15]. The declaration led to the development of an international standard ISO 14001, which was released in 1996 by the International Standardisation for Organisation (ISO) in Switzerland [16,7]. ISO 14000 consists of a whole series of environmental standards based on the 14001 standard [17]. In 1993, the European Commission issued a regulation, called the Eco Management and Audit Scheme (EMAS) [18]. The EMAS regulation is intended to act mainly as a document to provide a sustainable way of production in the European Union and it is a way to express the political request for the European Union. EMAS has also become an integrated part of laws regarding the environmental influence in the European Union. Both EMAS and ISO 14000 contain requirements for the EMS.

2.6. Environmental impact with the LCA-method

Life Cycle Assessment (LCA) is a useful tool for understanding the impact of the environment [19–22]. A product is evaluated step by step from cradle to grave, where cost, impact, expected lifetime, etc. can be evaluated in a quite easy way.

A simple way to account for an environmentally friendly production is to give every product an environmental load. This can be done with, for example, the Environmental Load Unit (ELU) index/kg or unit. ELU is a sum of the environmental load for a product with respect to production, material, transports, etc. during the whole lifetime of a certain product. The ELU can be seen as a way to express how much it will cost to restore the environment as it used to be before a certain impact.
However, note that there is no way that is 100% accurate when comparing different production, breaking down or recycling methods. It is for example not easy to compare glass bottles or paper packs, e.g., milk, and to say what is the most environmentally friendly (or sustainable) material for milk transportation. The paper pack is used only once and then normally burnt. The glass bottle is used a number of times but needs extra energy for transportation (because of its quite high weight) and needs detergents and water for cleaning before every new filling. The transportation to different customers and the environmental influence from the cleaning process must then be weighted and estimated. The emissions from burning or recycling of the paper must be compared with, e.g., the discharge from the detergents. Today we have a certain way of weighing the emission factors affecting the environment, but tomorrow it can be changed, because of increased knowledge of certain risks of a special emission.

The LCA methodology is probably the most widespread technique for evaluating environmental impacts associated with material products [23]. There are typically six important steps involved in an LCA evaluation [24]:

1. Extract from material.
2. Manufacturing with, e.g., ennobling and refinement.
3. Packaging stage.
4. Transportation of, e.g., material and the ready product.
5. Product user stage.
6. Product disposal stage.

These steps can then be divided into smaller steps in order to get a more precise view of the life cycle, like: Extract of material, Design, Market research and Product Development, Process planning, Purchase of materials, Production and Assembly, Product Control, Treatment of waste, emissions and noise, Packaging and storage, Marketing, Selling or Leasing, Delivery, Use, Service and Maintenance, Renovation/Upgrading, Reuse/Recycling and Final utilisation.

Some important methods for evaluating environmental impacts together with the LCA method are: Eco-Indicator '99 [25], Environmental Priority System (EPS) [26] and Tellus [27]. The evaluation makes it easier to compare different materials, manufacturing methods, service intensity, etc. side by side, which is of vital importance when developing sustainable products [28,29].

2.7. Eco-efficiency and eco-design

Eco-efficiency is a way of running a business in a more effective way in both ecological conditions [30]. However, the conception does not take into account the environmental impact after the product has been sold. The LCA is here a more comprehensive way of determining the total environmental impact. Eco-Design is also known as Design for Environment. The strategies for Eco-Design are, e.g., to use materials with low environmental impact, choosing clean production processes, avoiding hazardous and toxic materials, maximising the efficiency of the energy used for production and for the product in use and designing for waste management and recycling.

2.8. Environmental space

In order to achieve a sustainable development, the concept of Environmental Space has been developed [31]. The concept is a way to get a more equal distribution of the usage of the environment and the quantity of natural resources per capita. The concept is focusing on reduced use of resources in product development focused on, e.g., recycling, prolonged product lifetime, easy repairability as well as minimising materials, toxic emissions and consumption. Ecological design, reduced use of energy, and focus on utility instead of ownership are also important issues in this concept [32].

2.9. Market contacts and product phases in the market

Good market contacts, i.e., close contacts with customers, are essential for releasing products in the market. If a “sustainable product” is expected to be of minor interest for the market, do not release it. A failure can result in bad reputation for the releasing company and for sustainable products in general. Try to wait until the market is ready for a certain sustainable product or create a need for the product with for example advertising, logical arguments or combine the sustainability with another feature, which is attractive for the market [33,6].

Most products have a limited life on the market. A typical product can be classified into four different phases on the market: introduction, growth, maturity and decline [34]. A certain product should normally not be released on the market during the maturity or decline phase. An exception is when the product has something trend breaking which can lead to a new growth at an earlier products expense. A sustainable image could be such a trend breaker.

2.10. Legislation and safety precautions

Manufacturing and release of products are also restricted with different laws, which can differ from country to country [35,7]. Introduction of a new environmentally friendly technique or material can lead to successors and even be a reason to forbid older techniques. For example, when catalytic converters for petrol emissions from cars came, it was a reason to forbid the production of traditional carburettor cars, in many countries. A new material, which looks very good in the beginning, can almost over a night become dangerous when certain problems are verified. This was the fact for asbestos, which is now forbidden to be used in many countries because of the detection of its risk for causing lung cancer.
A product itself must also be safe to use. Safety is in many cases determined by different laws. However, many trend braking safety equipments like safety belts for cars and earth fault breakers in electric equipments are examples of inventions, which can give an extended lifetime for a product. Such safety arrangements can consequently lead to more sustainable products.

### 2.11. Cultural aspects

In order to develop sustainable products, it is of importance to know the cultural aspects. In Scandinavian countries wood is popular as a building material for outer walls, because it is cheap there and makes the houses easy to insulate, which is important during the cold winter seasons. In many other countries, wood is a material, which has a reputation to be inferior to stone or brick. This is sometimes true, but has also to do with the traditions among people, i.e., what people think and what they feel about a certain material. Wooden floors are, in many countries, popular because of their surface characteristics and softness, but in spite of the fact that a concrete floor is more sustainable and durable. The physical aspects, like hardness, lifetime, etc. are important for many people, while for others, the metaphysical aspects (feelings) are dominating when choosing a wooden floor [36,37]. Stainless steel or laminated wood is quite typical for kitchen benches in northern countries, while stone is dominating in the Mediterranean countries. This is another example of a cultural aspect and tradition.

### 2.12. Fashion and trends

Which kind of design, material, colour, etc. will be in fashion tomorrow? A sustainable product must be in fashion to be popular on the market. Fashion trends are not easy to predict, but very important to anticipate. Close market contacts are important here, but trend braking ideas can also direct the market into new trends [6].

A somewhat problematic trend today is the *Throwaway Society*. The mentality of “use, wear and throw away” must generally be regarded as a non-sustainable way of living. For example, most of the mobile phones used among younger people today seem to be replaced by newer ones after only three years of use. DVD-players, watches, clothes, etc. are used and changed more and more often because of the trend, which tells us to have only modern things, which are in fashion. An example of tackling this problem is to exchange ideas between designers, engineers, socialists, scientists and marketing specialists. A team from Sheffield Hallam University, with funding from Engineering and Physical Sciences Research Council (EPSRC), has focused on how products like furniture, cars, clothes, household appliances and other consumer products can be more sustainable [38]. This is an interesting example of cooperation between people from the academic as well as the industrial field.

### 2.13. Guidelines for sustainable development

In order to develop more sustainable products, some important points are to be noticed [20,39–41]:

- Reduce the materials and the use of energy for a product including services during its lifetime.
- Reduce emissions, dispersion and creation of toxics during its lifetime.
- Increase the amount of recyclable materials.
- Maximise the sustainable use of renewable resources.
- Minimise the service intensity for products and services.
- Extend the useful life for a product.
- Assess and minimise the environmental impact over the product lifetime.
- Having a “Functional economy” is a way to substitute products with services.
- Use “Reverse logistics” which means that all efforts are used in order to reuse products and materials.
- Increase the efficiency of a product in the usage phase.

### 3. Guidelines for materials selection and design

#### 3.1. Materials overview

A technical product is usually made of one or several materials. However, there are examples of immaterial products like computer programs. The sustainability of a certain material based product is mainly depending on the material or materials used for the product itself or during its lifetime according to, e.g., a LCA (Life Cycle Assessment). During the life cycle of a material product, different stages are passed, like material extraction, manufacturing, packing, transportation, product use and disposal. All these stages will give a certain environmental impact, which is mainly caused by the materials involved in the different stages [24]. Hence, the selection of materials for a certain product is of vital importance, while the material determines the use of our natural resources as well as the amount of energy used for the production and the use of the product [42–44]. Manufacturing of products typically involves chemical substances like cutting fluids during machining, cleaning aids, paint, etc. Technical lifetime, maintenance, service and repair of a product are other examples of areas, which are typically dependent on the material used for the product itself.

The use of renewable materials, like wood versus non-renewable materials, like plastics (made of raw oil), is also important to consider in product development. Renewable materials are materials which in a short time can be formed again in the nature and give no or very little impact on the environment. If, e.g., a tree is cut, used in a product and burnt and a new tree is planted, the new growing tree can bind the carbon dioxide formed when the old tree is burnt. If the ash, containing minerals and fertilizers, is...
brought back to the earth, the new tree will use the ash when growing. This is an example of the life cycle of a renewable material. However, if a forest has been cut down and no new trees have been planted again, the environmental balance is changed. This can lead to earth destruction, a change in the climate due to changed water balance and in the worst case the forming of a desert. When a tree is cut a price can be estimated to ensure the sustainability, which in this case means that a new tree is planted and the forests are kept and maintained in the future. A polymer made from raw oil is an example of a non-renewable material, while the raw oil cannot easily be brought back to its initial state again. This leads to an environmental impact when raw oil is used. The term renewable is typically used for organic materials.

Selection of material is traditionally made by technical demands like price, strength of material, temperature stability, density, hardness, etc. [45,46]. However, for a successful product development the technical or physical demands are not enough. Factors like reputation, fashion, product, cultural aspects, etc. must also be taken into account when developing sustainable products. As a result of metaphysical reasons like 'feelings' for a certain material, the materials selection is often not easy [36]. Clothes made of synthetic fibres are often more easy to clean and to keep free from wrinkles, but the natural materials are generally more popular because of its feeling and the fact that they are generally more popular. Wooden floors are more popular for certain people even if concrete floors are more wear resistant and durable. Anyhow, materials selection for sustainable products is mainly based on the ultimate impact on the nature as well as market demands and economic factors.

As mentioned earlier, estimations tell us that there are more than 100,000 different kinds of commercial materials on the market if we include all the variants in materials composition, blending, heat treatment, etc. The fact that not only objective methods for selection of materials, but also subjective have to be regarded does not make the selection easier. The following division of materials in groups is a way to simplify the selection as well as give an overview over the properties and the sustainability.

Structural materials for material products can be divided into six groups: Metals, ceramics, synthetic polymers, natural organic materials, natural inorganic materials and composites. These groups cover probably more than 99% of all materials used in mechanical, civil and electrical engineering. Exceptions are chemical substances like fluids and gases, which will not be covered here. See Table 1 below!

Comments to Table 1:

- **Metals** are typically cheap and easy to recycle into new products by re-melting. A disadvantage is the typical high weight (density) for many metals like steel and copper alloys, which may lead to energy consuming transportations, as well as the amount of energy required for re-melting due to typical high melting points for metals in general. The corrosion resistance for especially steel is also low. Corrosion protection often needs more or less toxic chemical treatments or paints. Aluminium and its alloys are on the other hand a common example of a quite corrosion resistant metal, which is also light, strong and easy to recycle due to a low melting point (about 600 °C). The sustainability gives generally the marks 2–3 depending on, e.g., melting temperature (high melting temperatures lead to high energy consumption for melting) and toxicity from the material itself or from extraction processes. Toxic metals even in thin layers or in alloys typically give the mark 1.

- **Ceramics** are typically light and non-toxic. The raw material is generally clay for traditional ceramics and pure oxides, nitrides or carbides for advanced ceramics. They are often not only very durable, hard, high temperature and corrosion resistant, but also brittle. Ceramics are seldom recycled into new products because of the need of crushing, grinding and re-burning, which is typically more costly and energy requiring than producing products from new raw material. The used products can for example be crushed and used as fillers in building technique. The sustainability mark is typically 3 for materials based on natural clays and 2 for materials containing toxic components or some advanced ceramics like fibres, which might give higher environmental impact due to the manufacturing process.

- **Synthetic polymers** or Plastics and rubber are generally made of raw oil. Anyhow, many polymers can be made from natural organic materials like wood. If raw oil based polymers are recycled by burning the material is not renewable, because the amount of oil is limited and new oil will not be formed in a short time. Many polymers like polyethylene (PE) can easily be burnt individually or together with for example paper during formation of carbon dioxide and water. Carbon dioxide is harmless in smaller amounts, but is regarded to increase the environmental impact due to the greenhouse effect in the atmosphere. Some polymers, especially those containing halogens, like Teflon® (PTFE) and polyvinyl chloride (PVC) are quite harmful to burn due to the harmful fumes. Re-melting is here recommended. Due to low re-melting temperatures for many thermoplastic polymers (typically about 200 °C) compared with those for most metals, the energy consumption is quite low. Controlled burning with exhaust cleaning is another possibility for recycling. A problem when recycling plastics is to determine which kind of polymer a product is made of. However, international labelling of polymers has minimised this problem during the last decades [42]. Thermosetting plastics and rubber are examples of polymers, which cannot be remelted which means that deposition or use as filler material or chemical dissociation is recommended for recycling. The sustainability marks vary from 1 for
The six typical product material groups, as well as examples and aspects for developing sustainable products are presented.

### Material Group

<table>
<thead>
<tr>
<th>Material group</th>
<th>Examples on materials</th>
<th>Typical Advantages</th>
<th>Typical Disadvantages</th>
<th>Classification of the Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>Steel (Fe + C), Aluminium, Bronze (e.g., Cu + Sn)</td>
<td>Durable and strong, Often plastic formable, Often cheap</td>
<td>High cost for machining, Mostly corrosion sensitive</td>
<td>Easy recyclable (re-meltable) 2–3</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Synthetic materials like: Porcelain (clay), Mineral glass, Al₂O₃, Si₃N₄, SiC, etc.</td>
<td>Non toxic, Light, Hard and durable, Corrosion resistant, High temp. resistant</td>
<td>Brittle, High cost for machining when burnt, Not suitable for load in tension</td>
<td>Easy to deposit (non toxic) 2–3</td>
</tr>
<tr>
<td>Synthetic polymers</td>
<td>Thermoplastics (e.g., PE, PS, PC, PP), Two component polymers (e.g., epoxy), Rubber (e.g., Isopren)</td>
<td>Non toxic, Light, Cheap and easy forming, Often easy to recycle (e.g., by re-melting or burning)</td>
<td>Sometimes very toxic when burnt, Sensitive to high temperatures</td>
<td>Typically non-renewable, Often easy to re-melt or burn 1–3</td>
</tr>
<tr>
<td>Natural organic materials</td>
<td>Wood, Cotton, Silk</td>
<td>Renewable, Light, Cheap and easy forming, Recyclable by, e.g., burning</td>
<td>Decomposes easily, Not durable, Toxic when impregnated</td>
<td>Recyclable by, e.g., burning, Renewable 2–3</td>
</tr>
<tr>
<td>Natural inorganic materials</td>
<td>Stone, Minerals</td>
<td>See ceramics above!</td>
<td>Brittle, High cost for machining, Not suitable for load in tension</td>
<td>See ceramics above! 3</td>
</tr>
<tr>
<td>Composites</td>
<td>Mixed materials, e.g., PS + glassfibres, Cu + W-fibres, Rubber + textilfibres, asphalt (oil + stone), Wood Polymer Composites (WPC)</td>
<td>Optimised use of the materials, Often very strong and light</td>
<td>Often expensive to produce, Very various properties for various composites</td>
<td>Typically low sustainability due to separation problems for the mixed materials 1–2</td>
</tr>
</tbody>
</table>

Note that the advantages/disadvantages and the ‘sustainability’ can change due to the specific material type and the examples are not valid for all materials in a certain material group.

*The sustainability is estimated from a scale 1 to 3, where 3 indicates the highest (or best) sustainability and 1 the lowest.*

- Natural organic materials like wood and cotton are always popular materials in various forms. Recycling can easily be done in the form of energy recycling in, e.g., thermal power plants for heating. Carbon dioxide and water are formed and carbon dioxide is here bonded directly from the air by new growing plants and trees. The carbon dioxide content in the atmosphere will therefore not increase when natural organic materials are burnt. Hence, these materials are typically renewable. However, colouring and impregnation to avoid breaking-down can be quite toxic [47]. Such toxicants can give serious environmental impact after energy recycling or putrefaction. The sustainability mark is typically 3 but for impregnated material the mark can go down to 2 (or even 1).

- Natural inorganic materials like stone, rock or various minerals are quite similar to the synthetic made ceramics. Therefore, the typical sustainability mark will be 3 if no toxic or radioactive elements are involved.

- Composites have become more and more popular during the last years especially in the form of ceramic fibres mixed in a plastic resin. If these materials can be burnt as a recycling method where no toxicants are formed, the sustainability can be even 3 if the materials are renewable. However, composites in general are not renewable and the problems to separate the different materials used in composites make these materials generally quite unsustainable, which gives the marks 1 or 2 for the sustainability.

According to Table 1 and the comments above, natural materials, polymers based on renewable raw materials, as well as ceramics and some metals seem to be sustainable materials for the future. However, excessive use of wood and cotton may lead to very serious environmental impact due to utilisation of forests and hence earth degradation, water problems, etc. This means that a material itself can be sustainable for the product during use and recycling, while the material extraction can lead to serious impacts. Polymers based on raw oil should be used carefully especially if it is not possible to recycle by re-melting. Composites must be used
restrictively with regards especially to the materials, which builds up the composite. It is also important to consider the possibilities of how to separate the specific materials.

3.2. Recycling

The last steps in an LCA process deal with recycling and final utilisation of the material in a product. However, in the early stages of product development, recycling or deposition must be taken into account to achieve sustainable products with a minimum of environmental impact. The materials selection today must strongly be directed to the future recycle-ability of a product in order to meet the demands of the future. Recycling can be done in different ways like:

- **Energy recycling.** The material is here burnt and the energy is used for heating.
- **Material recycling.** The material is typically re-melt or reshaped in order to make new products.
- **Re-use (or recycling).** The product or parts of it can be used again, sometimes after reconditioning. Reconditioned products or spare parts are sold at a lower price than a new part which is typical for second hand markets (used car parts, etc.).
- **Breakdown.** Natural organic materials, many synthetic polymers and some metals can be broken down naturally in the nature or by chemical methods to environmentally friendly products or chemicals. These materials are often referred to as degradable or biodegradable materials [48]. Typical processes are corrosion, composting and putrefaction.

When recycling is not possible or suitable, deposition can be an alternative:

- **Deposition.** Deposition can be an alternative if a product is not suitable for the processes mentioned above. This is a way to store materials during circumstances where as low environmental impact as possible for all time will be guaranteed. If the material is radioactive or toxic, it can be deposited in certain restricted areas or deep underground. Deposition is typically restricted by environmental legislation.

All processes mentioned above are generally restricted by environmental legislation, which is a way to minimise toxic products and/or emissions to be formed, which can lead to air or water impacts as well as affect human beings, animals and plants. Recycling can have different meanings as can be understood from the examples above and a clear definition of the word is recommended to avoid misunderstanding in specific cases [49].

3.3. Market aspects and customer demands

All materials selection must be adapted to the customer demand. Materials for more prestigious and expensive products must usually be chosen according to the following points [36]:

- Generally use pure or carefully improved materials.
- Expensive raw materials or carefully worked materials with expensive and advanced processes are usually popular.
- Avoid synthetic polymers (plastics), because of its doubtful reputation as a cheap substitute material. However, plastics can be used if advanced and expensive additives like carbon fibres are used.
- Ceramics can be used.
- No fake materials are accepted.
- Natural organic and inorganic materials are generally popular like wood, silk, cotton and wool.
- Cheap materials can normally be used if advanced production techniques like ennobling or refining are used.

For cheap products almost any material can be used which is cheap, sustainable and does not need expensive production methods like advanced surface treatment or machining.

Note that there are always market trends, which make certain types of materials popular under a certain period. Light and dark wood comes and goes and we can see how early car bodies made of wood in the early 20th century have changed to steel ones and during the last decades to composites and aluminium. In the kitchen, we can see how pans have changed from cast iron, glass enamelling, stainless steel, surfaces coated by polymers or advanced ceramics. Some materials seem to disappear in products for good, like stones in axes, wood in big ships or natural guts for strings in tennis rackets. In these cases, more suitable and advanced materials have been outraging the old ones like steel in axes or ships and synthetic polymers for tennis rackets.

3.4. Dematerialisation and MIPS

The availability of materials for products will typically not increase in the future, as the amount of materials is limited. An exception could be wood where replanting trees actually can increase the amount of trees in a region or a country. This has happened in Sweden during the late 20th century. Anyway it is desirable (due to, e.g., sustainability and economics) to design a product in such a way that the use of the material will be limited. A useful way of minimising the materials used in products is to use a concept, which is called dematerialisation. Dematerialisation is a way to reduce the environmental impact per unit of economic input. Another definition of dematerialisation is the waste generated per unit of every material product [50].

The environmental impact per produced unit can also be weighted as the cradle-to-grave Material Input Per units of Services (MIPS). The MIPS also includes materials used directly or indirectly for energy input for a certain product [51]. This means that the MIPS accounts for all material
and energy used along a products life cycle from extraction of materials until final disposal. The concept is however generally missing the flow of toxic substances during the life cycle of the product, which is a drawback.

3.5. Some general advices for more efficient use of materials

- Material substitution can reduce the environmental impact [52].
- Material efficient designing (dematerialisation) can be used. This means that as little material as possible is used. To obtain high strength in structural products, the Finite Element Method (FEM) can be used to optimise the strength of a product [53]. Another way is to use thin layers of rare or expensive materials like veneering of wood or plating noble metals on cheaper substrates.
- Composite materials can sometimes reduce the total amount of material used in a construction, because of the often better utilisation of the materials used [54]. However, it is generally more problematic to recycle mixed materials, i.e., utmost precautions must be taken when using composite materials.
- The materials selection and the product design should be done with the intention of future recycling of the material.
- Use MIPS (Material Input per Services) as described above.

3.6. Materials selection

Materials selection could be done in different ways, but the principles are quite similar. The selection of material is to optimise a product mainly with regards to the following aspects:

- Production methods.
- Function and structural demands.
- Market or user demands.
- Design.
- Price.
- Environmental impact.
- Lifetime.

Important situations motivating selection of material in a product as a whole or part of the product:

- Total new design.
- Improvements.
- Environmental demands.
- Delivery or supply problems for a material.
- Market demands.
- Adaptation to new methods for manufacturing.

Example of a common materials selection model based on specification of requirements is shown in Table 2, which is called a requirement property profile table:

In Table 2, we can see how product requirements are matched subsequently with the properties of possible materials. Materials 1, 2, 3 and so on are quite often the same type, e.g., different kinds of polymers or steel types. However, different kinds of material groups (like ceramics, metals and natural inorganic materials) can also represent materials 1, 2, 3, etc. In the example in Table 2, material 2 seems to be the best choice even if the price seems to be somewhat high. The total cost needs to be calculated for a special design, manufacturing method, etc. which means that a slight change in the design can change the price. The selection is typically an iterative process with subsequent optimisation. A slight change in design with some cooling might change the situation so that material 1 can be acceptable, which can result in a lower product price. Other examples are the use of qualification parameters to sort out unsuitable materials in an early stage. Qualification parameters can be used to select high temperature stable materials with low prices. This can be done by dividing the highest temperature for use with the price and maximising this value for possible materials. In this example it will be \( (T/E) \).

A material change in a certain product generally changes the design, in order to optimise the characteristics or the manufacturing methods for a product. A wooden chair has for example typically thicker legs to compensate for the reduced strength of wood compared to steel. Another example of the relationship between design and material is sharp radii, which typically gives high stresses for parts exposed to load. Ceramic materials are quite sensitive to high stresses in tension, which must be avoided by rounded inner corners in order to reduce the stresses. Metals, however, are typically less sensitive to tensile stresses and here sharp inner corners with small radii can be accepted in non-critical constructions with ductile metals. Hence, materials and design are very closely linked to each other.

<table>
<thead>
<tr>
<th>Requirements for the product</th>
<th>Properties for material 1</th>
<th>Result</th>
<th>Properties for material 2</th>
<th>Result</th>
<th>Properties for material 3</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-40 \degree C &lt; T &lt; 90 \degree C) (continuous service temperature)</td>
<td>(-50 \degree C &lt; T &lt; 85 \degree C)</td>
<td>?</td>
<td>(-40 \degree C &lt; T &lt; 150 \degree C)</td>
<td>OK</td>
<td>(-50 \degree C &lt; T &lt; 200 \degree C)</td>
<td>OK</td>
</tr>
<tr>
<td>Volume resistivity &gt; (10^{10} \Omega m)</td>
<td>(10^{15} \Omega m)</td>
<td>OK</td>
<td>(10^{10} \Omega m)</td>
<td>OK</td>
<td>(10^{11} \Omega m)</td>
<td>OK</td>
</tr>
<tr>
<td>Young’s modulus &gt; 1 GPa</td>
<td>1.2 GPa</td>
<td>OK</td>
<td>20 GPa</td>
<td>OK</td>
<td>3 GPa</td>
<td>OK</td>
</tr>
<tr>
<td>Total cost per unit &lt; 5 € per unit</td>
<td>3 € per unit</td>
<td>OK</td>
<td>5 € per unit</td>
<td>(OK)</td>
<td>9 € per unit</td>
<td>—</td>
</tr>
<tr>
<td>Impact load &gt; 20</td>
<td>25 kJ/m²</td>
<td>OK</td>
<td>30 kJ/m²</td>
<td>OK</td>
<td>22 kJ/m²</td>
<td>OK</td>
</tr>
</tbody>
</table>
3.7. Sustainability strategies for design

In the last decades, many new concepts have been created to fulfil modern product development as well as environmentally friendly production like DFE (Design for the Environment) [55,42]. DFE can be seen as a broad and general concept for promoting a sustainable design. The concepts below are typically not standardised, but they are helpful in promoting emphases in a certain sustainable direction. Some examples of common strategies in order to reach a sustainable design are [42,56–58]:

- **Eco-design**, which is also known as Design For the Environment (DFE).
- **Modular design.** Easy repair and change of components are here important. E.g., parts in copying machines and computers.
- **Design for material substitution.** Substitution of materials with high environmental impact to more superior materials in terms of sustainability.
- **Waste source reduction design.** Reduce the amount of material both in terms of the product itself and packaging.
- **Design for disassembly (DFDA).** A product should be easy to disassemble with, e.g., snap fits, mechanical locks, etc. in order to recycle the materials.
- **Design for recycling (DFR).** DFR focuses on maximum recycle-ability and a high content of recycled material in the product. Different materials should not be mixed if not necessary and different parts should be labelled for easy materials separation.
- **Design for disposability.** Assures that non-recyclable parts or materials can be disposed in an ecological way.
- **Design for reusability.** Focuses on possible reuse of different components in a product. The reused parts could be freshened up and reused.
- **Design for service (DFS).** The design of a product is made here in order to obtain easy service from the outer regions.
- **Design for substance reduction.** Undesirable substances, which are used during the products life cycle, should be minimised.
- **Design for energy recovery.** The design here is made with materials suitable for burning with a minimum of toxic or harmful emissions.
- **Design for life extension.** Reduced waste through prolonged life for components or products is the aim of this strategy.

The concepts above are typically not standardised. Anyway, they are helpful in providing more sustainable products. The abbreviations in parentheses above are quite widespread and well known.

DFMA (Design for Manufacturing and Assembly) is an example of another well-known concept, which is not typically connected with sustainable design. DFMA is a concept that includes both DFM (Design for Manufacturing) and DFA (Design for Assembly) [55]. DFMA integrates the design process, which typically includes the selection of material, process planning, testing, assembly and quality assurance. It is a method for simple production, which can also provide a more sustainable production because of the attempt to use a minimum of production resources.

Another interesting strategy is to optimise a product with a multi functional design like a fax/copier/printer device or to design the product in such a way so as to increase the lifetime of the product as well as having service possibilities in a greater range [59–61].

4. The use of sustainable products

There are some interesting ways to obtain a more sustainable use of products. One interesting approach is to consider re-manufacturing of old products, which can be an interesting alternative to produce new ones. New products can have longer expected lifetime or a new design. However, there are models like the End Of Life (EOL), which can inform if it is an acceptable cost to re-use, recycle or dispose a certain part in a product or the whole product itself [62]. Case studies for product manufacturing are also a possibility to make decisions about manufacturing of certain products [63].

The use of sustainable products can be transferred to the producing companies rather than to the consumer. Today we are living in a world where service becomes more and more important in many countries. More than half of the total labour in many industrialised countries is involved in services like transportation, health, retail and wholesale distribution, social welfare, finance, etc. [64]. When the service is dominating in a country and the products are substituted by services, it is common to call this system as a functional economy or a service economy [40,65]. A change from the focus of producing and consuming products to a system where service components replace the more materialised focus can be a way to reduce the environmental impact of consumption. Such a service system is usually called a Product Service System (PSS), which is a way to reach a more sustainable development [66]. A PSS means that product producers will be responsible for delivery, guarantees, repair, upgrading, maintenance, take back, recycling, etc. [67]. An example of this is leasing systems for copying machines, coffee automates, etc. This is a way to let the producer or supplier take care of the environmental planning and to extend the lifetime of a product. The environmental benefits can also be a result of more intense use of products such as car or boat rental.

5. Integrated sustainable product development impact evaluation

In order to get as low environmental impact for a product as possible, a side by side evaluation of different products or ways of manufacturing is useful. The idea here is that a price must be set for every step in a Life Cycle
Assessment. Even the ecological impacts degree of equity must be set a price to restore the environmental impact and to get fair salaries for the workers. The main basic steps of an LCA as mentioned above (material extraction, manufacturing, packaging, transportations, product user stage and product disposal stage), generally have to be increased according to the specific product. For a sustainable product, a price can be set for every step, which can tell the price for restoration of the environment and the cost for equity.

Evaluation programmes (e.g., computer based) typically give a certain numerical value for each step in the LCA. A numerical value is then a quite simple way to determine different materials, manufacturing processes, etc. with each other. Such programmes are generally developed by a team of experienced people who determine a certain impact in each step [www.ecoscan.nl].

As mentioned earlier a full restoration can never be obtained, hence, the total entropy for the earth will always increase when material products are made. This fact has to be kept in mind when the total cost for different products is compared. A quite problematic issue is to compare the cost for different environmental impacts. For example, how can waste of 1 kg toluene be compared with waste from 1 kg benzene or 1 kg CO2 be compared with SO2? If chemical substances are dissociated to harmless products like CO2 → C + O2, the efforts (e.g., energy to support such a reaction) must be kept in mind. Are the ‘efforts’ to make carbon (C) and oxygen (O2) higher than the environmental impact from CO2? From what we know today, the environmental impact from CO2 is much lesser when compared to the performance of the above-mentioned reaction when CO2 is dissociated. If we compare toluene with benzene, we must always keep in mind that the environmental impact might not be fully understood today and the assumed degree of impact might be changed in the future. Only some decades ago benzene was seen as a quite harmless liquid used for cleaning, etc. but today we know that it causes cancer. Today, CO2 is partly responsible for the greenhouse effect in the world.

How can, according to what have been said above, a reasonable cost then be estimated for a restoration of an environmental impact in practice? There are some common ways like regarding legislations, documents for sustainable production (like EMAS) or follow instructions from different marking systems like the ‘E star’, ‘Environmental protection agency’, ‘EU-sign’, etc. In fact for most companies the legislation is fulfilled and the minimisation of waste is often an issue, which is based on the lowest cost for the production or the use of the product. The steering from authorities is typically done in a way that environmental impacts are costly due to higher taxes for harmful wastes, etc.

The sustainable product development for successful products can also be simplified as a chain with important links, which has to be strengthened up as shown in Fig. 1.

The seven rings in the sustainability chain circle, in Fig. 1, can be explained as follows:

- **Material.** Minimise the material use and try to use renewable materials. Minimise the energy consumption during the LCA and avoid toxic materials, etc.
- **Economy.** Product and service must be cost efficient and comparable with similar products. Consider the total cost during the life cycle including the cost for restoring environmental impacts. What about ownership, serviceability, PSS?
- **Design.** Design for the environment and the product user as well as for recycling!
- **Market.** Develop products and design them according to the needs from the specific market and target group.
- **Equity.** Is the trading equitable and what is the impact on the local and global community? What about employee conditions of work?
- **Technology.** Optimise the extraction of raw materials, production, lifetime and quality and functionality of the product.
- **Ecology.** Eliminate emissions and waste and minimise the environmental impact.

The product development can be simplified with the following steps:

1. **Concept stage for the product.**
2. **Determine the life cycle stages (LCA) and calculate the total cost including environmental load.**
3. **Evaluate different products and the production step for each product side by side in order to minimise the environmental impact for the whole life cycle by optimising the sustainability impact.**

Examples of databases for evaluation of environmental load and materials selection:

6. Discussion

The availability of materials for products will not increase in the future, as the amount of material is limited. However, the resources of energy will probably be more critical in the future than the availability of materials and the relation between material and energy is quite obvious. A good designer and/or engineer must, e.g., be aware of these facts and be able to continuously look for new products where new materials and production methods can be used together with a sustainable design.

During only about two centuries, we have seen a development from an almost total dependence on an agricultural production through a rapid growth of manufacturing industries to a post-industrial era where service has been substituting many technically advanced products. We have observed a dramatic environmental impact, which has affected the whole earth including its life. The need of more products, which includes more fashionable and modern products, is still an unsolved issue in the sensitive ecological system we live in. A change to products with low environmental impact including longer lifetime and an end of the “Throwaway” society are examples of a society, which is not so easy to achieve. One reason for this is simply the fact that there will always be people with enough money who want to buy products regardless of the sustainability. Another problem is the poor people who just want to survive. For many people, the environmental impact is also more or less unimportant for different reasons. Even if there are sustainability directions like high taxes on fuel, some people still want to have big and powerful cars regardless of the fuel consumption. Legislation, which prohibits big cars, etc. is also problematic if it is not applicable for all nations. Political control of sustainability by legislation is often a balance, which is problematic in most countries. For example, too much control by legislation can easily result in massive actions from different groups of people and elections where new politicians with less interest in preserving the nature are elected. This is one of the great dilemmas for creating a sustainable society.

7. Conclusion

Over-consumption, resource utilisation, pollution and over-population are examples of the perhaps most basic problems for the environment in the future. A more sustainable future can be achieved by producing more sustainable products causing less environmental impact. Materials and design are and will always be very important areas when developing more sustainable products.

The Life Cycle Assessment concept might be the most effective way of determining the environmental impacts for all product stages from extract of material to the product disposal stage. A price must be set for restoration on every environmental impact. Information can be received from official authorities pertaining to the environment in different countries. Renewable and easy recyclable materials are preferably used together with a design for easy recycling and repair of the products. Minimisation of the energy connected to the product is also important. ‘Full sustainability’ can never be achieved for products according to thermodynamic laws. However, the attempt to achieve more sustainability is a requisite if we want to preserve the earth for the coming generations.

Education, research and spreading of information will be very important for the future in order to receive more sustainable products especially because the market demand is important in order to develop successful sustainable products.

8. Future visions

Optimisation of product sustainability by computer programs, as well as more educated and conscious people will be important for a sustainable future. New and more sustainable production methods will come into existence and it is important to be up to date with the new methods. Many new types of materials will also be presented, which demands for more experienced and trained engineers and designers. Adjustment to the market will be more and more important as well as informing people about the necessity for more sustainable products. A more integrated product development with the help of advanced computer programs including advanced Life Cycle Assessment will probably be more common.

The poverty among many people will still be a problem, which must be taken more seriously. Who wants to preserve rain forests and rare animals when it comes to a critical point, like getting food for a starving family? In the long run people will succeed in preserving the nature, but it is not easy to tell people in crisis about such issues.

Important things to do, in order to prevent the earth from an ecological collapse in the future, are to:

- Increase the knowledge among people, of what it means to live in a sustainable way. This can be done by education in schools, spreading information in articles, seminars, mass media, etc.
- Have political control and support sustainable companies. Waste and emission control of toxic products, etc. can be done by legislation and taxes.

- www.plaspec.com/web/qwMain (PLASPEC Materials Selection Database by Bill Communications Inc., USA).
- www.stn-international.de/stdatabases/databases/pdlcom.html (PDLCOM by William Andrew Inc., USA).
• Spread the knowledge among people that the world is unique and need to be preserved also for the coming generations.
• Buy more sustainable products and support companies with ecological aims by buying their products.
• Increase the research and development of more sustainable products.

This paper is one example of spreading increased knowledge of how to use materials and design in order to create more sustainable products.

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References