11 Green Engineering

11.1 Green Engineering

11.1.1 Green Design

Most environmental impacts occur when materials accumulate in the biosphere. The materials may be naturally occurring and extracted from the earth, or they may be man-made. The management of the material flows is critical for efforts for materials conservation. One way to manage the material flows, aiming to avoid accumulation, is to close the material cycles of production and consumption systems.

The idea of closing the materials cycles is not new. It comes from the observation that in natural systems, waste as we see it, does not exist. Materials discarded by one organism generally are used by others to grow and survive. In contrast to the situation in nature, material and energy in our economy mainly flows in one direction only – from raw materials towards final disposal as industrial or municipal waste (part (a) in Figure 11.1.) Sustainable development requires a change in these flow patterns. We need to establish cyclic flows of material.

The different ways to achieve this are collected under Cleaner Production concepts such as Green Engineering, Green Design, or Sustainable Products Design and Production Design. The focus is on the efficient use of materials and energy, reduction of waste toxicity, and reuse and recycling of materials (part (b) in Figure 11.1).

Green engineering uses a series of different techniques. These include Ecodesign or Design for Environment (DfE). Ecodesign directs research and development (R&D) teams to develop products that are environmentally friendly. Toxics Use Reduction (TUR) considers the internal chemical risks and potential external pollution risks at the process and worker level. Life Cycle Assessment (LCA) defines the material usage and environmental impact over the life cycle of a product.

In this chapter the different strategies, approaches and techniques used in the area of green design will be reviewed. Some of these are covered in more detail in other books of the series, especially Book 3, *Product Design and Life Cycle Assessment*.

In this Chapter

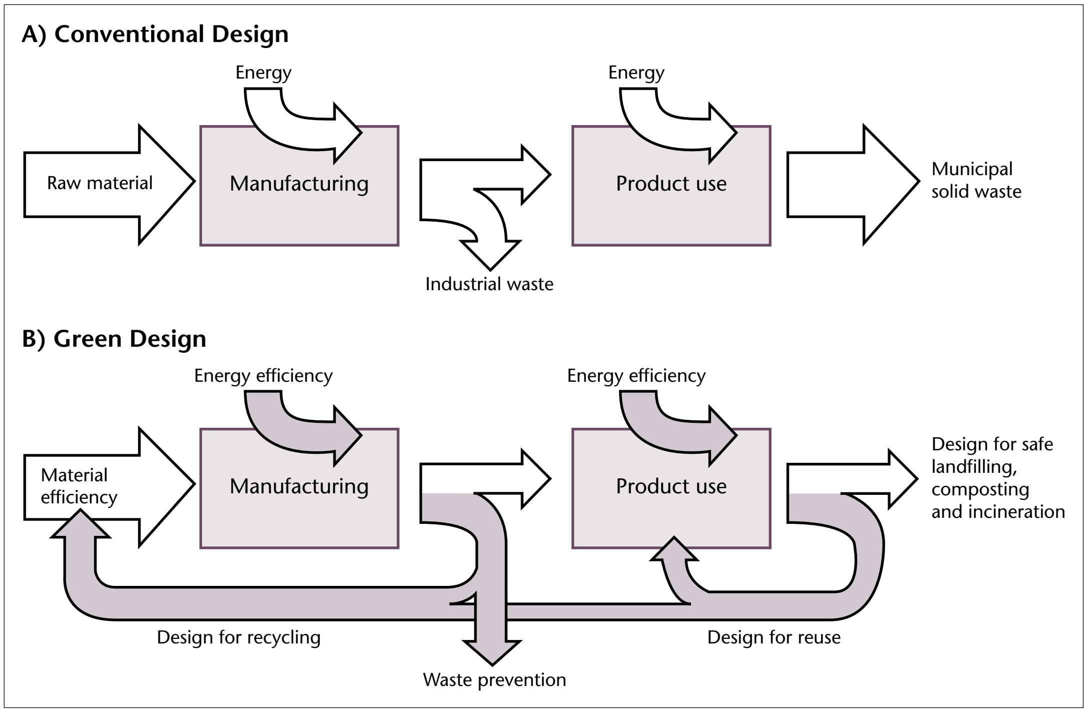

Figure 11.1 How product design affects material flows. *Making changes in a product's design reduces overall environmental impact. The green design emphasises the efficient use of material and energy, reduction of waste toxicity, and reuse and recycling of materials. [Reprinted from OTA, 1992].*

11.1.2 Corporate Strategies

Green Design may be seen as a comprehensive business strategy that maximises the economic and environmental returns on a variety of innovative pollution prevention techniques. Green Design or Sustainable Design of products and production seeks to meet consumer demands for products without compromising the resource and energy supply of future generations. It embeds corporate environmental responsibility into material selection, process and facility design, marketing, strategic planning, cost accounting, and waste disposal.

In the recent development of environmental strategies the focus has been on pollution from the point of view of industrial production. At the same time, advances in areas like materials and production technologies are creating openings for new developments.

An increasing number of companies with truly integrated global production systems direct their products to an increasingly homogeneous global market. The primary opportunities to reduce the adverse environmental impacts of economic activities continue to be technological. Conservation actions such as reducing waste or saving energy are important but among the simpler strategies one may adopt.

Efficiency improvements, such as modernising with more energy-efficient systems or re-engineering so that little or no waste is produced, or developing and deploying processes and systems that offer superior environmental quality, provide the greatest opportunity for improving environmental quality. These improvements are often driven by innovations in technology.

11.1.3 The Strategies of Green Engineering

Green engineering practice requires that concerns about environmental quality include not only production and product use but also useful materials or potential energy embedded in products. In this strategy, products are used in several systems or product cycles, either as parts, materials, or embedded energy. Product becomes input to several product cycles instead of merely ending up as waste ready for landfilling after one life cycle.

An important distinction is the lifetimes of products. Some are made to function for a decade or more; others have lives measured in months or weeks; still others are used only once. The designer must adopt different design approaches to these different types of products according to their durability, materials composition, and recyclability.

These approaches are implemented in a variety of business processes: product design, production design, materials management, supply chain management, order fulfilment, as well as service, maintenance, and asset recovery.

Below we will discuss sustainability strategies in production on several levels, all of them possible to improve by engineering.

On the *level of the industrial system*, the focus is on how one plant is coordinated with other production units in the same area. This is a close parallel to how an ecosystem works and is called industrial ecology or industrial symbiosis. This is a level where changes are slow to introduce since several companies are involved and each one has to agree on the profitability of the change. The essential of the strategy on this level is to organise the material and energy flows in such a way that what is coming out from one unit will be the input in another one.

On the *level of the product*, the focus is to make products such that they do not pollute and that their use does not require too much energy and other resources input. It is also important that products can be recycled or at least the material in the products can be recycled. They thus need to be designed in a way that makes this possible.

On the *level of materials management*, the focus is on material flows. We need to find materials which are renewable, we need to reduce the material flows, e.g. by dematerialisation of products, and we need to find materials which are not toxic.

On the *level of the production system*, the focus is on cleaner production methods. In addition, the up-stream factors are addressed by supply chain management and distribution and transport, and the down-stream factors on recycling as an important part of the end of life system of a product.

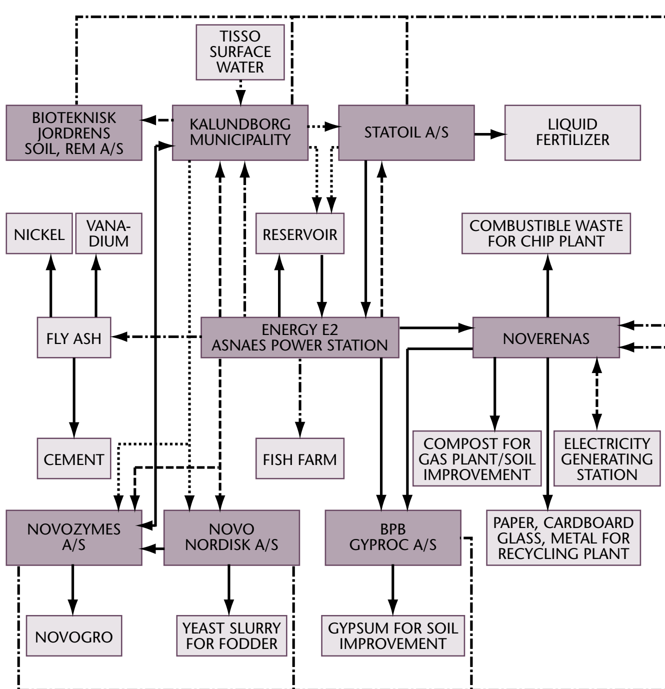

Figure 11.2 *Flow sheet of the Industrial Symbiosis of Kalundborg, Denmark. Dark colour indicates a company; lighter colour a product. [adapted from http://www.symbiosis.dk].*

11.2 Industrial Ecology

11.2.1 The Kalundborg Case

Industrial Symbiosis mimics the natural ecosystem by setting up a system of recirculation of residual materials from industrial processes or discarded products from consumer matter. Industrial Symbiosis attempts to optimise the industrial system as a whole, rather than a particular process or subsystem, to increase the efficient use of a material. In fact, a larger, more complex, more diverse system may offer greater opportunities for efficient use and reuse of materials.

Industrial Symbiosis typically is pursued in a limited area, in a municipality or industrial area in a municipality. Cases are not very common but are found in several countries, in the far East, in Canada in Europe in e.g. Denmark and Sweden. An example of optimisation, which may be reached also in a larger scale, is illustrated by the Industrial Symbiosis cooperation between a number of industries in Kalundborg, Denmark.

Kalundborg Municipality, together with a power plant, an oil refinery, a gypsum board manufacturing plant, a pharmaceuticals plant, a biotechnical plant for production of enzymes, a plant for remediation of polluted soil, a waste handling company and a fish farm and the surrounding farming community benefit from joint utilisation of material residue that otherwise would end up as waste.

The description below is divided between cycles of energy, nutrients, inorganic waste etc. One needs to remember however that truly integrated systems rely on these flows being coupled, as they are in the body metabolism. Water is a carrier of material and energy, waste is a carrier of energy, etc. Many municipalities have established their own symbiotic strategies. Examples include the use of energy in waste for incineration, nutrients in sludge to improve soil in parks, and the energy from wastewater streams by heat pumps.

11.2.2 Energy Cooperative Systems

Energy cooperation might be the most easy and typical case of symbiosis. In Sweden seven municipalities reported agreements with local industries on using residual heat for their district heating system. Some pulp and paper factories in the north are selling steam to other companies in the vicinity. Selling steam or hot water is a straightforward task and obviously should be profitable for all partners, as long as the needed infrastructure is available.

In Kalundborg, the Power Station produces heat for the city of Kalundborg and process steam for the oil refinery and for the enzymes factory. The combination of heat and power production results in a 30% improvement of fuel utilisation compared to a separate production of heat and power. Approximately 4,500 households in Kalundborg receive district heat from the Power Station. District heat has replaced approx. 3,500 small oil-fired units.

The oil refinery receives process steam and water from the Power Station. The steam covers about 15% of the refinery's total consumption of steam. The refinery uses the steam for heating oil tanks, pipelines etc. The enzymes and pharmaceuticals plants use steam from the Power Station for the heating and sterilisation of the processing plants.

11.2.3 Water Recycling in Kalundborg

The Kalundborg Region, as well as its industrial companies, is a large consumer of water. This is why the Symbiosis companies are seeking to recycle as much water as possible. The Power Station has, for example, reduced its total water consumption by 60% by recycling schemes. Previously the Power Station used ground water for its power and heat production only. The ground water has now been substituted by surface water from Lake Tissø and treated wastewater from the refinery. These efforts have enabled the Power Station to reduce its ground water consumption by 90%. Earlier, the enzymes company also used ground water exclusively for processes requiring drinking water quality. 1 million cubic metres of ground water have now been substituted by lake water from Tissø, whose water has been processed up to drinking water quality by Kalundborg Municipality.

As the water from Tissø is not an unlimited resource, the consumption of lake water has been reduced by 50% by recycling of the wastewater from the power plant.

The wastewater of the industrial park companies is led to a recycling reservoir together with the run-off from the surrounding fields and surplus water from Tissø in the winter period. The recycling reservoir has a capacity of 220,000 cubic metres of water, which are used in the power station processes.

The wastewater from the enzymes and pharmaceuticals plants is part of a genuinely symbiotic relationship: The enzymes company treats all wastewater up to a level corresponding to the wastewater of an ordinary household. The treated wastewater is pumped to the treatment plant of Kalundborg Municipality where a final treatment process takes place.

The wastewater from the enzymes plant is of a relatively high temperature, making it easier for the municipal treatment plant to treat its wastewater. In this collaboration process, the environment is also the winner as the overall discharge of nitrogen into Jammerland Bay is very limited. Wastewater is also discharged from the Power Station into the treatment plant of Kalundborg Municipality.

11.2.4 Gas and Inorganic Material Recycling

An "eternal" flare of surplus gas is part of the safety system in any refinery. But today the refinery flare in Kalundborg has been reduced to a mere night-light, because the refinery now exploits its own surplus gas internally. Formerly a large portion of the gas was transported by pipeline to the gypsum plant and the Power Station to be used in their production.

The desulphurisation plant of the Power Station removes sulphur dioxide (SO_2) from the flue gas, producing about 200,000 tonnes of gypsum on a yearly basis. Desulphurisation is a chemical process in which sulphur dioxide (SO_2) reacts with a lime slurry while forming the by-product gypsum. The gypsum is sold to the gypsum company that manufactures gypsum board products for the construction industry. The gypsum from the power station reduces the import of natural gypsum significantly. Being more uniform and pure than nat-

Figure 11.3 Oil refinery in Kalundborg, Denmark. *A collaboration – an industrial symbiosis – is pursued by the refinery with several other production companies in the Kalundborg area, which make commercial use of each other's spent coolant water and waste products. (Photo: TA Foto Scandex AS)*

ural gypsum, power station gypsum is therefore well suited for the gypsum board production.

Also gypsum stemming from the municipal recycling station of Kalundborg is delivered to the gypsum company, thereby contributing – on a smaller scale – to reducing imports of natural gypsum and the amounts of solid waste for landfilling.

The Power Station removes fly ash from the flue gases while producing about 30,000 tonnes of fly ash on a yearly basis. Ash deriving from orimulsion firing (orimulsion is a bitumen and water mixture mined in Venezuela) is recycled in a plant in Great Britain. Nickel and vanadium are reclaimed from this ash. The largest ash customer is a Portland Cement factory.

11.2.5 Biomass Recycling

The use of residual biological material is worldwide the most typical kind of industrial symbiosis. Of course a plant that has biological material as a residual product tries to sell it rather than pay for its destruction. Until recently a poultry farm on Gotland in the Baltic Sea shipped its dead chickens to Denmark for destruction. Since spring 2005 the dead chickens are instead incinerated in a power plant to produce heat. This is a win-win situation. In Uppsala in Sweden, the organic waste from the local slaughter house (a rather big one) is fermented by the municipality. The biogas formed is used by the local bus company to run 43 of the local buses. Typical cases of cooperation include the use of sludge from wastewater treatment in agriculture. The old view that waste is a resource, that nutrients is money, is expressed in a modern situation by industrial symbiosis.

In Kalundborg enzyme production is based on fermentation of raw materials such as potato flour and corn starch. The fermentation process generates about 150,000 cubic metres of solid biomass. At the same time, 90,000 cubic metres of liquid biomass is produced. After inactivation and hygienisation, this product is used by some 600 West Zealand farmers as fertiliser in the fields, thereby reducing their need for commercial fertilisers. The product contains the by-products nitrogen, phosphorus and lime.

The insulin production of the pharmaceutical company also provides feed for pigs. The insulin production builds on a fermentation process in which some of the main ingredients are sugar and salt, which are converted into insulin by adding yeast. After a heating process, the yeast, a residual product in this production, is converted into a much appreciated feed: yeast slurry. Sugar water and lactic acid bacteria are added to the yeast, making the product more attractive to pigs. The yeast slurry replaces approx. 20% of the soy proteins in traditional feed mixes. Over 800,000 pigs are fed on this product.

The refinery's desulphurisation plant reduces the sulphur contents of the refinery gas whereby SO_2 emissions are reduced significantly. The by-product is ammonium thio-sulphate, which is used in the production of approx. 20,000 tonnes of liquid fertiliser, roughly corresponding to the annual Danish consumption.

Sludge is a major residual product stemming from the municipal water treatment plant in Kalundborg. The sludge is utilised at the soil-remediation plant as a nutrient in the bioremediation process.

The waste handling company collects waste from all Symbiosis companies. Further, it produces electricity on the basis of landfill gas. This electricity is fed into the national power grid. In addition, a total of approx. 56,000 tonnes of combustible waste on a yearly basis is produced corresponding to the energy consumption of approx. 6,500 private households in terms of power and district heating.

11.3 Product Design

11.3.1 Ecodesign or Design for Environment (DfE)

A second main concern for green engineering is Ecodesign or Design for the Environment (DfE). Ecodesign aims to minimise environmental impacts of a product and achieve major reductions in resource and energy use throughout the life cycle of the product (including the manufacturing phase).

One of the methodologies developed for sustainable product design is the Ecodesign Strategy Wheel (Figure 11.3). It provides a basic framework to systematically review the entire life cycle of a product. It is a tool that can stimulate a creative design process and bring up opportunities for improvement.

The Strategy Wheel begins with the strategy called new product concepts, and then includes a series of strategies on materials selection, production, distribution, use, and end of a product's life, etc.

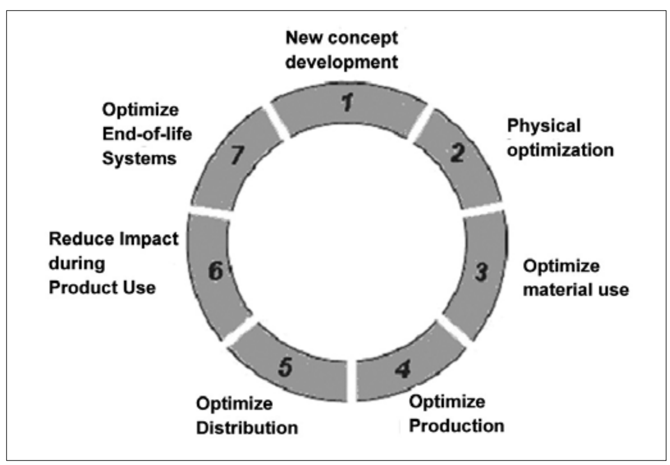

Figure 11.4 *The ecodesign strategy wheel [NRC, 2001]. (See also Figure 4.7)*

11.3.2 New Concept Development

In the strategy *New Concept Development* the function(s) of a product in terms of both development assumptions and the needs of the end-user are examined. The strategy focuses on basic assumptions regarding the function of a product. It determines the end-users' needs and how the specific product meet these needs.

The most radical form of New Concept Development is to replace the physical product with a *service*. One example is when a customer buys a transport service instead of a car. Then a company assumes responsibility for maintenance, repair, disposal, and/or recycling of the product – here the car – during its use and end-of-life phases. It is environmentally a better strategy for many reasons. It is in the interest of the company to make their cars long-lived, economical and maximally used.

Another road to decreased physical production is to increase *shared use*. When several people make joint use of a product without actually owning it, the product is used more efficiently. Good examples of products that can be shared include equipment such as photocopiers, laundry equipment, hardware, and construction tools. The products then have to be robust enough to stand heavy use.

Other examples are replacing a material product with an immaterial substitute, e.g., mail replaced by e-mail; and/or reducing the use of material or infrastructure-intensive systems, e.g., telecommuting vs. use of automobiles for work purposes.

11.3.3 Dematerialising Products and Services

An important part of ecodesign is to look for dematerialisation opportunities. Dematerialisation, of course, leads to less pressure on resources, less environmental impact, as well as smaller waste streams as the material stream as a whole is reduced. In addition, with dematerialisation less energy is used during production, transport and storage.

The most common form of dematerialisation is to make an existing product smaller or lighter. This may be possible due to technical developments, as illustrated by the dramatically reduced size of computers, phones, and other electronic equipment over the last decades. To design products so that they are of equally high quality but with less material may also be possible due to a change of material. Examples include the use of optical fibres instead of copper wire for electric transmissions or a strong alloy instead of iron for specific purposes. Sometimes dematerialisation is trivial. An American fast-food franchise reduced material input and solid waste generation by decreasing the paper napkin weight by 21%. Store tests revealed no change in the number of new napkins used compared to the old design.

A particular case is products which are deliberately designed to be heavy or large in order to project a quality image. However, a quality image can be achieved through other techniques, i.e., creating a lean but strong design. In many cases, a reduction in the weight or volume of materials is possible without affecting their technical life.

11.3.4 Extending the Life of a Product

Extending the life of a product is another objective in ecodesign. Making more long-lived products saves resources and generates less waste because fewer units are needed. If, however, new generations of products are environmentally better, which is sometimes the case, it may on the other hand be counter productive. Many cars illustrate this.

The reasons for products being wasted may be that the new generations are technically improved, that fashion asks for a new product, that they are worn out, either by normal wear or because of poor quality, because of degradation e.g. by environment or chemically, that they are damaged by accident or inappropriate use. Therefore, to make longer-lived products the designer needs to address *durability*, *adaptability* and *reliability*.

Durable products can withstand wear, stress, and environmental degradation over a long useful life. Designers should enhance durability as appropriate. For example, a company leases all the photocopiers it manufactures. The company designs drums and other key components of their photocopiers for maximum durability to reduce the need for replacement or repair. Because the company maintains control of the machines, they select materials to reduce the cost and impact of disposal.

Adaptable design requires that parts can be replaced as needed. For example, an adaptable strategy for a new razor blade design ensures that the new blade mounts on the old handle so that the handle does not become part of the waste stream.

Reliability refers to the ability of a product to serve its use for a certain period of time. Parts reduction and simplified design can increase both reliability and manufacturability. A simple design may also be easier to service. All these factors can reduce resource use and waste.

11.3.5 Making Products Recyclable

Recycling products in whole or in part is another key strategy in ecodesign. Recycling includes *reuse*, e.g. a bottle which can be refilled; *remanufacturing*, e.g. of a used car motor if most of it can be reused; *material recycling* e.g. in recycled glass, or at least *energy recycling* if the material can be used as fuel, as when paper is burned.

Remanufacturing restores worn products to a like-new condition. The used product is disassembled, its usable parts are cleaned and refurbished, and a new product is reassembled from both old and new parts. Designs must be easy to take apart if they are to be remanufactured. Adhesives, welding, and some fasteners can make this process impossible. Critical parts must survive normal wear, and extra material present in used parts allow re-finishing. Design continuity increases the number of interchangeable parts between different models in the same product line, as common parts make remanufacturing products easier. For example, a manufacturer remanufactured plastic moulders for one-third the cost of new machines. The remanufactured machines increased efficiency by 10 to 20% and decreased scrap output by 9% compared to the old equipment; performance was equal to the new moulder.

Reuse is the additional use of a product several times. Normally cleaning or maintenance is needed when going from one use to the next. Containers, bottles, are classical examples of reused products; other examples include reusable parts of machinery to filters in coffee machines.

Material *recycling* is the reprocessing of a recovered material. In *closed loop* systems, recovered material and products are suitable substitutes for virgin material. In theory a closed loop model can operate for an extended period of time without virgin material. Solvents and lead in batteries are common materials recycled in a closed loop. *Open loop* recycling (sometimes called down-cycling) occurs when the recovered material is recycled only once or a few times before disposal. The classical example is paper that may be used up to a maximum of six times. When the paper has been used for paper board or packing, it is not valuable enough to recover any more. Most consumer material is recycled in open loops.

In most projects, the *material selection* is not coordinated with environmental strategies. For instance, a passenger car currently uses 50 to 150 different materials. Separating this mixture from a used car to recycle them is impossible. Designers can, however, aid recycling by reducing the number of incompatible materials in a product, for example by using a single polymer for all plastic parts. The polymer has a moulded-in finish, eliminating the need for additional finishes, and moulded-in identification symbols. In addition, if parts snap together the use of metal pieces such as hinges and brackets can be avoided. Design features which facilitate recycling, include easy disassembly, elimination of costly plastic parts sorting, and easy identification of polymer composition.

11.3.6 Reducing Impact During Use

Many products consume considerable energy, water and/or other consumables during their life span. Resources consumed in maintenance and repair add to the environmental impact. An important product design strategy focuses on reducing environmental impact during product use. Energy-efficient products reduce energy consumption and greenhouse gas emissions.

Energy-efficient products use the lowest energy-consuming components available. If energy is required to move the product they should have light-weight materials. If energy is used for heating or cooling appropriate components are well insulated, and the temperatures used are as close to room temperature as possible. If batteries are needed passive solar heating and rechargeable batteries are good alternatives. Sometimes it is possible to use human-powered alternative designs. Electronic equipment should have a default power-down mode.

The use of *clean energy sources* for a product can greatly reduce harmful emissions at the energy-generation stage.

Ecodesigned products should also reduce the use of consumables such as water, oil, filters, cleaners/detergents and organic materials during a product's life span. The design may also foresee possible leaks from machines that use high volumes of consumables by, for example, by installing a leak detector. Some products may also re-cycle consumables, e.g., newer dishwashers re-circulate some wash water to reduce total water usage. Ecodesigned products should also reduce the handling of hazardous/dangerous materials, and prepare for reduced disposal costs of hazardous/dangerous materials. Implementing a collection/recycling/re-manufacturing system is a way to eliminate the disposal of filters, cartridges and dispensers in landfills or for incineration.

11.4 Materials Management

11.4.1 Choosing Material

Material selection is a fundamental part of design, and it offers many opportunities for reducing environmental impact. Materials management deals with the environmental impact caused by resource acquisition, processing, use, and wasting.

Substituting toxic materials and selecting the most environmentally appropriate materials, substances and surface treatments for product manufacture can be made for product as well as process materials, such as solvents and catalysts. For example, water-based solvents or coatings can sometimes be substituted for high-VOC alternatives during processing. Also, materials that do not require coating, such as some metals or polymers, can be substituted in the product.

For example, an American company replaced its five-layer finish on some products with a new three-layer substitute. The original finish contained nickel (first layer), cadmium, copper, nickel, and black organic paint (final layer). The new finish contains nickel, a zinc–nickel alloy, and black organic paint. This substitution eliminates cadmium, a toxic heavy metal, and the use of a cyanide bath solution for plating the cadmium.

The new finish is equally corrosion resistant. It is also cheaper to produce, saving the company 25% in operating costs.

Some materials or additives are best avoided because they cause hazardous emissions during production, when they are incinerated, or if they are landfilled. Reducing the use of toxic chemicals results in fewer regulatory concerns associated with handling and disposing hazardous material and less exposure to corporate liability and worker's health risks. For example, a water-based machining coolant can reduce the quantity of petroleum oils generated on-site and allow parts to be cleaned more effectively using a non-chlorinated or water-based solvent.

The use of *renewable materials* can represent a good environmental and societal choice for many reasons. They have reduced net emissions of CO_2 across their life cycle as compared to materials derived from fossil fuels. They result in biodegradable waste, and may be possible to grow and use locally, which promotes sustainability.

The energy assembled in a product during its production is called *embodied energy*. The number and type of processing steps for a material and its embodied energy are correlated. The fewer and simpler the extraction, processing and refining steps involved in a material's production, the lower its embodied energy. The embodied energy of a material is often reflected in its price. In some cases, the most technically appropriate material will lower energy costs over the life cycle of a product. For example, composite materials involving carbon fibres or ceramic compounds may have a relatively high embodied energy, but when they are used appropriately, they can save energy in a product's use-phase due to their advanced physical properties, e.g., strength, stiffness, heat or wear resistance.

11.4.2 Recycled Materials

The use of virgin material may be minimised by maximising the incorporation of *recycled material*. *Recyclable materials* are those that can be easily recycled, depending on the type of material and the available recycling infrastructure. Sources of recycled feedstock include in-house process scrap, waste material from another industry, or reclaimed post-consumer material. The quality of incoming material determines the amount of unusable feedstock and the amount of time required to prepare the material. Therefore, product design dimensions should closely match incoming feedstock dimensions to minimise machining, milling, and scrap generation. Reformulation is an appropriate strategy when a high degree of continuity must be maintained with the original product. Rather than replacing one material with another, the designer alters the percentages to achieve the same result. Some material may be added or deleted if the original product characteristics are preserved.

Recycling provides cost-benefits. Reducing the amount of waste a company sends to landfill can produce significant cost-savings. The waste materials could itself be a source of income. By implementing product take-back programmes, companies have a cost-effective source of materials and/or parts. Unique features of recycled materials such as variations in colour and texture can be advantageous when used appropriately in product production. This can include using recycled paper, steel, aluminium, other metals and plastics.

11.5 Production Design

11.5.1 Cleaner Production Strategies

Production optimisation focuses on practices for cleaner production. *Alternative production techniques* aim to process optimisation, quality control, energy conservation and preventive management. It can also lower energy and costs associated with raw materials, energy, labour, treatment and disposal, insurance and liability.

In optimisation of product production, techniques and processes should be undertaken with the objective of *reducing the number of production steps*. Means to do this include multiple production steps to be performed on a single part or component simultaneously; single production steps to be performed on multiple parts or components simultaneously; reducing the movement/transport distances of parts and components within the production facility; using materials that do not require additional surface treatment or finishing for performance or aesthetics.

Lower/Cleaner Energy production can be achieved by making production processes more energy efficient. Measures that may be explored include the use of cleaner energy sources; introducing cogeneration of heat and electricity; optimising the heating/ventilation/energy needs and set up systems and controls tailored to each specific process; more efficient compressed air systems; optimised use of space requirements.

Less Production Waste can be obtained by optimising production processes with respect to the output of waste and emissions. This optimisation increases the efficiency of material use and decreases the amount of material sent to a landfill by reducing or eliminating the "non-product output" per unit of production. Measures to promote this include elimination of processes such as sawing, turning, milling, pressing and punching in order to reduce waste, and secondly the recycling of production residue in-house.

Using *fewer/cleaner production consumables* is another strategy. The use of water, solvents, de-greasers, oil/lubricants, abrasives, solders and cutting tools can be correlated with per unit production and minimised. For example, identifying and using solvents, lubricants or de-greasers with low volatile organic compounds (VOCs) can reduce the use of ventilation systems and/or pollution prevention equipment.

Improved inventory control and materials handling reduces waste from oversupply, spills, or deterioration of old stock. Storage facilities are important elements of inventory and handling systems. If toxic chemicals are needed in a process less harmful precursors may be stored and reacted to form the toxic chemicals for immediate consumption. This system in addition avoids transporting toxic materials.

11.5.2 Distribution and Transport

Another way to reduce environmental impact is to use efficient ways of transport of products from the producer to the distributor, retailer and end-user. The factors involved in distribution optimisation include packaging, mode of transport, mode of storage/handling and logistics.

Packaging development should be considered separately from product development since packages have their own life cycles and associated environmental impacts. Also packaging can undergo ecodesign. The key is to reduce packaging. Packaging is a dominant part of waste streams in industrial countries. Less and smaller packaging result in less waste, less energy for transport, less emissions and less cost. Transport and bulk packaging, may rely on re-usable materials and a return system between producer and the retailer and, if possible, between the retailer and end-user. A package deposit/refund will encourage such a system. A returnable packaging should be durable to withstand several cycles and possible to fold to be easier to return.

Well-designed *transport* of the products may greatly contribute to a decreased environmental impact. Thus transport by rail is many times more energy saving than by car, and shorter distances are of course better than longer.

Logistics refer to the organisation of distribution and transport. Choosing a better provider of a material or product will reduce impact; a local provider if possible will avoid long distance transport. Coordination of transports may also greatly reduce the need for transport. Use of standardised pallets, boxes or bags to load products may also reduce impact. Efficient routing of transportation and distribution can significantly reduce the environmental impact. Efficient computer systems for distribution may also be part of improved logistics.

11.5.3 Supply Chain Management

Supply Chain Management (SCM) is, according to the Ryzex Group, "the oversight of materials, information, and finances as they move in a process from supplier to manufacturer to wholesaler to retailer to consumer. Supply chain management is the way a company finds the raw components it needs to make a product or service, manufacture that product or service and deliver it to customers. Supply chain management involves coordinating and integrating these flows both within and among companies."

Supply chain management flows can be divided into three main flows: The product flow, information flow and financial flow. The product flow includes the movement of goods from a supplier to a customer, as well as any customer returns or service needs. The information flow involves transmitting orders and updating the status of delivery. The financial flow consists of credit terms, payment schedules, and consignment and title ownership arrangements. The proper choice of supplier of raw material offers a very important possibility to reduce the environmental impact of a product. One needs to find a provider close by and with the product needed.

11.5.4 Optimising the End-of-life System

Optimising the end-of-life system is aimed at re-using valuable product parts/components and ensuring proper waste management at the end of a product's useful life. Optimised end-of-life systems can reduce environmental impacts through reinvestment of the original materials and energy used in manufacturing. Companies should consider various end-of-life scenarios to optimise the end of a product's life. Can the product/components/parts be reused? Can parts/components be remanufactured and then re-used? Can parts be used for material recycling? Can parts be safely incinerated? Should parts be disposed of in landfill?

Reuse of the product, either for the same application or a new one, is easier the more the product retains its original form, and the more environmental merit is achieved. The possibilities for re-use are dependent upon the product's technical, aesthetic and psychological life span, and the product being possible to clean, maintain and upgrade. Recycling depends on the existence of take-back programmes and the willingness of a secondary market to accept used products. It is easiest with recyclable materials for which a market already exists. Designing for disassembly should be considered. This type of design is also closely related to making a product more serviceable for users and aiding in maintenance and repair.

Factors such as the life span of parts/components, their standardisation, maintenance requirements, and instructions for servicing and re-assembly, play a major role in designing for disassembly. If the product can be easily disassembled the levels of recycling increases. If non-destructive disassembly is not possible, the different materials should be possible to easily separate into groups of mutually compatible materials.

This is important, for instance, in efficient metal recovery and recycling.

When product, component or material re-use and recycling are not possible, incineration is an end-of-life option. Design for safer incineration avoids the use of materials that can lead to toxic emissions if the product is incinerated without adequate environmental controls.

Study Questions

1. What is included in the concept of green engineering?
2. List the four levels of manufacturing at which green engineering strategies can be used.
3. Describe what is meant by *industrial symbiosis* and give two cases where it has been applied.
4. Explain how energy cooperative systems between different plants or activities can be designed. Give an example.
5. Explain how biomass cooperative systems between different plants or activities can be designed. Give an example.
6. Make a drawing of the ecodesign strategy wheel for *product* development, and give examples of each of the eight strategies.
7. Explain how recycling can be an important strategy in green engineering. Describe each of the levels of product, material and energy.
8. Describe green engineering strategies used in *production* design.
9. In what ways can supply chain management of *materials* contribute to cleaner production?
10. Make a personal assessment of the role of green engineering in cleaner production.

Abbreviations

DfE Design for Environment.
LCA Life Cycle Assessment.
OTA Office of Technology Assessment, USA.
R&D Research and Development.
SCM Supply Chain Management.
TUR Toxics Use Reduction.
VOCs Volatile Organic Compounds.

Internet Resources

U.S. EPA – Green Engineering
http://www.epa.gov/oppt/greenengineering/

The Greenbusch Group – Green Engineering/LEED (Leadership in Energy and Environmental Design)
http://www.greenbusch.com/GreenEngineering.html

National Industrial Symbiosis Programme (NISP)
http://www.nisp.org.uk/

Industrial Symbiosis: Literature and Taxonomy, by Marian R. Chertow, in "Annual Review of Energy and Environment"
http://arjournals.annualreviews.org/doi/pdf/10.1146/annurev.energy.25.1.313

The Kalundborg Centre for Industrial Symbiosis
http://www.symbiosis.dk

CleanerProduction.com – Design for Cleaner Production
http://cleanerproduction.com/Directory/tools/design.htm

The Ryzex Group – Glossary of Terms for Bar Coding
http://www.ryzex.com/barcodeGlossary.cfm

The Centre for Sustainable Design,
Surrey Institute of Art & Design University College, UK
http://www.cfsd.org.uk/index.html