The Environmental Impacts of Packaging

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CHAPTER 9

THE ENVIRONMENTAL IMPACTS OF PACKAGING

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1 INTRODUCTION

The need for packaging and the development of packaging was caused by the fact that the production and the consumption took place at separate places and times, and the produced goods had to be distributed and transported. Packaging became a connecting link between production and consumption, and the importance of this link is growing in urbanized societies. More than 150,000 people are being added to urban population in developing countries every day. In the mid-twentieth century, only one-third of the world's population was urban. The prediction is that by 2025, two-third of the world's people will live in cities. This means that more people will live in cities than occupied the whole planet in the 1980s.[1] In such level of urbanization, distribution of goods, especially food, is crucial, and the role of packaging is enormous.

Since the 1970s, when litter was of significant concern, packaging has often been associated with wasteful behavior. This is partly due to the fact that packaging wastes are a very visible part of environmental problems. The negative image of packaging does not, however, translate into consumer hostility at point of sale. Products and not packages are bought. The package is not noticed during purchase, transport, and use of the product—infact, it is not noticed until the minute the product is consumed and the package had fulfilled its function and turns into waste. At that minute, the package is already seen as an environmental burden, wasting resources. Those concerned about the state of the environment can take part in reducing this burden through packaging recovery programs.

Packaging has positive and negative impacts on the environment. The negative impacts include resources use and the effects of packaging-related wastes and emissions. The positive impact is that packaging consumer goods facilitates their distribution, and thus makes it possible to obtain goods otherwise not

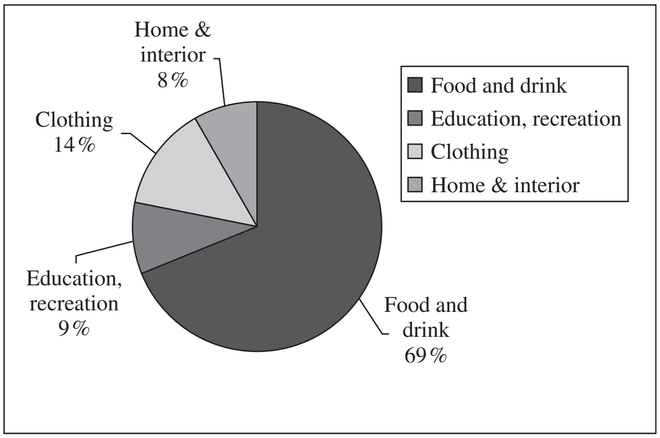

Figure 1 Packaging use by type of goods. (From Ref. 2.)

accessible. Environmentally conscious packaging enables satisfying human needs in an effective way.

In developed countries, food packaging represents more than two-thirds of all packaging.[2] Due to this reason, this chapter is mainly concerned with food packaging. Figure 1 illustrates the breakdown of packaging types.

2 FUNCTIONS OF PACKAGING

Although the package is tailor-made for the product, all products are made for consumers. Until the middle of the twentieth century, groceries were a meeting point: People talked there, discussed with the shopkeeper, asked information about the products. In modern supermarkets the function of the shopkeeper is taken by packaging. Modern packaging is an expressive form of the consumer lifestyle, giving character to the product. Geiger listed the functions of packaging as follows: protection, distribution, household, intermediate, advertisement, image-component and value forming functions.[3] In addition, packaging, especially food packaging, can have an important waste reduction function.[4]• • Q1

2.1 Protection Function

Today, an important function of packaging is protection and preservation. This was not always the case. Until the early nineteenth century, food was preserved by salting, smoking, and drying. The situation changed, however, during the Napoleonic Wars. While on the campaign trail, French troops suffered from scurvy and starvation. Napoleon issued a challenge for a better way to preserve food, and in 1809 Nicolas Appert discovered that cooked foods could be kept from spoiling if the air were eliminated. Appert preserved food by boiling it and packing it in jars, thus creating the process of canning.[5]

In the 1860s, Louis Pasteur discovered why removing air preserves food. Air carries living organisms, including mold and bacteria. By heating liquids such as milk and beer to at least 70°C for 15 seconds, these harmful organisms can be killed.[6] Today, food spoilage in Western Europe is less than 3 percent for processed food and 10 to 15 percent for fresh food. In lesser-developed countries where packaging is minimal, food spoilage can reach 50 percent.[7]

The protective function is more and more important in the present trend of increasing urbanization. For example, in Finland, the Finnish Association of Packaging Technology and Research concluded that future packaging trends do not depend on materials on hand but on more important factors such as product protection and distribution. Recently, the use of active packaging became widespread, in which packaging is combined with the use of means that assure the preservation of the product, such as protective gas, oxygen removal, and so on. *Smart* packages are also more common: The packaging includes an indicator for additional safety, with which one can follow the state of the product, such as temperature, leaking, spoilage, and so on.[8]

2.2 Distribution Function

Packaging helps loading, collection, and transport of the product. Distribution of bulk and liquid products is virtually impossible without packaging. Protective packaging such as bubble wrap or foam peanuts ensures safe journey. Corrugated paperboard and polystyrene foam hold expensive electronics equipment securely in their cartons and cushion them against falls, shifts, and bumps. Prior to loading onto ships, trucks, or planes, these cartons are stacked on pallets and wrapped with a sheet of self-clinging stretch wrap. This very strong, yet thin, film stabilizes the load, keeping it from shifting and falling. Fewer falls mean reduced damage and breakage, keeping both waste and related disposal costs to a minimum.

Fragmentation of consumer markets is considered one of the major challenges of the future of packaging. Packages should function both in the traditional and new channels of distribution, such as via the Internet. In the latter case, the package must protect the product delivered in the same transport package together with other products that may require different storage temperatures.[9]

2.3 Household Function

Some packages directly enhance consumption or further preparation of the product. Probably, the most famous example is the *TV dinner*, which allowed meals to go from the freezer to the oven to the table. Later, the metal tray was replaced by a plastic one, permitting even faster food preparation in the microwave oven. Many packages make it easy for us to use the products they contain (e.g., squeezable bottles, reclosable liquid board containers, plastic bottles with handles, and pop-up dispenser tops).

A change in social trends has been noted in Finland. Although home-cooked meals still hold value, few women can afford the time it involves on a daily basis. Because of the growth in jobs held by women in the professional sector, after a busy working day, convenience calls for pre-prepared food. However, the social aspect of the family spending time together is still significant.[8] Interviews conducted in Finland led to the conclusion that consumers anticipate growth of take-away dining in the future, which will increase the demand for convenience packages in which the food can be delivered, heated, and served by the consumers.[9]

2.4 Intermediate Function

The intermediate function of packaging is very important in modern marketing. The product is offering itself, and promotes the meeting with the purchaser. The package takes over the role of the sellers, helps to make a favorable impression, aids identification, and stimulates purchase.

2.5 Advertising Function

Today, it is universally acknowledged that packaging decisions can have a significant impact on sales.[10] A visually pleasing package attracts attention, which is important in an increasingly competitive environment. Generally speaking, a new, more appealing, and/or visually effective packaging system is unlikely to immediately change the well-established shopping habits of people who do not buy the brand. Instead, the impact is more subtle: A new design may drive nonusers to take a second look at the brand, shift their perceptions somewhat, and perhaps lead them to consider it as an acceptable alternative. Above all, the package offers information about the content, the product itself. It is a message of the manufacturer to the consumer. Food packages contain preparation instructions; they also provide nutritional, dietary, and ingredient data. Packages of all types include safety and storage information, plus any necessary warnings.

2.6 Image-component Function

The brand, trademark, and other media elements are integral parts of a package, promoting the creation of an image. One of the most recognizable packages in the world is the Coca-Cola bottle; its shape is designed to be recognized even in the dark by touch.

2.7 Value-forming Function

From an economic point of view, packaging has a very important role in the sales process. Without packaging, many products, especially bulk products, cannot be sold to the customer. For instance, a barrel full of toothpaste would be very difficult to sell, but portioning it into squeezable tubes makes it possible to put on the market. Thus, packaging creates value for the toothpaste. The role of packaging as a marketing tool will be strengthened in the future.[9]

2.8 Waste-Reduction Function

Packaging reduces waste in two important ways. First, it keeps food from spoiling and having to be discarded. In the United Kingdom, the proportion of food that is unfit for consumption before it reaches the consumer is 2 percent, whereas in developing countries, where packaging is not as widespread, this loss can be in excess of 40 percent[11] Second, packaging permits foods to be processed more efficiently. For example, 50 years ago, people went to a butcher for chicken. For every 1,000 chickens sold, the butcher threw away 750 kg of feathers, viscera, and other waste products. Today, chicken producers ship the edible parts to market and process the rest into byproducts such as animal feed and fertilizer. It takes only about 7.7 kg of packaging to ship those 1,000 chickens to grocery stores. That 7.7 kg of packaging permits the 750 kg of waste to be used efficiently rather than merely thrown away.[4] As paper, metal, and glass packaging increase, food waste decreases. Increases in plastics packaging create the greatest reductions in food waste.[12] Overall, for every 1 percent increase of packaging, food waste decreases by about 1.6 percent.[13]

It is important to note that while increasing the product-per-package size, one can save on the packaging material, as well as on the unit price of the product for the consumer. This solution is not always generally applicable. Recent trends in Finland point at the increasing number of one- and two-member families that prefer smaller packages.[9] Buying a large package also has the risk that the product will not be consumed within warranty time and thus will be disposed of. Although one ought to aim at overall waste reduction, packaging material cannot be saved to the detriment of product spoilage and discard.

3 PACKAGING MATERIALS

The first packages served as containers, and their principal function was to hold food and water. They were probably taken directly from nature, such as leaves and shells. Later, containers were fashioned from natural materials: wooden logs, woven plant fibers, pouches made from animal skins. The next containers developed by early societies were clay pots, which date back to 6000 B.C. The first known pottery is from Syria, Mesopotamia, and Egypt. Besides being functional, clay bowls, vases, and other vessels were an artistic medium that today provide important clues regarding the culture and values of ancient peoples. Although no longer a significant packaging medium, clay still continues to have a major artistic value.[14]

Today, a wide range of materials are used for packaging applications, including metal, glass, wood, paper or pulp-based materials, plastics, ceramics, or a combination of more than one materials as composites. They are applied in three broad categories of packaging:

1. *Primary packaging,* which creates sales unit and is normally in contact with the goods
2. *Secondary packaging,* or collection packaging such as cardboard boxes, wooden crates, or plastic containers used to carry quantities of primary packaged goods.
3. *Tertiary packaging,* or transport packaging that is used to assist freight transport of large quantities of goods, such as wooden pallets and plastic shrink-wrap

3.1 Paper/board

Paper manufacturing uses cellulose fibers that form bonds with each other. Carton boxes are very effective and versatile packaging media and provide protection against contamination and breakage. It is easy to print on, collect into secondary packages, and pile on shelves at the point of sale. After use, carton is 100 percent recyclable and is often used as raw material for the manufacture of packaging papers and boards. Corrugated board is made by combining several layers or paper, with the inner layers called fluting. The cardboard box is a very versatile and widely used packaging medium. It is the most broadly used material in secondary packaging.

Proper management of forests can guarantee a continued supply of wood for paper and other purposes. Most of the trees used to make paper are trees planted explicitly for manufacturing paper. Thus, less paper usage means fewer trees planted by commercial harvesters. Moreover, harvesting and planting trees may have other environmental benefits. Trees consume large amounts of carbon dioxide. For example, U.S. forests could be consuming as much carbon dioxide as the United States emits, if they were growing forests. Mature forest ecosystems made up of combination of growing trees and dead material, give off as much carbon dioxide as they consume.[13]

3.2 Glass

Glass continues to be an important packaging material. It was first used in Egypt • Q2 and Babylon as long ago as 2500 B.C. when it was formed into jewelery• and small containers. The major event in the history of glass was the discovery of blow molding. Around the first century A.D., Syrian artisans found that molten glass could be blown into different shapes, sizes, and thicknesses. This eventually led to the mass production and wide availability of all types of glass containers.[15]

Glass is manufactured by fusion at very high temperatures (up to 2500°C) of naturally occurring minerals such as sand (SiO_2), soda ash ($NaCO_3$), and limestone ($CaCO_3$). On the one hand, cullet melts more readily, and the melting does not significantly degrade the materials. No physical difference can be measured between virgin and recycled grades. This alone makes glass recycling sensible. On the other hand, supply of sand is plentiful. 27.72 percent of the Earth's crust is made up of Si, the second in quantity after oxygen. Soda ash is rare and expensive, and is mainly produced from NaCl. Na as an element makes up 2.83 percent of the Earth's crust, and also is largely present in ocean matter. Limestone is abundant, and relatively inexpensive. Ca makes up 3.83 percent of the Earth's crust. Approximately 70 percent of total glass consumption is used for packaging purposes.[16]

3.3 Steel

Although metals such as copper, iron, and tin began coming of age at the same time as clay pottery, it is only in more modern times that they began to play a unique role in packaging. In many cases, metal containers proved to be stronger and far more durable than other materials.[17]

Steel is smelted from naturally occurring iron ore at around 1400°C. Iron alone is in abundant supply, makes up 5 percent of the Earth's crust. Iron is scarcely known in a pure condition, but is used in impure form, containing carbon. If low carbon concentration is required, steel must be purified. The carbon content of the steel is burnt out at temperatures of around 1550°C. Alloys for special applications require further processing and adding minerals such as chromium, nickel, tungsten, vanadium, and titanium for enhancing the physical and/or chemical properties. For packaging purposes, the *tinplate* is used: a cold-reduced low-carbon sheet protected by coating on both sides with a very thin layer of tin.[16] The British Navy began using tin cans widely in the early 1800s, and canned food began appearing in English shops by 1830.[17]

The *tin-free steel* is made corrosion-resistant by a very thin coating of chromium phosphate, chromium or chromium oxide, or aluminium. Steel use for packaging purposes makes up around 5 percent of the total world steel consumption. Tin and chrome are in rather short supply; tin makes up 0.4 percent, and chromium 0.01 percent of the Earth's crust, but because amounts used are so small, supply does not appear likely to be a problem in the near future.[16]

3.4 Aluminum

Tin and steel cans became widely accepted during World War II. This rising demand also led to rising costs of tin plate, causing can producers to look for an economical replacement. Aluminum filled this need and, according to the Coors Web site, in 1959, the Adolph Coors Company became the first American brewer to package beer in an aluminum can.

Different alloys and gauges of aluminum foil are used for different packaging applications, with most alloys including up to around a 3 percent mix of iron, silicon, and manganese, with tiny amounts of copper occasionally added for extra strength. The thinnest foil used for wrapping chocolates may be only 6 microns thick, with household wrapping and cooking foil between 11 and 18 microns, foil for packaging lids between about 30 and 40 microns, and foil for containers generally between 40 and 90 microns.[18]

Aluminum itself is plentiful, makes up 8.13 percent of the Earth's crust—but never as free metal but as silicates, from which the extraction is expensive. Commercial production of aluminum is from bauxite. Aluminum from bauxite is smelted in electric arc-furnaces on temperatures of around 800°C. Thus, the overall energy consumption of aluminum manufacture is very energy demanding. However, the main aluminum smelting plants are in countries such as Norway, Canada, and Scotland, where renewable resources are used for energy production (water power). Again, near-term material shortages seem unlikely, mostly due to the ready recyclability of aluminum. About 25 percent of total aluminum consumption is used for packaging purposes.

3.5 Plastics

Plastics are macromolecular polymeric materials. The majority of plastics in packaging are thermoplastic organic polymers, that is in the main chain have only carbon-carbon bonds, such as polyolefines, polystyrene (PS), polyvinyl-chloride (PVC), but there are semiorganic polymers, as polyamide (PA), and polyesters (PE). Plastics for packaging are in the form of foils (up to 0.2 mm thick), and sheets (above 1 mm). Foils are used for packages with flexible wall as bags, and sheets are used for rigid wall packages.[19] The five largest volume polymers used in packaging are polyethylene, polypropylene, polystyrene, polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Packaging is the major use for polyethylene and polypropylene. High-density polyethylene (HDPE) is used in applications such as containers, milk and detergent bottles, bags, and industrial wrapping. Low-density polyethylene (LDPE) is used for pallet and agricultural film, bags, coatings, and containers. Polypropylene is employed in film, crates, and microwavable containers. Polystyrene finds use in jewel cases, trays, and foam insulation, while PET is used in bottles, film, and other food-packaging applications.[20] Plastics are also increasingly used in secondary and transport packaging; re-usable plastics boxes and trays are replacing single-use cardboard and wooden boxes.

The role of plastics in packaging is substantial. Plastics represent 20 percent by weight of all packaging materials and are used to package 53 percent of all goods. In comparison, glass, which also represents 20 percent of all materials, packages only 10 percent of all goods[2] Plastics, for the most part, are based on petroleum and natural gas, but plastics' production accounts only for about 2 to 4 percent of overall consumption of oil and natural gas.[16] The packaging industry is one of the major users of plastics; however, plastic packaging often accounts for just 1 to 5 percent of the product's overall weight. In Western Europe, about 37 percent of plastics are used for packaging purposes. Figure 2 illustrates the plastic consumption by industrial sector in Western Europe in 2003.[21]

Plastics have a negative image due to their fossil content. A comparison between plastics and gasoline based on their crude oil equivalent reveals that the average per-capita plastics consumption in Western Europe equals approximately 32 liters of gasoline. In the United States, an equivalent amount of gasoline used for the production of all plastics for packaging would equal a mere 19 days of automotive travel.[22] This suggests that only a 5 percent improvement in gasoline mileage would offset the total amount of energy required for the production of plastics into packaging markets. This would appear to be a relatively small improvement to enjoy the benefits of plastics.

3.6 Composites

Composites are a combination of materials used for enhancing the content protection. Two or more separate layers materials are joined, most frequently paper

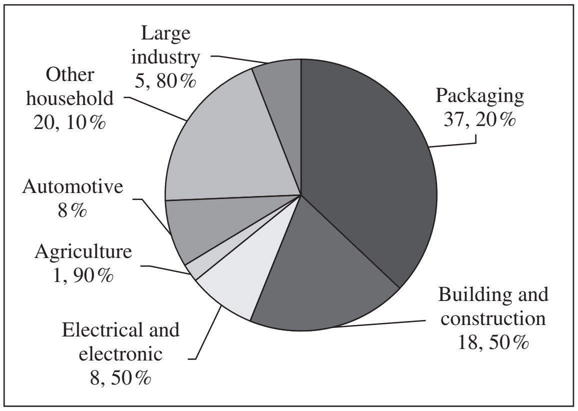

Figure 2 Plastic consumption by industrial sector in Western Europe in 2003. (From Ref. 21.)

or board, and aluminum foil or plastics. The use of combinations has advantages from technological and economic point of view. Often their use is the only technologically feasible solution. Flexible and semi-rigid-wall packaging materials are produced by the following methods: coating, laminating, and co-extrusion. The most commonly used combined packaging materials follow.[19]

Paper–plastic Composites

Paper–plastic composites are the most commonly used combination. The paper gives rigidity, and the plastic gives low permeability and heat sealability. All the paper–plastic combinations can be used with board; the most commons are the cardboard–PE and the board–PP combinations.

Cellophane Composites

To reduce the water absorption of cellophane, and to improve its resistance properties and sealability, the most frequently used method is lacquering. Cellophane can also be combined with several plastics by extrusioning or laminating.

Plastic–plastic Composites

The concept of modern multilayer packaging means that there is a minimum use of plastic material, because various characteristics can be combined into one thin packaging film. The most widely used plastic for combination is PE. The PA–PE combination processed by coextrusion has a good gas resistance. It can be deep drawn, and its fat resistance and flexibility are suitable, too. These combinations are very widely used for vacuum packages. In addition, the PET–PE combination is heat resistant, and the PE–PP is sterilizable. As an illustration of the effectiveness of plastic composites, Williams presents multilayer plastic film used for sausage packaging (about 0.1 mm in thickness) containing a layer of polyethylene (an excellent barrier to moisture) and a layer of polyamide (an excellent barrier to oxygen).[7] If polyamide alone was used, the film would need to be at least five times thicker to provide the same barrier to moisture. If the film was pure polyethylene, it would need to be 100 times thicker to provide the same barrier to oxygen. What is more, the multi-layer film offers excellent puncture and abrasion resistance, as well as heat sealability.

Composites add substantial savings in materials and energy, considerably lower costs, and much less packaging waste. Saving fuel also means lower emissions during transportation. Williams's estimate for Germany indicated that if the 32,000 tons of multilayer packaging used in 1991 should be substituted by other materials, 71,000 tons of paper, 100,000 tons of glass, 110,000 tons of steel, and 9,000 tons of aluminum would be needed, a total of 293,000 tons altogether.[7] Not only it is nine times more packaging weight, but four and a half times more energy would be needed to produce the packaging, and the cost of packaging would increase three times. Going a step further, even assuming 90 percent collection rate, 90 percent of that quantity to be sorted and 95 percent of sorted material recycled would leave 67,000 tons of waste for disposal by other means. Even if certain amounts of the substitute materials would be combusted—such as paper—there would be 36 percent lower energy recovery than with plastics. Williams concluded that multilayer plastic packaging minimizes the quantity of waste destined to landfill. It uses less energy to produce, its energy content can be efficiently recovered, and it is a cost-effective solution.

3.7 Degradable Plastics

In nature, all organisms re-enter the carbon cycle by degradation into basic elements that serve as a foundation for development and continues sustainment of life. This same logic leads to the development of degradable plastics: To design and engineer strong, lightweight, useful disposable plastics that can break down under environmental conditions in waste disposal systems to products that can be utilized by the ecosystem (carbon cycle).[23] One contribution to a more sustainable recovery of plastic waste might be the use of compostable plastics.[24] The American Society for Testing and Materials (ASTM) provides a definition of degradable plastics:

- *Degradable plastics.* are plastic materials that undergo bond scission in the backbone of a polymer through chemical, biological, and/or physical forces in the environment at a rate that is reasonably accelerated, as compared to a control, and that leads to fragmentation or disintegration of the plastics.
- *Biodegradable plastics.* are those degradable plastics, where primary mechanism of degradation is through the action of micro-organisms such as bacteria, fungi, algae, yeasts.

- *Photodegradable plastics*. are those degradable plastics where primary mechanism of degradation is through the action of sunlight.
- *Biodegradation of plastics*. is conversion of all constituents of a plastic or hybrid material containing plastics to carbon dioxide, inorganic salts, microbial cellular components, and miscellaneous byproducts characteristically formed from natural materials.

There are specialized applications where biodegradable materials have an edge, such as in conjunction with organic waste. According to Reske,[24] compostable plastics and packaging are ready for the market. In many applications in the food sector (especially for fruit and vegetables), increasing amounts are being used in a number of EU countries and worldwide. Items that could help avoid floating marine litter would be invaluable.

3.8 Wood

Wood as packaging material is largely used for transport packaging, in the form of crates and pallets. Pallets are a universal and critical part of product transportation. Forty percent of all hardwood lumber produced in the United States is reported to have been made into solid wood packaging. The pallet industry uses approximately 1.4 billion board feet of hardwood lumber and 2.1 billion board feet of softwood lumber for the production of 400 to 500 million solid wood pallets annually.[25] While the amount of new wood pallets manufactured increases slightly, in the same time the percentage of hardwood used is reduced and the recovery of pallets increases.[25]

4 CONSUMPTION OF PACKAGING MATERIALS

The average household buys goods packed in 190 kg of packaging, using 7 GJ energy each year. Packaging is typically 9 percent of the weight of the packaged product.[2] Table 1 summarizes the package weight to product weight percentage for some consumer goods.[26]

The most effective packages, those that contribute only 1 to 10 percent of the packed product's overall weight, are paper, plastics, or composites. From 11 to 20 percent, the fairly effective packages include plastic and aluminium packages. In the category of 21 to 40 percent, the less-effective packages, we have mainly large volume, light weight products (cereal flakes), liquid goods in more sophisticated, rigid-wall plastic containers (roll-on deodorant, dishwasher detergent), and tin-canned goods. From 40 percent up, the "ineffective" packages include glass packages and extremely low-specific-weight goods, such as deodorant spray, and goods portioned into extremely small and light quantities, such as tea, seasoning, and pills. This would indicate that a move toward more effective packaging options requires the use of flexible wall packages, plastic-plastic, or paper-plastic combinations, avoids low-specific-weight products and goods in extremely small

Table 1 Percentage of the Package's Weight, Compared to the Packed Product

Package Weight to Product Weight Ratios (%)	
1–10%	
1	500 g of pasta in PE bag
	61 g bar of chocolate in plastic wrapper
2.7	1 l milk in paper+PE box
3	1 l soft drink in PET bottle
3.3	1 kg of coffee in brick pack
3.5	1/2 kg of meet on foam tray
4	0.33 l soft drink or beer in aluminium can
	1 l ice-cream in HDPE box
5	fruit juice in aseptic box
	250 g of cold cuts vacuum packed
5.3	2 dl yogurt in plastic cup
5.29	bag of potato chips
6.6	400 g of margarine in plastic tub
	150 g of cold cuts vacuum packed
6.7	1 l ketchup in plastic squeeze-bottle
7.4	10 eggs in pulp tray
9	bar of soap in paper box
9.5	fabric softener in HDPE bottle
11–20%	
11.9	85 g cat food in aluminum pouch
12.4	1/2 l oil in plastic bottle
13.4	500 g of canned food
18.5	2 dl of shampoo in plastic bottle
21–30%	
23	400 g cereals in PP bag and paper box
25	150 g of canned food
31–40%	
34	deo roll-on in HDPE bottle
40	150 g cereals in PP bag and paper box
49	1 l dishwasher liquid
41–60%	
53	0.3 l glass bottle of beer or soft drink
56	deodorant in spray bottle
57	150 g jam in glass jar

(*continued overleaf*)

Table 1 (*continued*)

61–100%	
68	0.5 l salad dressing in glass bottle
74.5	100 tablets in PS bottle and carton box
80	0.5 l oil in glass bottle
>100%	
160	a box of 25 tea bags
588	tablets in blister package and paper box
611	20 g of seasoning in glass bottle

Note: From Ref. 26.

Table 2 Availability of Packaging Raw Materials

Packaging Material	Raw Material	Fossil Resource	Renewable Resource	Overall Resource
Paper/board	Wood, natural fibers	Nil	All	Very abundant
	Auxiliary chemicals	All	Nil	
Metals:				
Iron	Iron ore, scrap iron	About half	About half*	Limited
Tin chromium	Tin and chrome ores	Nearly all	Insignificant*	Severely limited
Aluminium	Aluminium ore Scrap	Majority (but plentiful)	Minority* but growing	Moderately limited
Glass	Sand, soda	Majority (but abundant)	Minority* but growing	Abundant
Plastics	Crude oil (now)	Almost all	Little	Moderately limited
	Biomass (wood sugar)	Nil	All	Very abundant
	Auxiliary materials, e.g. N, Cl, S, O	Some, but abundant	Some	Very small factor, no limitation

Note: From Ref. 27. *Recycling

portions, and uses only refillable glass. The availability of all packaging materials is summarized in Table 2.[27]

5 ENERGY USE

Packaging materials use energy in their manufacture and distribution, and contribute to the energy required for transporting products. Energy input is required

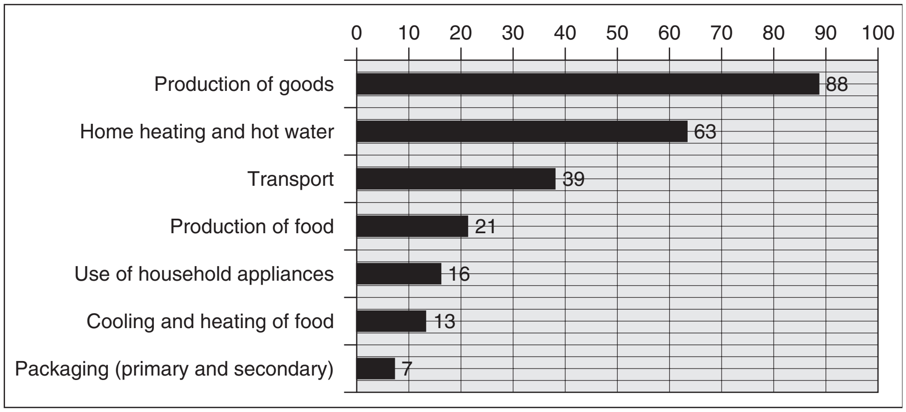

Figure 3 Energy consumption of household activities (GJ/household/year). (From Ref. 2.)

in several ways to produce and distribute packages. First, energy is used in converting the basic raw materials into packaging raw materials. Second, energy is used to convert the packaging materials into packages. Generally, all stages take place in different geographical locations. Recycling systems add to this energy demand, with further transportation need and processing of discarded packages. Notwithstanding, studies show that the household activities with the highest environmental impact are:[2]

- Production of food and goods
- Home heating and hot water
- Transport
- Use of household appliances.

As Figure 3 illustrates, the energy consumption of packaging is relatively small. From the different packaging materials, aluminium and glass manufacture consume the most energy. Aluminium manufacture uses large amounts of electrical energy in refining the metal from ore. Smelting of one ore batch of around 800 kg takes 3 to 4 hours. Glass manufacture, apart of being an energy-intensive, high-temperature process, also contributes to large transportation costs due to its heavy weight. The practice of refilling is also very energy intensive due to high transportation distances from numerous shops to refill centers. Plastics use primarily petroleum and natural gas, both for the energy needed in manufacturing and for the content of the material itself. It is estimated that around 2 to 4 percent of all petroleum consumption is used for plastics manufacture.[16]

6 ROLE OF PACKAGING IN POLLUTION

6.1 Litter

Litter constitutes only a minor part of total wastes, but it is of widespread concern. It is an unpleasant sight, constitutes a hazard to many animals, and is a possible health hazard to humans. Litter is often equated with packaging. Packaging materials (glass and plastic bottles, cans, paper cups, paper and plastic wrappings) are indeed the main constituents of litter. Excluding unofficial dumps, the proportion of packaging is usually a quarter to half by weight, but because of the low bulk density, packaging is often the majority by volume. Packaging litter constituted 11.91% of all litter in Ireland in 2006 and is the third largest component after cigarette and food related litter.[27]

The effect of plastics litter on the marine environment is also of particular concern. It originates from both land and sea sources, and the debris is of three types: fishing gear, such as nylon lines, buoys and nets; packaging bands, straps, and synthetic ropes; and general litter, such as bags, bottles, and plastic sheeting.[28] The UN Group of experts on the Scientific Aspects of Marine Pollution (GESAMP) concluded the following: chemical contamination and litter can be observed from the poles to the tropics and from beaches to abyssal depths—in short, throughout the whole length, breadth, and depth of the world ocean. The Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL), which came into force in December 1988, makes it illegal for vessels of the 31 ratifying nations to dispose "into the sea . . . all plastics, including but not limited to synthetic ropes, synthetic fishing nets, and plastic garbage bags."[29]•

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6.2 Water Pollution

Pollution arises from wastewater discharge of some packaging material manufacturing or related activities. One of the basic water-polluting activities is paper production, releasing biological oxygen demand (BOD), chemical oxygen demand (COD), volatile suspended solids (VSS), and total suspended solids (TSS). In addition, the manufacture of miscellaneous materials used in packaging, such as adhesives, coatings, and inks is a source of hydrocarbon pollution. The discharge of cooling water from electricity generation in turn causes thermal pollution. Subjects of concern are also accidental emissions during production, or processing of packaging materials, especially the drainage of fire-fighting activities during accidental fires.

Finally, water pollution arises from landfill leachates, although the causes of leachates are, rather, the remains of products on the packages. Historical packaging can also be the source of organic plasticizers for PVC, or lead and cadmium from pigments.[16]

6.3 Air Pollution

The main source of air pollution is the packaging material manufacturing process. Some of the emissions, such as vinyl chloride, CFC, and hexane can arise from accidental fires, or waste-incineration activities. Direct packaging-related emissions arise from landfill sites, as a consequence of decomposition of wood and paper, releasing CO_2, and methane. In addition, CO_2 emission arises from glass and steel manufacture.

Packaging-related sources of pollution are also electricity generation (CO_2, SO_2, NO_x emissions) and transportation-related emissions (e.g., CO_2, SO_2, NO_x, dust, hydrocarbons). It is increasingly important to take into account the transportation-related emissions, especially when considering reuse, or recovery.[16]

6.4 Solid Wastes

Packaging-related solid wastes arise already at extraction and processing of raw materials. These wastes often end up in landfill sites. Further preconsumer and postconsumer wastes have to be distinguished. The general public is conceiving of only the postconsumer solid wastes, although that is only a part of all packaging-related wastes. Most of the preconsumer packaging waste of packaging material, or package manufacture is, however, recycled in house. The nonrecyclable part of preconsumer packaging wastes is disposed.

Recovery, and in particular recycling of postconsumer packaging wastes, does not stop further generation of wastes. First, not all the collected material is recycled and, second, the product made from the recycled material will end up being a waste sooner or later as well. As for incineration of postconsumer packages, it may mean a volume decrease of 20 to 40 percent.

An indirect packaging-related solid waste source is slag for producing the electricity that was consumed by packaging activity.[16]

7 ENVIRONMENTAL ASSESSMENT OF PACKAGING MATERIALS

The Danish minister of environment in 1988 announced that within a few years the manufacture and use of polyvinyl chloride (PVC) products had to be reduced as much as technically and economically possible due to their environmental impacts of production, use, and disposal. This preventive environmental policy was mainly based on the emission of hydrogen chloride and dioxins from waste incineration. A study of the technical, economic, and environmental consequences of a substitution was initiated by the National Agency of Environmental Protection. The goal was to collect background data for the upcoming negotiations between the environmental authorities and PVC-industry and manufacturers of PVC products in Denmark. The environmental assessment focused on PVC and 11 alternative materials, such as polyethylene (PE), polypropylene (PP), polyethylene terephtalate (PET), polystyrene (PS), polyurethane (PUR), synthetic rubbers (EPDM, CR and SBR), paper, impregnated wood, and aluminum.[30]

The assessment of each material was conducted in three steps. First, a screening of the life cycle for the potentially most severe impacts of the material was accomplished by consulting experts in material-, health-, and environmental sciences, and a chemical profile, including four to five chemicals or chemical groups

Table 3 Comparison of PVC with Alternative Packaging Materials

Material	Impacts
PVC	• Potential severe impact areas of exposure to the carcinogenic vinyl chloride monomer in the work environment and the discharge of dioxins in wastewater. • Exposure to vinylchloride, chlorine, or hydrogen chloride, heavy metals, phosgene, and dioxins generated in accidents (e.g., fires), or in the production and use of PVC • Incineration of PVC-containing waste generates hydrogen chlorine, dioxins and heavy metals that are emitted to the atmosphere, or contaminate incinerator ashes or filter residuals.
EPDH (ethylene-propylene-diene)	• Use of halogen-based flame retardants in special products as well as possible exposure to neurotoxic n-hexane and carcinogenic benzene at production and processing. *PS*:
PS	• Production requires more energy, than the production of PVC. Some typical products are expanded with CFC or azodicarbonamide (sensitising agent) with severe external and work environmental impacts, respectively.
Impregnated wood	• Manufacturing involves high exposure to wood dust, expected to be carcinogenic, and accidental releases of tributyotin (wood preservatives) constitute a major risk to the aquatic environment.
Paper	• Production is dominated by sulphate-mass and, in some countries, chlorine-based bleaching resulting in waste water strained with oxygen-consuming pollutants and chloroorganics, for example dioxins.
Aluminum	• Production of virgin aluminium involves very high energy consumption, and the work environment includes severe potentials of exposures to carcinogenic polyaromatic hydrocarbons (PAH's). • Approximately only one fifth of the raw material ends up in the final product, thus the production results in major amounts of solid waste and sludge to be disposed of.
PUR	• Implies occupational exposure to highly toxic isocyanides in the production, processing, manufacturing and in fires. • PUR is commonly expanded with CFC. • Halogen-based flame retardants are frequently used in the production of PUR.
Synthetic rubbers, CR(chloroprene), SBR (styrene-butadiene):	• Involve carcinogenic substances in the work environment of production and processing (vulcanisation). • CR may generate hydrogen chloride and dioxins when incinerated or burned.

Note: From Ref. 30.

characterizing the material, was established. Second, data on the key consequences were collected and evaluated from readily available literature and interviews with experts from Danish Technological Institute, the industry, and environmental authorities. Finally, the evaluation of each material was used to develop an impact profile for the material as such, and for each of the alternative materials a comparison to PVC was made. The results of the study are summarized in Table 3. In summation, from the alternative materials evaluated, *PE, PP* and *PET* proved to be environmentally preferable to PVC.[30]

8 RECOVERY OF POSTCONSUMER PACKAGING

8.1 Waste Packaging in Municipal Solid Waste

Packaging is required to give protection to a product until the last bit of the product is consumed. This would mean that most packages, especially the reclosable ones such as plastic containers, glass jars, are still in perfect shape when empty. They could still continue to be used for the same purpose as designed: containment, protection, and use of the product. Discarded waste packages are thus not necessarily useless; they just are not used anymore. The problem is not in the package itself, but in the possibilities. If there are no containers for separate waste collection, and there is no need for constantly rising amount of butter boxes, jam jars, and no possibility to burn part of the waste, then the only choice is to send the packaging waste to landfill, regardless of the environmentally consciousness of the consumer.[22] Some thin, lightweight packs may not be worth collecting for recycling because too much energy would be needed to collect and clean them. But they have environmental advantages in other ways, such as allowing more goods and less packaging to be packed in fewer trucks thus reducing transport pollution.[2]

Packaging is often cited as one of the reasons of rising amount of municipal wastes. In the United States the amount of municipal waste increased five times as quickly as the population over the period 1920 to 1970.[31] It is, however, not due to packaging only. The reasons of the growing amount of municipal waste are rising level of affluence, advent of build-up obsolescence, demand for convenience products, cheaper consumer products, changing patterns of taste and consumption, and, in part, the proliferation of packaging.[31]

Generally, it is estimated that packaging constitute one third of household waste. The other two components of high percentage are biogenic material at 30 and newsprint, 20 percent.[32] In the United States, the trend is similar. By volume, packaging constitutes up to 30 percent of household waste; by weight, about one-third is biogenic material and one-fifth is newsprint.[28] The importance of distinction between classification by weight or volume can be shown with the following examples: In Austria, packaging constitutes 30 percent of household waste by weight, and 50 percent by volume[33] Table 4 illustrates the amount of packaging waste (PW) related to municipal solid waste (MSW).

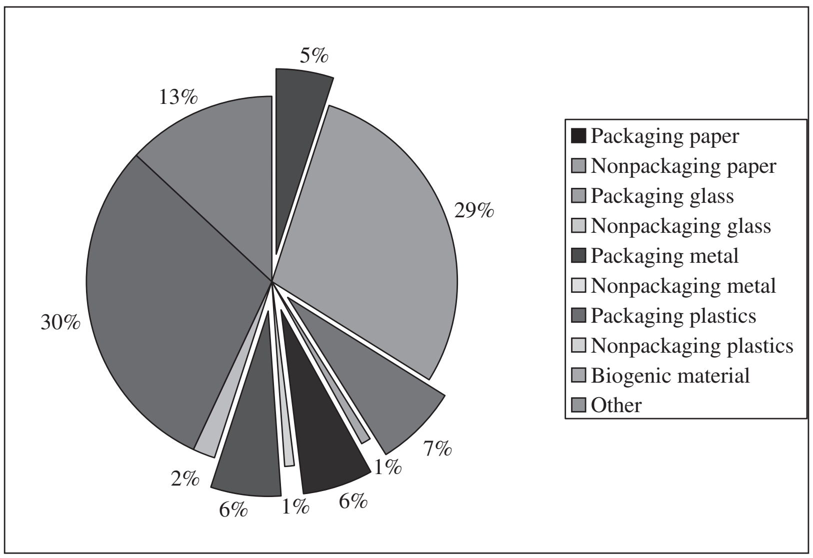
In the United Kingdom in the 1975 to 1995 period, although the volume of discarded packaging materials in the domestic waste bins has risen, but the weight remained approximately the same.[34] Most probably, this is due to lightweighting

Table 4 Packaging Waste Generation in Selected Countries and Communities

	Packaging Waste (million tonnes)	PW/MSW (%)	PW per capita (kg)
OECD	140.0	33	181
EEC	50.5	49	154
USA	56.8	27	210
Japan	20.0	41	163
United Kingdom	7.7	44	134
France	10.0	59	181
Germany	10.0	49	181
Italy	12.0	68	188

Note: From Ref. •

• Q4



• Q6

Figure 4 composition of garbage in domestic wastebaskets in UK (Portec .

of packages, and the widespread use of plastics. Figure 4 outlines the composition of garbage in domestic wastebaskets in the United Kingdom.

8.2 Packaging Waste Reduction

The most-effective way of reducing packaging wastes is lightweighting of packages. It combines the commercial benefit of lower unit cost with the improved resource efficiency. It is a result of improved packaging material and package manufacture, which allows the use of lighter, thinner-walled packages. An important way of lightweighting is also the product innovation as the introduction of concentrated, and dried products. There are, however, limits to lightweighting of individual packages, which could overweigh the benefits:[35]

- Increased amounts of secondary and transport packages, are needed.
- Thinner packages are more fragile and may result higher wastage.
- Inadequate product protection may lead to greater spoilage.

Reuse of packages also contributes to waste reduction. Refillable bottles are the best-known examples of reusable packages, but not the only ones. Refillable bottles are returned into the bottling plant in reusable crates; reusable crates are also traditional in bakery industry. Another application of reuse is the so-called *refill pack*. The consumer buys a sturdier reclosable container once, and further on purchases the product in lighter refill poach. With no need for an opening and reclosing device, the refill packages can be reduced to the minimum needed to protect and contain the product. It is a lightweight, space-efficient system that minimizes distribution costs and transport pollution while giving the consumer all the benefits of a durable and convenient container to use at home, the refill pack has many advantages.[36] Refill packs are attractive for the consumer for their lower price. Refill-pack systems also instill brand loyalty, a considerable marketing benefit for the company.

8.3 Choice of Waste Management Options

Nations are considering restrictions on packaging and controls on products in order to reduce solid-waste generation rates. Local and regional governments are requiring wastes to be separated for recycling, and some have even established mandatory recycling targets. Secondary and tertiary packaging materials are normally in larger quantities and have less material variation. Thus, they are relatively easier to collect and sort by wholesalers or retailers for recycling or reuse purposes. Primary packaging materials are not only more dispersed into households, they are also largely mixed, contaminated, and often damaged. Thus, they pose problems in recycling or reuse of the materials.[37]

Previously considered as a local issue, it is now clear that solid waste management has international and global implications. The European Community has been criticized for setting rigid recycling percentages for packaging materials. Isoaho argues that regulation based on material, product or source classifications are very difficult to manage, especially if they are too detailed at international level.[38] Conditions in the countries are different, citizens react in a different way. The international political supervision should remain to decide policies, to create general strategies, and to agree to standards of environmental effects and management quality. This implies focusing on energy and material policy, supervision instruments, and management environments rather than on, for example, recycling percentages or single products. Within countries there are different waste management regions, and within these, there are different collection areas characterized by waste generators, their density, and the specific waste stream volume.

8.4 Package Recycling

The concept of recycling to conserve resources is based on the assumption that a recycling requires fewer raw materials and less energy, and generates fewer emissions into the environment, than manufacturing new material. However, for recycling to be environmentally beneficial, the effects of the collection, transportation, and reprocessing operations must be less harmful than those resulting from the extraction and processing of the virgin raw material that the recycled product replaces.

Germany has long been regarded as the most advanced country in Europe in packaging recycling. The Law on Waste Management (Abfallgesetz) passed in 1986 laid the foundations for later German packaging waste-management strategies. The law gave the environmental ministry extensive rights, and resulted in the packaging Directive (Verpackungs-verorderung) in 1991. The ordinance obliges the producers and retailers to take back and dispose of the packaging waste in an environmentally sensible way. In order to take care of the packaging waste, which now had to be dealt with separately, the Duales System Deutschland GmbH (DSD) was set up. The concept behind the DSD is that the organization gives various packaging materials the right to bear the "green dot" and thus be recycled by the disposal network set up by the DSD. Companies that want their packages to bear the green dot must first pay a per-package fee to the organizations. DSD has a rather controversial and difficult history, attacked by the public, environmental, and trade organizations, political parties, and the media. In its early years it was on the edge of bankruptcy. It has received a lot of bad press and political criticism for exporting collected waste abroad to countries such as Indonesia and China instead of recycling them in Germany. Hanisch quotes that, at that time, Germany faced a severe landfill shortage, with packaging waste amounting to a significant percentage—30 percent by weight and 50 percent by volume—of the nation's total municipal waste stream.[39] However, according to Rathje and Murphy, the claim that packaging waste is a major constituent in landfills is simply a myth.[40] Over a period of five years, a U.S. "Garbage Project" excavated 14 tons of waste from nine municipal landfills. This project sought to address the claim that fast-food packaging and polystyrene foam were the major elements of American trash. They found that out of the 14 tons of excavated waste, 1 percent was polystyrene foam, and less than 0.5 percent was fast-food packaging.[40] Similarly, it was calculated that, in Finland, packaging waste constitutes approximately 1.5 percent of all landfilled waste[41]. Viewed in such a context, packaging waste does not appear to be overflowing landfills.

The European Parliament and Council Directive 94/62/EC on Packaging and Packaging Waste ("Packaging Directive") first came into force at the end of

1994 and has both environmental and single market objectives. The Packaging Directive aims to harmonize the management of packaging waste in the EU and tackle the impact that packaging and packaging waste have on the environment. Although the primary objective is to increase the recovery and recycling of packaging waste in a consistent way in all member states of the EU (so as to avoid barriers to trade), priority is also given to reducing the amount of packaging used and the reuse of packaging. The Packaging Directive sets member states mandatory recovery and recycling targets, the first of which were to be met in 2001. A revised Packaging Directive (2004/12/EC) was published in February 2004. It sets new recovery and recycling targets, as a percentage of all packaging waste to be met by December 31, 2008, illustrated in Table 5.

8.5 Recycling of Plastic Packages

Plastics packaging wastes present a number of challenges in terms of recovery due to the composition and diversity of the plastics used and the fact that mixed waste is often dirty or contaminated. First, the two different ways of recycling need to be distinguished: *mechanical recycling* and *feedstock recycling*. At mechanical recycling, the plastic waste is used as a secondary raw material to replace primary (virgin) plastics. Water pipes are produced from collected bottles, detergent, and fertilizer bottles, can be manufactured by mechanical recycling. Waste plastic films can be recycled into waste bags, or cable coatings In Western Europe good progress has been made, and most countries have increased their recycling rates. However, challenges still remain for many countries to meet the minimum recycling target of 22.5 percent, set by the European Packaging Directive. As a whole, mechanical recycling of post-user plastic packaging waste increased by 12.6 percent in Western Europe in 2002—in the meantime, packaging waste increased by just 3.5 percent. Consequently, the recycling rate went up from 20.5 percent in 2001 to 22.4 percent in 2002. In terms of the total recovery (recycling

Table 5 Revised Targets of the Packaging Directive (2004/12/EC)

The new targets are:	
Minimum recovery	60%
Recycling	55–80%
Minimum material-specific targets are:	
Glass	60%
Paper/board	60%
Metals	50%
Plastics	22.5%
Wood	15%

and energy recovery) of plastic packaging waste in Europe, comparing recovery in 2001 and 2002, the rate increased from 49.4 percent to 52.5 percent as a result of an increase in mechanical recycling and countries adopting best waste collection practices.[21]

There are several limits to plastic packaging recycling. Most restrictive are the technical limits. Due to the aging of the material and pollutants such as additives, colors, and dirt, recycled postconsumer plastics can never completely replace virgin material.[42] Citizens are generally eager to recycle plastics; however, in Finland, for example, local authorities perceived plastics recycling as problematical due to difficulties in separating different types of plastics.[43] A survey of developmental needs in waste management by the Technological Research Centre of Finland concluded that the realisation of plastics recycling is not meaningful when plastic waste is collected from municipalities.[44] Due to the restrictive technical limits, mechanical recycling is not the major route in packaging plastics waste management and recommend feedstock recycling such hydrogenation, pyrolysis, gasification, or others.[42]

8.6 Feedstock Recycling

The expression *feedstock recycling* is used for methods when the waste plastic's energy content is used by other methods than simple combustion, also referred to as *tertiary polymer recycling*.[45] These processes are not recycling by the classical understanding of the word. Since plastics are generally high-caloric-value products ranging from approximately 18,000 to 38,000 kcal/kg, using them for their energy alone or for related chemical production could be an alternative option.[46] For example, one could take the view that the crude oil content of the plastic is temporarily used by the plastic to serve as a package. After its function as a package has been served, the fossil energy could be used. Feedstock recycling includes the following methods:

Use in Blast Furnaces

A potential use of plastic waste is in blast furnaces as a reducing agent to withdraw oxygen from the iron ore, substituting heavy oil currently used. Since the use of solid plastic waste involves significant additional investments, the main interest is in using plastic oil obtained from the fluidized-bed pyrolysis process. The plastic oil does not contain sulphur, so its use involves process-technical advantages, as sulphur variations in fuel oil can be regulated with the aid of plastic oil. Plastic oil may also substitute for heavy fuel oil, either as such, or mixed with fuel oil, if the waste plastic does not contain chlorine. Plastic types produced from polyethylene and polypropylene were found to be best suited for the production of plastic oil. In autumn 1999, blast furnace tests were carried out in Raahe Steel factory in Finland, and plastics were melted successfully in heavy fuel oil, without any additives.[47]

Thermolysis

Thermolysis is performed at a temperature lower than 500°C and in the absence of oxygen.[45] Compared to incineration, *thermolysis* is considered as a viable alternative to treat MSW, especially in regions with a low population density. At the end of thermolysis, the waste will have lost approximately 60 percent of its weight. As opposed to incineration, thermolysis does not produce slag. There remains only a mixture of carbonaceous solid fuel, metals, and minerals. The thermolysis process can be called thermolytic sorting, since it isolates the combustible organic compounds from the noncombustible ones (water, minerals, metals), and only the combustible ones are burned.[48]

Pyrolysis

Pyrolysis for the simultaneous generation of oils and gases can be convenient to obtain hydrocarbons and even recover crude petrochemicals, or to generate energy from waste plastics.[49] *Pyrolysis* involves heating of a feed in an inert atmosphere at a temperature ranging from 500° to 800°C, to produce three forms of energy: gas, liquid, or charcoal. Pyrolysis is an extremely versatile process, and the reaction products can be controlled by means of the type of process and the operating conditions. The main purpose is to convert biomass and waste into high-energy condensable *pyroligneous liquid*, which is much easier to manage than bulky waste. Pyrolysis is an endothermic (heat-absorbing) reaction. While at higher temperatures the gas yield increases, char yield is maximized at low heating temperatures.[50] Pyrolysis of high-PVC solid waste in a fluidized bed at low temperature gives a chlorine-free fuel for a fluidized-bed combustor (FBC), plus concentrated HCl. The process has thermal efficiency of approximately 36 percent, depending on the pyrolysis temperature and the PVC content. Hydrochloride recovery can be above 90 percent at a pyrolysis temperature of 310°C.[51]

Gasification

Gasification is, technically, a compromise between combustion and pyrolysis: It proceeds in reaction with air, oxygen, or steam at temperatures in the range of 700° to 1,000°C. It can be considered to be a partial oxidation of carbonaceous material leading, predominantly, to a mixture of carbon monoxide and hydrogen (rather than carbon dioxide and water produced by direct combustion), known as *synthesis gas* or *syngas*, due to its application in a variety of chemical syntheses.[50] These gases contain *chemical energy* that can be tapped as required. The advantage of this technology, over straightforward combustion, is that the lower bed temperatures employed in the process give good chances that problematical elements such as potassium, sodium, and chlorine can be retained in the ash.[52]

Hydrogenation

Hydrogenation, usually in the presence of catalysts, is the final method of feedstock recycling considered. In the process, the polymers are cracked in a hydrogen atmosphere at a temperature in the area of 400°C, and at a pressure of 300 bar. Compared to treatment in the absence of hydrogen, *hydrogenation* leads to the formation of highly saturated products, avoiding the presence of olefins in the liquid fractions, which favors their use as fuels. Moreover, hydrogen promotes the removal of hetero-atoms (Cl, N, and S) that may be present in the polymeric wastes.[50] The end product is a synthetic crude oil, which can then be used as a raw material by the petrochemical industry. Hydrogenation suffers from several drawbacks, mainly the cost of hydrogen and the need to operateunder high pressures.

8.7 Comparison of Mechanical and Feedstock Recycling

A study by the Association of Plastics Manufacturers in Europe (APME) assessed the environmental impacts of mechanical and feedstock recycling and energy recovery of waste plastics. It was compared in terms of consumption of resources and environmental emission pollution potential. The criteria of "consumption of energetically exploitable resources" and "contribution to the greenhouse effect" lead to the following order of preference for feedstock recycling and energy recovery processes:[53]

- Use as feedstock in blast furnaces
- Thermolysis to petrochemical products
- Fluidized-bed combustion
- Hydrogenation, together with vacuum residue oils
- Incineration in domestic waste incinerators
- Fixed-bed gasification, together with lignite
- Gasification together with lignite in the fluidized-bed

The first three processes reduce the contribution to the greenhouse effect in comparison to landfilling. All these processes reduce the eutrophication and acidification potential in comparison to landfill. The overall volume of waste produced was found least in the waste incineration. In summary, from an ecological point of view and on the basis of the comparative analysis of feedstock recycling and energy recovery, APME recommends the following recovery processes:[53]

- Use as reducing agents in blast furnaces
- Thermolysis to petrochemical products
- Fluidized-bed combustion

Mechanical recycling processes have ecological advantages over feedstock and energy recovery processes, if *virgin* plastic is substituted in a ratio of 1:1.[53] With this prerequisite, mechanical recycling processes reduce the consumption of resources and emissions in comparison to feedstock recycling and energy recovery processes. However, because of the aging of the material and presence of pollutants such as additives, colors, and dirt, recycled postconsumer plastics can never completely replace virgin material. As a consequence of the restrictive technical limits, Plinke and Kaempf believe that physical recycling will not be the major route in plastics waste management, and other routes must be applied. APME concurs, and asserts that if considerably less than 1 kg of virgin plastic is substituted by 1 kg of waste plastic, mechanical recycling processes no longer have an advantage over feedstock recycling and energy recovery processes.[53]

Notwithstanding, feedstock recycling is not widely used in Europe, and the amount of plastics recycled by tertiary method has been rather low and stagnant, while mechanical recycling has steadily grown since 1991.[54]

8.8 Glass Recycling

While the plastics industry is faced with a jumbled collection of mixed plastics types, which is their responsibility to sort, glass has been collected for a number of years and sorted by color, with very low levels of contamination. Despite both those factors, and despite the fact that governments everywhere are proposing measures to further increase glass recycling, the amounts of glass collected are giving rise to considerable problems. The EC Packaging Directive, and worldwide various national initiatives, require significant increases in the tonnage of packaging collected. Glass is recycled to save raw materials and energy and to reduce waste. The glass industry across Europe has always referred to the fact that an additional 10 percent of glass scrap (cullet) results in 2 percent energy reduction. The amount of energy used per kilo to make bottles dropped 11.8 percent between 1986 and 1990, which can be attributed to the increased recycling rate (11 to 26.3 percent) and general improvements in furnace technology. The glass companies, however, may not always get the full benefit of energy saving. The cullet may cause problems in the furnace and one of the possible solutions involves using that energy saving.[55] The glass industry has claimed that every tonne of cullet used in the manufacture of new glass saves the equivalent of 30 gallons of oil. However, the experience of the British Glass Recycling Company is that the extra handling involved with more cullet going into the furnace outweighs the energy savings.[56] Glass manufacturers whose production processes were designed for using virgin raw materials of a specified and predicable quality cannot easily replace those virgin raw materials with contaminated and nonstandard secondary materials. They will have to make modifications to their facilities. Contamination from paper, plastics, and the original contents of the jars and bottles does not offer any real problems. The cleaning processes for cullet use no water and very little energy. Aluminum and tin-plate caps have been more of a problem. The major problem, however, is caused by ceramics. They can escape detection, be broken up like glass, but then do not melt in the furnace. Also, the type of glass used for oven-safe dishes is chemically quite different from container glass and is not compatible with it.[55]

In Finland, glass is still perceived as *the* symbol of recycling; however, authorities find glass recycling the most problematic, due to its relatively low retail value, contrasted with high collection, transport, and treatment costs.[43] The raw materials for glass are cheap and rather plentiful. Processing facilities are sparse requiring long distance transport of collected cullet. Moreover there is an over-supply throughout Europe and North America, causing quantities of glass to be landfilled. In many countries there is more green glass collected than can be used for reprocessing, because of lack of market demand. As one way to use some of the surplus green cullet in America's northwest, a company in Portland, Oregon, has constructed a 3,000s foot-long recreational trail, The Emerald Path, which used *glassphalt* that is crushed glass-asphalt mix.[55]

8.9 Steel Recycling

Purchased scrap as industrial scrap or obsolete scrap makes up approximately 26 percent input in steel production. Use of postconsumer packaging material is problematic because of the contaminants. Organic residues burn out, producing fumes, and the tin coating is difficult to remove if dissolved, but it can be removed with electrolytic, or alkaline method. These methods are very costly, and due to low percentage of steel used in packaging, the income of tin is too low to make the process profitable. Tin left in the steel, up to 0.1 percent, does strengthen the steel, but above that amount it makes the steel more brittle. The major problem, however, is lead from solder. It has a low solubility, basically causes no problem in steel production, but penetrates through furnace bricks and may cause steel breakout. Moreover, it is toxic so it must be removed from the dust.[16]

8.10 Recycling Aluminum Packages

Aluminum is one of the success stories of recycling. The major fact in aluminum recycling is that approximately 95 percent of the energy needed to produce virgin aluminum is saved and 97% less water pollution is created by using reclaimed aluminum rather than producing new metal from ore.[34]

Recycling one kilogram of aluminium also saves up to 8 kilograms of bauxite, four kilograms of chemical products and 14 kilowatt hours of electricity. The recycling rate for aluminium cans is already above 90% in some countries such as Brazil and Japan, the European average is 52%, Norway being the champion with 93%. The average can coming out of a store is re-melted and back on the shelf within 6-8 weeks. (International Aluminium Institute) In some places, similarly to PET and glass bottles, aluminum cans have a deposit. Cans are dropped into re-vending machines, which spit out a receipt you can use in the shop. The deposit/refund system is generally welcome by shops, since it increases consumer goodwill.

8.11 Recycling Multimaterial Packages

A criticism against multimaterial packages is that they cannot be recycled, and monomaterial packages should be preferred. However, there are hardly any monomaterial packages on the market today. Glass packages have plastic and/or paper labels and nonglass closures; metal containers have polymer coatings on the inside to prevent product-package interaction, and are either lithographed on the outside or have a paper label. Even the traditional tinplate is a multimaterial package of steel coated with tin. Many plastic packages have labels made from paper or plastic, the latter frequently being a different polymer than the package itself. Most packages are thus multimaterial.

The most widely recognized multimaterial package is the aseptic package. *Aseptic packaging* means that a sterilized product (e.g., fruit-juice concentrates) is packed in sterilized conditions. This results in a considerably increased shelf life. The aseptic beverage carton consists of three materials: a central core of paperboard (typically 80 percent by weight) coated on the outside by a thin layer of polyethylene and on the inside by two layers of polyethylene with a very thin layer of aluminium foil in between. This use of multiple layers, also called *lamination*, makes the best use of the resources required to produce the carton by optimizing the physical properties of each material. No monomaterial could give the same performance achieved by these three materials in combination. This type of packaging saves energy, because a truck carrying filled cartons contains 95 percent product and 5 percent package.[58]

The aseptic beverage carton can be incinerated. The calorific value is 20.5 MJ/kg, approximately half of fuel oil. The carton not only releases a lot of energy during combustion, but it also burns cleanly. The thin layers of polyethylene become water vapor and carbon dioxide when burnt. If aseptic cartons are incinerated, the aluminium foil becomes aluminium oxide, a compound that occurs naturally in the Earth's crust. Beverage cartons can also be recycled by several different ways, including compressing them into chipboard and separating the different component materials to produce other products. In the latter case, the paper fibers are repulped in a hydrapulper. After 20 to 30 minutes, the paper fibers become separated from the polyethylene, and the aluminium foil remains trapped between the polyethylene layers. The separated fibers can be used to manufacture writing paper and household tissue. The remaining components can be individually recycled into raw materials, or used as a clean source of energy.[58] One of the biggest challenges for effective recycling of the beverage cartons, however, is efficient collection and separation.

8.12 Safety of Recycled Materials in Packages

A safety issue arises in conjunction with the use of recycled materials that come into contact with foods and beverages. The concern here is whether the original containers were used to store poisonous materials.

The consumption of PET for mainly packaging purposes has reached an amount of over 2.5 million tonnes per year in Western Europe.[21] PET is not limited to bottles and jars; various types of disposable cups and trays are popular as well. It is, therefore, not surprising that the reintegration of recycled PET into the manufacture of packaging is of much interest. However, the chronic exposure to even small amounts of toxic contamination can be hazardous for the consumer. Since PET is considered to be an effective barrier against contaminants, there was a proposal to encapsulate postconsumer PET into unused PET. The resulting multilayer PET product is recyclable and can be reintegrated into the manufacture of packaging in the same way. In the case of soft-drink bottles, postconsumer recycled PET is *coinjected* as a middle layer between two unused PET layers, the one inside preventing the beverage from direct contact with the recycled material. Also in the case of cups made of *coextruded* PET film, the postconsumer recycled material is again brought back into the loop of recycling. The effectiveness of such *functional barrier layer* was tested by varying its thickness.[58]

The use of recovered fibers in food packaging was also reported by.[59] The paper from recovery operation arrives at the recycling mill in bales. The source of these bales varies from high-quality virgin fibers, such as envelope and boxboard clippings, to lower-quality materials including old newspaper, used paper, corrugated board from grocery stores, and paper of various types collected in curbside collection programs. Fibers from high-quality sources mixed with some from other origins would not cause adulteration of packaged food. First, the process of resuspending the fibers in water will accomplish some cleaning even without the addition of chemicals to enhance this action. The agitation and high water-to-fiber ratio present in direct entry processes would be expected to reduce many types of contamination. Second, the short fibers, commonly called *fines*, are expected to hold more than their share of contaminants, due to the higher specific surface area. This effect is observed, for example when PCBs are present in recovered fiber. Since the loss rate of these fines will exceed the loss rate of the longer fibers (the system design is likely to accomplish this segregation), unwanted contaminants will be selectively removed from the final paperboard product. Taken together, the two removal processes should provide significant reductions in the levels of unwanted substances in the finished material. Third, any remaining unwanted substances seem unlikely to migrate to food in quantities sufficient to pose unacceptable levels of risk of adverse health effects. The risk of adverse health effects due to exposure to any substance or mixture rests on the level of the exposure. It was concluded that the levels of the few substances likely to be found in recycled board are unlikely to result in migration of these substances to food at harmful levels.[59]

8.13 Disposal of Biodegradable Polymers

For biodegradable polymers, organic recycling is the most desirable choice. However, for this, a recovery system for organic waste must exist. As a prerequisite for coming on the market, biodegradable polymers may neither leave behind harmful materials in the compost nor impair the organic recycling process. The most crucial problem of composting, however, is the market of the compost. The experience of the European Investment Bank is that compost derived from municipal waste has difficulties in finding markets, in particular when there is a lack of separate waste collection, because of the risk of heavy metal contamination.[60]

8.14 Used Packages as a Source of Energy

Dry combustible fraction of household waste can be utilized for energy production. Those used packages, which cannot be recycled in a practical way but are dry and combustible, could be separated and used as fuel in existing boilers. Weight for weight, plastics and paper contain more energy than coal. This makes plastic and paper waste an invaluable fuel source, helping other materials to burn and also reducing fossil-fuel consumption. Even more resources are saved when energy is harnessed to provide heat and power.[7]

A research project in Finland investigated the use of different types of packaging waste as a secondary fuel in a circulating fluidized bed (CFB) boiler.[61] The effect of limestone addition and the role of the sulphur-to-chlorine ratio in the fuel on the emissions were also investigated. Emissions from the co-combustion of packaging waste were compared to the reference peat-coal combustion. The main primary fuel was peat and coal at a ratio of 55/45, which also was used as a reference when evaluating emission data. The shredded waste was cocombusted at a rate of 10 to 20 percent of the thermal feed. Four different waste materials were tested, two representing clean postindustrial and two dirty postconsumer combustible wastes, as follows:[62]

1. The liquid packaging board (LPB) consisted of unprinted polyethylene-coated board cut-out waste from the production of milk cartons.
2. The mixed board and flexible packaging material (MB/FP) consisted solely of printed production waste. The main components were cardboard, paper, plastics, metallized foil, and laminated aluminum foil.
3. Refuse derived fuel (RDF) consisted of shredded fuel derived from municipal solid waste. It was processed at Stormossen mechanical waste treatment plant at Vaasa. The pretreatment of RDF consisted of shredding, separating the organic fraction by a mechanical classifier, crushing, separating the magnetic metals with a magnet, and secondary crushing.
4. The mixed plastic waste (MP) was collected from Helsinki in public, separate-bin, municipal collection. All fuels were handled outdoors in bulk with a frontloader, and consequently were wet and contained sand.

The result of this investigation showed that the combustible fraction of waste materials, mainly consisting of used packaging, can be safely utilized as co-fuel in modern power plants, as up to 20 percent of the thermal feed with fossil fuels. In addition, local utilization would save energy in transportation.[62]

8.15 Recovery of Wooden Packaging

Wooden pallets are often used only once and disposed of afterward. Approximately 171 million of the 400 to 500 million pallets are recovered and used as fuel.[62] The new packaging waste directive of EU (2004/12/EU), prescribing recycling targets for packaging materials also includes wooden packaging and its recovery. For example, in Finland about 90 percent of wooden packaging is recovered and used as fuel.[63]

8.16 Construction Materials from Waste

A number of studies have been carried out to assess the feasibility of manufacturing constructional materials from rubbish to avoid landfill disposal. An example of these is the *neutralysis process*, which combines pulverized MSW with clay to form pellets, which are calcined to produce a light aggregate material.[64] In addition, several reports are available on the use of the ash of incinerated MSW as a concrete aggregate.[65,66]

9 PACKAGING SYSTEMS

Packaging systems can be defined a set of operations that fulfill the function of creating sales units of the product.[22] Figure 5 illustrates the packaging operation, and Figure 6 depicts a schematic of the packaging system.

Identifying the boundaries of the packaging system is especially important when considering life-cycle studies. The following can be pointed out:

- *The packaging operation is a crucial part of the packaging system*. Raw-material acquisition reaches over the product's system: During the acquisition of the raw materials, such secondary materials may appear that are not needed for the given system. For example, woodchips at tree cutting for paper production is not brought into the products system, but is used for another purpose.
- *The product's manufacturing or processing is partly included in the packaging system*. The product's properties may be modified (e.g., portioning) to ease packaging, or eventually embedded in the packaging operation as, for example, vacuum treatment of ground coffee.
- *Waste treatment is reaching into product's system, since the product system also creates wastes*. All the effects of the waste treatment are part of the given product's or package's system.
- *The impacts of secondary material processing may be part of the package or the secondary product system*. It is a matter of allocation.

The choice of the packaging operation is a complex decision, and it is based on the following main groups of factors (shown in Figure 7):[22]

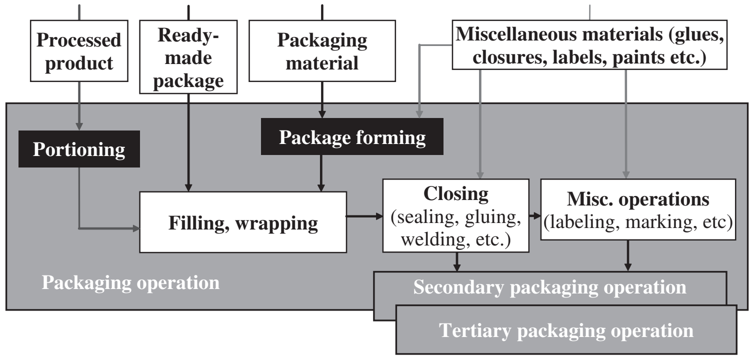


Figure 5 The steps of the packaging operation. (From Ref. 22.)

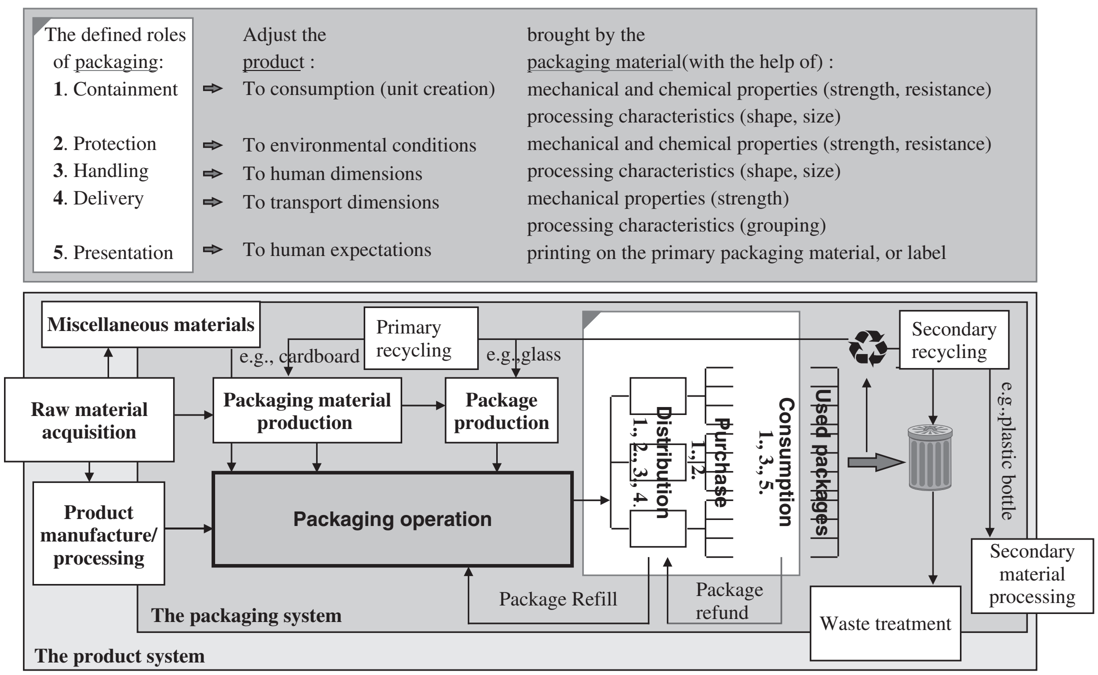


Figure 6 The packaging system as part of the product system. (From Ref. 22.)

1.a *Quality protection:* This involves protecting the product from the environmental, such as physical effects: damaging the unity of the product by force, pressure, or chemical effects, as damages by moisture, gases.

1.b *Loss prevention:* This involves protecting the product from losses, by chemical (evaporation, sublimation), or physical way (leaking, scattering), or pilferage in the shop.

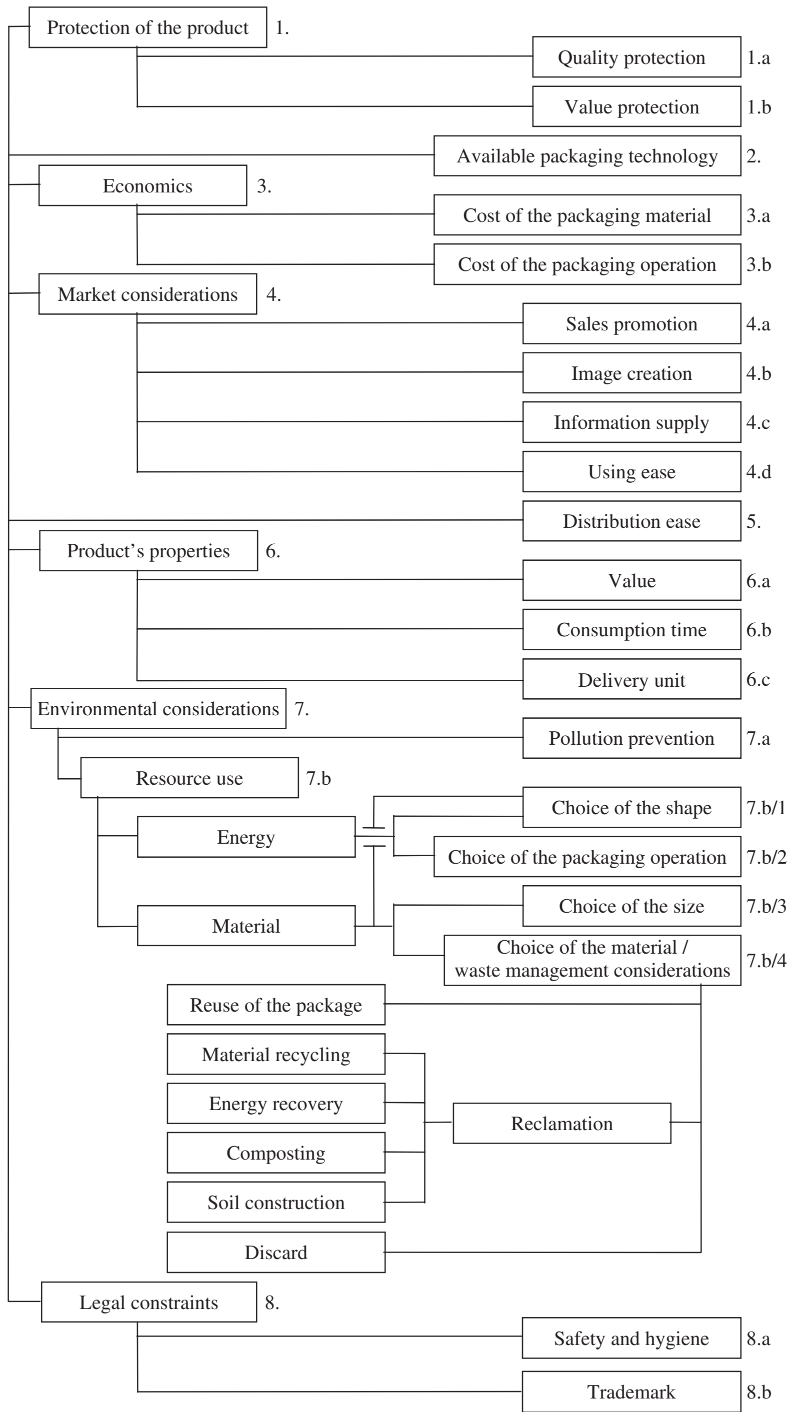


Figure 7 Factors influencing the choice of a package. (From Ref. 22.)

2 *Available packaging technology:* All the technologies used for packaging goods. This does not necessarily mean the best available technology.

3.a *Cost of the packaging material:* Cost will be allocated to the product's price.

3.b *Cost of the packaging operation:* Cost includes the cost of the packaging machinery, and also the cost of running the technology (handling, maintenance, amortization, energy consumption).

4.a *Sales promotion:* The advertisement value of the package, or certain property of the package that makes the product more attractive for the consumer is a consideration.

4.b *Image creation:* The package should create a positive image of the product or company. This is generally an aesthetics issue but could also be a property of the package, such as its strength or reliability.

4.c *Information supply:* Information is printed on the package about the product, or package, such as wastes management instructions.

4.d *Using ease:* The package should promote the use and consumption of the product.

5. *Distribution ease:* The package's function should help the product get to the consumer.

6.a *Value:* The worth of the product.

6.b *Life-cycle of the product:* This indicates, for how long, and within what conditions, the packed product will be kept before purchased, and used, once opened (consumption time).

6.c *Delivery unit:* The amount (weight, volume, piece) of the product in the package.

7.a *Pollution prevention:* The package's function should prevent the environment from being polluted, disturbed, or affected by the product, especially when the product is harmful to the environment.

7.b1 *Choice of the shape:* The shape should contain a unit of product using the least amount of packaging material, with high operational performance.

7.b2 *Choice of the packaging operation:* There are *resource use considerations*. The choice is between the least energy-consuming operation, or a high operational performance ensuring low percentage of waste.

7.b3 *Choice of the size:* The packaging material per product ratio should be minimized. This choice will also consider resource use.

7.b4 *Choice of the packaging material: (Waste management considerations)* Choice of the material, with considerations of the package's possible re-use or recovery (material recycling, composting, energy recovery, soil construction, etc.) after the product has been consumed.

Generally, the package's properties are adjusted to the packed product, but in rare cases the product's properties are changed (e.g., avoid unnecessary protruding parts) with the purpose of creating a more practical package shape. The motives are primarily economic; simpler shapes are easier and more effective to collect into secondary (retail) packages. Another motive is the environmental concern: simpler shapes use fewer materials, and effective collection to secondary packages also entails reduced resource exploitation. Waste management options are considered already at package design; design for reuse, recovery, or eventually disposal, are important tools of environmental marketing.

10 LIFE-CYCLE ASSESSMENT OF PACKAGING SYSTEMS

LCA has its roots as far back as the early 1960s. That time, resource and environmental profile analyses (REPA) were done, with the goal to predict how changes in population would affect the world's total mineral and energy resources. In 1972, the office of solid waste at USEPA initiated regulatory activity for the packaging industries in the United States. The environmental effects of packages, especially of beverage containers, were of particular interest in the 1970s, due to litter problems. The Commission of the European Communities introduced its Liquid Food Container directive in 1985. Finally, in 1995, a standard methodology for LCA for packaging was developed for the European Community. Based on this methodology, an LCA study was done for compact detergent-packaging systems. The study showed that from an environmental point of view, it is advantageous to use refill packages compared to master packages.[67]

Many life-cycle assessments (LCA) and life-cycle inventories (LCI) have been carried out on packages and packaging materials since the 1970s. Most of those, which were analyzing whole packaging systems, were made to compare beverage packaging systems. The main question was whether single-use plastic or refillable glass bottles should be used. Generally, glass and returnable bottles are conceived as environmentally more acceptable. However, the long transportation distances, ineffective returns of empty bottles, and the simple fact that for the lighter weight of plastic bottles, a fully loaded truck transports 1.867 times more water in polyvinyl chloride (PVC) bottles than in glass bottles, shed a different light on plastic bottles.[68] For example the study promoted by Lox concluded that one-way plastic bottles can be environmentally preferable to returnable glass because of the role of transportation. The fossil fuel use and the consequent contribution to global warming are higher for glass, even if it is assumed that it is refilled 20 times.

A thorough study on Finnish beverage systems (refillable bottles, recovered steel cans, and single-uses PET bottles) was also done. The study stated that environmental quality does not correlate with the sole energy intensity. Topology and operational relations have a decisive effect in the assessed environmental quality of the studied system. In Finland, there is no clear winner in the comparison between different packaging options. Assessed environmental quality depends strongly on how the system is assumed to be put together and operate. When whole packaging systems are assessed, and the results may affect the material flows in the society, it is not enough to assess only ecological consequences. It is probable that if there is a working system of a beverage packaging system, either returnable glass, single-use plastic or recycled aluminum, to change it may involve environmental effects that may surpass the expected benefits of the change.[69] In Finland, packaging of brewery products and soft drinks is predominantly based on refillable bottles (glass and plastic, respectively). Return and reuse systems of bottles are comprehensive and effective, and thus the degree of reuse is high—about 80 percent.[70]

There are also several points in an LCA that can significantly change the result of a study. These are, among others: the functional unit, system boundaries (geographical, natural as well as life cycle), data quality, and allocation. A traditional problem in LCA is how to deal with processes or groups of processes with more than one input and/or output, and how to deal with the use of recycled material in another product than the original. A crucial problem of evaluation and interpretation of the inventory results is that they depend on social and political preferences rather than on technical development.

11 CONCLUSIONS

The concern about the effect of packaging on the environment derives from their relatively high percentage in the household waste. This, however, indicates rather the level of consumption than excessive packaging. Packages are made to deliver the product to the consumer; hence, they cannot be viewed separately, either from the product or from consumption. Increasing amounts of packages in the waste stream only indicates increasing consumption.

Packaging is strongly influenced by social desires, political preferences, and regulatory and economical effects. In addition, packaging is not only a product—a package—but a system, and the package itself cannot be separated from its content. Consequently, an environmental assessment cannot mean only ecological impact analysis; neither can the judgment of environmental friendliness be based solely on the type of packaging material. Plastics have perhaps the most negative image, albeit of being lightweight and sturdy, thus giving high protection value with low environmental impact. It is especially true for composites, which combine several materials for better protection, while using minimal amount of the individual materials.

The use and reuse of glass packaging is a state-specific question. The raw material is in plentiful supply and there are no technical barriers to its reuse or recycling. If there is a well-working system of glass reuse, changing it may involve significant expenditures, as well as environmental impacts. While in several countries reusable glasses are not efficient due to large transportation distances, in other countries, with a good infrastructure, reuse is preferred. Another form of packaging reuse, the refill packages, are environmentally and economically preferred, and their increment would be preferred. Reducing package weight and making products more concentrated also lead to better resource use.

Reclamation of packaging wastes through recycling is strongly promoted by legislative bodies in the European Union as way of reducing the environmental impacts of packaging. From an ecological point of view, mechanical recycling processes have ecological advantages over feedstock and energy recovery processes if virgin plastic is substituted in a ratio of near 1:1. On the basis of the comparative analysis of feedstock recycling and energy recovery, the following recovery processes can be recommended: use as reducing agents in blast furnaces, thermolysis to petrochemical products, and fluidized-bed combustion.

Finally it can be asserted that while packaging plays an important role in achieving a sustained development, its most important actors are the consumers themselves. No regulation can be as effective as a well informed, environmentally conscious, ethical public.

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