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Reduction of CO_2 emissions by improved management of material and product use: the case of primary packaging

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Abstract

Approximately 40% of the global primary energy use and emission of CO_2 is related to the production of materials. Therefore, improved management of materials is likely to lead to substantial reductions in CO_2 emissions. The objective of our study is to investigate the potential and cost efficiency of CO_2 emission reduction by means of improved management of material use for primary packaging in western Europe. CO_2 emission related to primary packaging accounts for $\approx 3\%$ of western Europe's CO_2 emissions. Measures for improved use of primary packaging material are identified and evaluated. The potential and cost of each measure is established. A supply curve for CO_2-emission reduction is presented based on data on the use of primary packaging in 1995. We show that technically it appears possible to reduce the CO_2 emissions related to the production and use of primary packaging in 1995 by 51%, by implementing new packaging technology that is expected to become available between 1995 and 2010. In this investigation, improvement of energy efficiency in material production processes and changes in packaging demand are not taken into account. All evaluated measures can be implemented cost effectively when considering life cycle costs. Evaluation of the improvement measures shows that 9% reduction of CO_2 emissions related to primary packaging is feasible by using lighter packages. Material substitution can lead to a reduction of 10%. From a CO_2 emission reduction point of view, the most promising

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improvement is substitution of single use packaging by re-usable packaging. This may lead to 32% reduction in CO_2 emissions. However, large scale implementation of this option may be very complex. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Modern economies require massive amounts of fossil fuel. The combustion of fossil fuels leads to the production of carbon dioxide. The emission of carbon dioxide changes the earth's energy balance, which is likely to influence the global climate. In 1997, targets and timetables were set at the third Conference-of-the-Parties of the United Nations Framework Convention on Climate Change in Kyoto to reduce the emission of greenhouse gases. The member states of the European Union have jointly agreed to a reduction of 8% of the emission of the six most important greenhouse gases[1] in the period 2008–2012 compared to the 1990 emissions [1].

A large part of the fossil fuel consumption is related to the production and use of materials. The industrial sector, where the production of materials and products takes place, consumed about 40% of the total world primary energy use in 1995[2] [2]. Reduction in fuel consumption associated with the production and use of materials can be achieved in particular by energy efficiency improvement in the life cycle of materials and by improved management of use.

Improving the energy efficiency of production processes has been the subject of many studies for a long time. Improved management of material use, on the other hand, has had little attention in the light of reducing the consumption of fossil fuels and the emissions of carbon dioxide.[3] Studies on material management generally have a waste reduction perspective. The few studies that have been done on carbon dioxide emission reduction by means of material efficiency improvement show that an integrated approach for improving both energy and material efficiency can lead to an increase in CO_2 emission reduction potential and a decrease in CO_2 abatement costs [3,6].

Improved management of material use can be reached by improving the material efficiency and by substitution. Improving the material efficiency means a reduction of the amount of primary materials used to fulfill a specific function. Examples of a function are: to pack an amount of food or to carry a load. Material substitution

[1] The greenhouse gases considered in the third Conference of the Parties are CO_2, CH_4, N_2O, HFC, PFC and SF_6.

[2] Excluding refineries.

[3] Improved management of material use means taking measures that lead to more efficient use of materials; this can be done in any stage of a material/product life cycle.

can result in material efficiency improvement but it may also lead to an increase in the use of primary materials. However, when this increase results in a lower energy use and a reduced emission of CO_2, we consider this to be improved management of material use.

All materials that are used in the economy are per definition discarded as waste at the end of the life cycle. A large part of the municipal solid waste in western Europe ($\approx 40\%$) is packaging [7–9]. The production and consumption of packaging materials is good for $\approx 4\%$ of western Europe's CO_2 emissions [10].

The objective of our study is to calculate the potential and cost efficiency of CO_2 emission reduction by means of improved management of material use of packaging in western Europe,[4] and to investigate which types of improvement options can largely contribute to CO_2 emission reduction. In this article we will focus on primary packaging in order to limit the amount of material management options that need to be described. Contrary to secondary and transport packaging, primary packaging is all packaging that is directly used to pack products. It is also called sales packaging. Furthermore, we will focus on technologies that are already available now or most probably will be soon. The time horizon of this study is set at 2010.

The method we use to investigate material options to reduce CO_2 emissions is based on an approach presented in Worrell et al. [3]. First, we will describe this approach and indicate how it will be applied to evaluate the improvement of primary packaging. Second, we will present the basic data used in this study. Third, we will describe possible measures to improve the current management of material use. Fourth, we will present an overview of the potential costs and CO_2 emission reductions of the identified measures, and the CO_2 emission reduction potential of all measures together. Finally, the approach and results are discussed. We will end with conclusions.

2. Method

In Worrell et al. a four step approach for analyzing material efficiency improvement is presented [3]. First, the current consumption of materials embodied in the product is analyzed for all products studied. Second, the life cycle of the product is broken down in individual life cycle stages. In Fig. 1, a simplified picture of the life cycle is depicted.[5] To calculate the total energy requirement of the life cycle and the life cycle costs, the energy requirements and costs of the individual life cycle stages

[4] Western Europe is defined as Norway and Switzerland plus the European Union (15 countries) which includes Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and the UK.

[5] The life cycle is defined as the combination of processes needed by a product to fulfill the function of the product. Life cycle stages include production, use and processing after disposal, including processing of the waste generated in these stages [4].

are summed. Third, improvement measures are defined that reduce the amount of materials used. Implementation of these measures leads to new life cycles. Fourth, the energy effect of these measures is calculated by subtracting the energy requirement of the new life cycle from the reference life cycle.

Our method for calculation of the potential and cost efficiency of CO_2 emission reduction by improved material management is based on the approach described in [3]. However, two differences can be discerned. First, we add an economic evaluation in order to analyze the cost efficiency of the identified measures. Second, we include material substitution as a measure, even when it does not improve the material efficiency. The reason for this is that we focus on reduction of CO_2 emissions and not on reduction of material consumption. Therefore, an increase in material consumption is considered a positive development when the total CO_2 emission of the life cycle is reduced. This can be the case when, for example, natural organic materials substitute synthetic materials.

We will now describe in more detail the method used in our study.

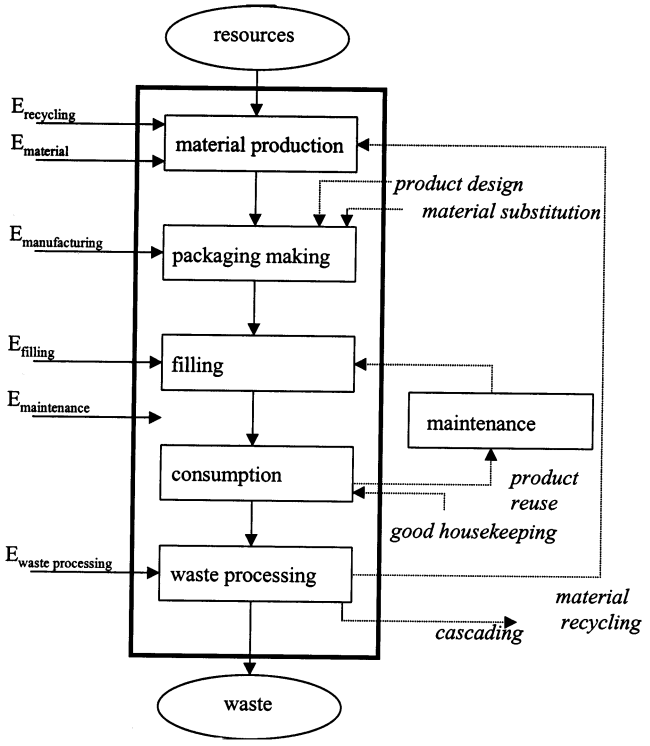

Fig. 1. Life cycle of primary packaging. The simple life cycle is depicted in the box, improvement options are depicted as dashed lines. On the left side the separate energy requirements of the processes are stated.

2.1. Analysis of current consumption

First, the current consumption of materials to pack products is analyzed. Since many different products exist with a large variety in packaging characteristics we cluster these products and the associated packaging materials in eight categories: (1) beverages, carbonated, (2) beverages, non-carbonated (3) dairy products, no milk, (4) wet food, (5) non-food liquids, (6) dry food, susceptible, (7) dry food, non-susceptible and (8) dry non-food. These categories are chosen based on demands regarding the package. Carbonated beverages need containers with good barrier characteristics for carbon dioxide. Dairy products, except milk, have a higher viscosity and are often packed in PS and PP packaging, which is not used for other liquids. The category 'wet food' contains jam, jelly and all food packed in steel food cans. Packaging for non-food liquids, such as shampoos, does not have to meet specific requirements (e.g. influence on taste) as does food packaging. Contrary to non-susceptible foodstuffs, dry foodstuffs that are susceptible need packaging with high barrier characteristics.

2.2. Definition of reference packages

To model the wide variety of packages that exist within each category, *reference packages* are defined. The number of reference packages that is defined within a category is based on the variety of packages that exist.

2.3. Breakdown of life cycle energy consumption and CO_2 emissions of the reference packages

After defining the reference packages and knowing the material streams, we calculate the CO_2 emission of the life cycle of the reference packages. This is done by multiplying the life cycle energy use by the CO_2 emission factors of the energy carriers. The energy use is calculated by summation of the energy consumption of the following life cycle stages: material production, manufacturing of package, transport of package, recycling of material, and waste processing (see Fig. 1). The energy consumption during material production (E_{material}) is obtained by multiplying the GER[6] by the amount of packaging material needed to pack 1000 l of product. The latter is the specific function that all reference packages need to fulfill, also called the *functional unit* (f.u.). The energy consumption for manufacturing the package ($E_{\text{manufacturing}}$) is obtained by multiplying the specific energy consumption of the manufacturing process (in GJ/t material) by the amount of materials needed per functional unit. The transportation energy ($E_{\text{transport}}$) is obtained by multiplying the transportation energy for transporting 1000 l of product per km by the transportation distance. The transportation energy is allocated on a weight basis over packaging and products. The energy consumption of recycling ($E_{\text{recycling}}$) and

[6] GER stands for Gross Energy Requirement which is defined as the amount of energy (in terms of enthalpy) which is sequestered by the production of a material from energy sources [5].

waste processing ($E_{\text{waste processing}}$) is obtained by the specific energy consumption of these stages (in GJ/t) multiplied by the amount of materials discarded after packaging 1000 l of product. $E_{\text{waste processing}}$ can be negative if material is incinerated with energy recovery. The total energy use during the life cycle of the reference packages is expressed by formula 1 where the summation signs indicate that more than one material can be involved in the process.

$$E = \Sigma E_{\text{material}} + \Sigma E_{\text{manufacturing}} + \Sigma E_{\text{transport}} + \Sigma E_{\text{collection}} + \Sigma E_{\text{recycling}} + \Sigma E_{\text{waste processing}} \quad (1)$$

2.4. Breakdown of the life cycle costs of the reference packages

The next step is to determine the life cycle costs of the reference packages. We can use the same breakdown as for calculation of the total energy requirement. The cost of the materials (C_{material}) is obtained by multiplying the market price (ECU/kg) of the material by the amount of material needed per functional unit. The cost of manufacturing ($C_{\text{manufacturing}}$) is obtained by means of formula 2.

$$C_{\text{manufacturing}} = (\alpha I + \text{OM/CAP}).\ \text{number of packages per f.u.} \quad (2)$$

In which:

α = an annuity factor depending on the interest rate r and the depreciation period n: $\alpha = r/(1-(1+r)^{-n})$,

I is the initial investment, OM is the operation and maintenance cost, and CAP is the capacity of manufacturing plant expressed in number of packages per year.

The transport costs ($C_{\text{transport}}$) are obtained by multiplying the time to deliver 1000 l of product by the labor and truck costs per hour. The transportation costs are allocated on a weight basis over packaging and products. The costs of recycling are determined by multiplying the collection costs per t material by the volume that was necessary to pack 1000 l of products. If recycled material is used for packaging production the costs are obtained by multiplying the market price of the recycled material by the amount of material needed per functional unit. The costs of waste processing ($C_{\text{waste processing}}$) are obtained by multiplying waste treatment costs (ECU/kg) by the amount of waste per functional unit. The total costs of the life cycle are expressed by Formula 3.

$$C_{\text{lc}} = \Sigma C_{\text{material}} + \Sigma C_{\text{manufacturing}} + \Sigma C_{\text{transport}} + \Sigma C_{\text{recycling}} + \Sigma C_{\text{waste processing}} \quad (3)$$

To determine the cost effectiveness of the measures we calculate the costs per t CO_2 saved, as expressed in Formula 4.

$$\text{Costs per t } CO_2 \text{ saved} = -(C_{\text{lc new}} - C_{\text{lc old}})/(CO_{2\text{lc new}} - CO_{2\text{lc old}}) \quad (4)$$

In which:

$C_{\text{lc new}}$, $C_{\text{lc old}}$ = life cycle costs of new and old life cycle, respectively

$CO_{2lc\ new}$, $CO_{2lc\ old}$

= emission of CO_2 in new and old life cycle, respectively

2.5. Definition of improved packages

The next step is to identify measures that lead to an improved use of materials in the life cycle of the reference packages. These are all measures that result in a lower energy use and a reduced emission of CO_2 in the life cycle of the package. In Fig. 1 these measures are presented by the dashed lines. Possible measures are the use of thinner materials, new product design that leads to a lighter package, product re-use, material recycling, and material substitution. New packages that are the result of these improvement measures are called *improved packages*. The characteristics of improved packages are based on recent developments in packaging technology. For The Netherlands, data on improvement options are available due to the voluntary agreements between the Dutch government and the packaging industry to reduce the amount of packaging waste. Data from the international packaging industry (packaging journals plus interviews) are used to gather information on new technologies in other European countries.

Options are only taken into account if they are technically feasible in the near future or are a proven technology. Therefore, the time horizon in this study is set at 2010. We use 1995 as the reference year.

2.6. The CO_2 emission reduction supply curve

The last step of the method is calculation of the total CO_2 emission reduction potential when all individual measures are implemented. Furthermore, the measures are evaluated in terms of cost effectiveness.

In energy efficiency studies, improvement measures are often evaluated by means of a supply curve. The supply curve depicts the individual improvement measures ordered by cost effectiveness. The measures with the lowest costs per t CO_2 saved are depicted first. The CO_2 reduction potential and the costs of the individual measures per t CO_2 saved are calculated, assuming a certain order of implementation, e.g. first end use measures and then measures influencing energy conversion [11]. Choices about the order of implementation are important because some measures can influence the potential savings of others, or even prevent the application of others. Generally, the order of implementation is not shown in supply curves; they show the measures in order of cost effectiveness. This shortcoming of supply curves is often criticized. We will present a supply curve where the order of implementation is visible.

We have chosen to implement the individual measures in order of implementation difficulty, so that the potential of 'easy to implement' options is visualized apart from options that are more difficult to implement.

To determine the implementation difficulties associated with the individual options is complex because many factors influence the difficulty of implementation.

These factors may be technical, social, or economical. To understand the influence of these factors additional research is necessary that is beyond the scope of this study. For a first estimate, we studied 275 cases of changes in packaging technology that were implemented in The Netherlands in the period 1992–1996 [12–16]. A vast majority of these cases (215 cases) involved small changes in the packaging system, e.g. thinner materials, removal of unnecessary material, increase of packed volume, etc. About 40 cases involved larger changes in the packaging system, e.g. use of recycled materials and material substitution. About 20 cases involved very large changes in the packaging system. A typical example of a large change in the packaging system is the introduction of re-usable packaging, which involves a totally new infrastructure and several new activities like collection and cleaning.

Based on these cases we make a first assessment of the difficulty of implementation by assuming that the most critical factor that determines the difficulty of implementation is the necessary change in the entire packaging system. This means that measures that change only a small part of the packaging system are assumed to be relatively easy to implement and factors that result in changes in the whole system are assumed to be more difficult to implement. We will use the *number* of life cycle stages that need to adapt to the improved package as an indicator for the size of change in the packaging system.

Based on the assumption stated above we cluster the improvement measures in terms of implementation difficulty. The measures with low implementation difficulty are introduced first and measures with high implementation difficulty are introduced later.

When more than one measure within the same category can be taken to improve a reference package, the indicated implementation order is based on cost effectiveness of the measures.

3. General input data

To calculate the CO_2 emissions and costs of the life cycle of reference and improved packages two types of data are essential. First, specific data are required on the physical characteristics of the packages, e.g. weight, type of material, trip number,[7] and volume. These data are presented in the next section where we describe the reference and improved packages. Second, general data are required on energy use and costs of the different stages in the life cycle of the packages. These data are presented in this section.

3.1. Data on energy use and CO_2 emissions

For all reference and improved packages, the life cycle is described in terms of energy consumption. We discern energy consumption for material production, packaging manufacture, transport, recycling, and waste disposal management.

[7] Trip number is a measure for the number of times that a package is used for the protection and transportation of products from producer to customer.

Table 1
GER values for materials used for primary packaging [17]

	Feedstock GJprim/t	Primary energy GJprim/t	Electricity GJel/t	Total GJ/t
PE	47.7	30.1	7.9	85.7
PP	47.7	25.5	6.9	80.0
PVC	29.6	25.4	11.9	66.8
PS	49.7	47.6	4.8	102.1
PET	45.8	29.0	9.0	83.8
Duplex/triplex cartonboard	15.9	11.4	1.2	28.4
Liquid packaging board	16.8	24.8	11.0	52.6
Glass	0.0	9.6	3.1	12.7
Aluminum	0.0	48.5	90.6	139.1
Steel	0.0	25.9	6.8	32.7

To calculate the energy consumption for material production we use GER values. In Table 1 these values are stated for the materials used as packaging material in this study. The GER values for both aluminum and steel are strongly dependent on the recycled material content. In this study for both aluminum and steel packaging a recycled matter content of 20% is assumed.

The energy use for the manufacture of packages depends on the type of package that is manufactured, e.g. blowmoulding of bottles, extrusion of plastic films, thermoforming of plastic boxes, and making of cans. In [17] the energy requirements of these processes are presented in MJ_{el}/kg package making. The energy requirement for glass bottle blowing and cardboard box making is negligible to the energy requirement of material production [17]. Data on packaging manufacture are presented in Table 2.

After producing the package it needs to be filled. The energy needed for filling is very low compared to the other processes. We assume the same energy requirement for all filling processes. The energy requirement is measured in MJ_{el} for packaging 1000 kg of product (see Table 2).

Filled packages are transported to the stores. For the energy demand of transport we assume an average transportation distance of 200 km. The energy consumption of a truck is 0.24 l of diesel per km for a fully loaded 20 t truck and 40% less when the truck is empty [18]. For a return trip for reusable packaging, we only consider the marginal energy costs compared to an empty return trip. The energy use for transporting 1000 l of product depends on the type of package used, since some packages use less truck space than others. To take this into account we calculate the number of packages that can be loaded on a truck for all reference and improved packages. For example, 11 520 large (1.5 l) bottles can be loaded in a truck (24 pallets, carrying 40 crates that contain 12 bottles) compared to 16 800 small (0.3 l) bottles (24 pallets, carrying 50 boxes that contain 14 bottles) [19]. In Table 2 transport data are presented for several types of packages with different sizes.

Table 2
General energy use data for several packaging processes and packages

	Packaging making MJel/kg pack	Filling MJel/t prod	Cleaning MJprim/1000 pack	Transport MJprim/1000 pack	Return transport MJprim/1000 pack
Blowmoulding	12.2				
Thermoforming	5.5				
Film making	2.6				
Can making	2.3				
Plastic bottle (1.5 l)		202	426	107	0.01
Plastic bottle (0.5 l)		202		83	
Aluminum/steel can (0.33 l)		202		83	
Glass bottle (1 l)		202		107	
Glass bottle (0.3 l)		202	426	83	0.07
Film (1 l)		202		90	
Cardboard box (1 l)		202		90	
Plastic box (0.5 l)				45	

For calculation of the energy demand for recycling, we differentiate between packages that use recycled material and packages that generate recycled material. In the first situation we take recycling into account by using a different GER value. In the second situation the recycled material is used for other purposes than packaging production. Here, the environmental advantage of recycling has to be allocated over both the packaging life cycle and the life cycle of the other product. Since it is not clear which products are made from the recycled plastics, it is not possible to allocate the recovered energy based on regular allocation rules like value based allocation. As a first estimate we allocate 50% of the recovered energy to the packaging cycle.

Packaging waste is either landfilled or incinerated. Incineration plants can produce heat and electricity. In western Europe 75% of the final packaging waste[8] is landfilled and 25% is incinerated [7]. Thirteen percent of the waste is incinerated with energy recovery, either heat (54%), power (12%), or combined heat and power (34%) [7,20]. For plants that just produce electricity, we assume an efficiency of 24%; for plants that produce heat we assume an efficiency of 80%, and for the CHP installations we assume an electrical efficiency of 19% and a thermal efficiency of 27% [20,21].

When the energy use of the packaging life cycle is calculated and specified for the different energy carriers used, the CO_2 emissions for that packaging life cycle can be calculated. For emissions from electricity production and primary energy use, we use average CO_2 emission data for western Europe [7,22]. CO_2 emission factors for incineration of plastics are derived from the oxidation reactions. For paper and board packaging, we assume that no net CO_2 emissions are emitted due to the renewable nature of the feedstock. In Table 3 the CO_2 emission factors for the different energy carriers are stated.

3.2. Data on costs

The life cycle costs of reference and improved packages are estimated by the assessment of costs for material production, packaging manufacture, transport, recycling, and waste disposal management.

We use market prices of the packaging materials as an estimate for the material production costs. These costs are stated in Table 4. All costs are expressed in 1995 ECU (European Currency Unit), which equals $\approx$ US$1.3 (1995) [23].

Table 3
CO_2 emission factors for electricity, primary energy carriers and packaging materials as used in this study

	Electricity	Coal	Oil	Gas	Wood	PC	PE	PP	PVC	PET
kg CO_2/GJ	123.6	94.6	73.3	63.1	0.0					
kg CO_2/kg						2.8	2.8	2.8	1.3	2.3

[8] Final waste is waste that is left after recycling.

Table 4
Material costs for several packaging materials

Material	Market price (ECU/kg)
Aluminum	1.51 [27]
Packaging steel	0.58 [28]
PE	0.72 [28]
PVC	0.68 [29]
PP	0.70 [29]
PS	0.92 [29]
PET	1.03 [30]
Glass	0.18 [31]
Paper	0.47 [32]
Cardboard	0.75 [33]

Table 5 presents the other costs that are taken into account. The costs of packaging manufacture and filling can be broken down in investment costs and operating and maintenance costs. The investment data for packaging machines and filling lines are based on actual investment figures for many different packaging machines [24]. An interest rate of 10% and a depreciation period of 5 years was used. For the labor costs of manufacturing and filling of bottles and cans, we use data on the crew sizes of beer and beverage production plants [25,26]. For packages that are produced and filled on a smaller scale, we assume an increase in labor costs by a factor 2.

For transport, the costs are estimated by assuming an average transport distance of 200 km and a total delivery time of 4 h. Furthermore, we assume that 1 h is needed for loading or unloading a truck [19]. A total cost (truck + labor) of ECU 22 per h is assumed [19]. For returnable packaging, the total costs increase because extra loading of the truck for the return trip is necessary. Furthermore, extra costs for storage of empty bottles at the premises of the retailer are taken into account. These costs are based on the assumptions that floor surface costs ECU 162/m^2*yr and that an empty bottle is stored for a maximum of one week before it is returned to the producer [19].

Waste management costs can be divided onto costs for landfilling (95 ECU/t) and costs for incineration (156 ECU/t) [27].

The costs of recycling are only taken into account when the recycled material is used for packaging purposes. This is done by using market prices of recycled material.

4. Material use for primary packaging in Europe

To estimate the potential of material efficiency improvement for primary packaging information is needed about the current material input for primary packaging. In Table 6 the material input per packaging category is stated based on [7,32,33].

Table 5
Costs of packaging making, filling, transport, storage, waste treatment

	Unit	PET bottles	Cans	Glass bottles	Other bottles	Boxes	Flexibles	All packaging
Packaging making [23]	ECU/1000 packages	1.5	5	3.5	1.5	3	2	
Filling [19]	ECU/1000 packages	5	1.5	3	5	0.3	0.3	
Labor filling [24,25]	ECU/1000 packages							15
Transport [19]	ECU/1000 packages	44.5	8.9	8.9–26.7	26.7	25	25	
Return transport [19]	ECU/1000 packages	11		2.2–6.6	6.6			
Storage [19]	ECU/1000 packages	8		1.6				
Landfilling [26]	ECU/t product							95
Incineration [26]	ECU/t product							156

In these sources the total material input for packaging in Europe is given. To create a breakdown of the total material input over the packaging categories, we use consumption data of the packed products and make the following assumptions based on [34]: All steel and aluminum cans are used to pack carbonated drinks. All non-carbonated water is packed in PVC bottles. All wine is packed in glass bottles and the remainder of the glass bottles used in Europe is used to pack carbonated beverages. All dairy products, except milk, are packed in either PS or PP packaging. Seventy five percent of the cardboard boxes are used in the food sector and 25% are used in the non-food sector. For plastic blister packing, we assume that 20% is used in the food sector and 80% in the non-food sector. For the division of films over susceptible and non-susceptible food products and non-food products, we use the 1990 data of [35]. This shows that 65% is used for non-susceptible food packaging, 23% for susceptible food packaging, and 12% for non-food packaging.

Table 6 shows that 'beverages', 'wet food', and 'dry food, non susceptible' are important categories regarding the amount of material used. Glass is by far the most used material (17 250 kt[9]) followed by cardboard (4051 kt) and steel (2329 kt).

Table 6
Use of packaging materials per packaging category in Europe

Packaging category	Material	Amount (kt)	Packaging category	Material	Amount (kt)
Beverages/carbonated	Glass	7500	Dry food/non susceptible	cardboard	2475
	PET	570		PP	756
	Steel	329		LDPE	735
	Aluminum	283		metallocene	220
Beverages/non-carbonated	Glass	6500	Dry food/susceptible	LDPE	0
	Cardboard	751		PP	270
	PET	530		aluminum	160
	PE	200		PET	110
	Aluminum	41		metallocene	65
				HDPE	45
Dairy products/no milk	PS	448			
	PP	72	Non-food dry	cardboard	825
				PVC	544
Wet food	Glass	3250		LDPE	235
	Steel	2000		PP	125
				metallocene	40
Non-food liquids	LDPE	1000			

[9] kt = 1000 t = million kg.

The PE and aluminum use for non-carbonated packaging refers to liquid board packaging that contains aluminum[10] and PE for packaging of juices and milk.

5. Description of reference and improved packages

In this section we describe both the reference packages and improved packages. We will describe the packages per packaging type (bottles, boxes, and flexible packaging) and per material type used. For all packages, the life cycle costs and CO_2 emissions are calculated as well, based on the specific characteristics of the packages and on the general data presented in Section 3. The life cycle costs and CO_2 emissions are shown in Table 7.

5.1. Bottles

5.1.1. Glass bottles and jars

The glass bottles used in Europe vary strongly in volume, weight, and shape. This variety is the result of marketing considerations and strength requirements. We define three reference bottles to take this variety into account. The first reference bottle is a 1 l bottle that is used to pack soft drinks and milk. The average weight of this bottle is estimated at 500 g [12]. The second reference bottle is the 0.3 l bottle that is often used to pack beer. The average weight of this bottle is estimated at 250 g [36]. Glass is also used to pack non-liquids like jelly and vegetables. To model these packages we define a reference glass jar with a volume of 0.5 l and a weight of 250 g; the volume of the glass jar is in between the often used 37 and 72-centiliter jars [36]. The weight of the reference bottles is calculated based on the weights of several types of bottles that are sold on the Dutch market [37].

Several options are possible to reduce the material input for glass packaging. In The Netherlands many projects have been performed to reduce the weight of glass bottles. In the period 1992–1994, the weight of milk bottles was reduced by 33% and in two projects the weight of liquor bottles was reduced with 20% and 22%, respectively [14,38]. Based on these experiences it appears possible to reduce the weight of large glass bottles in Europe by 25% in 2010. Projects were performed in 1993 to reduce the weight of small glass bottles, such as beer bottles, with 5.5% [14]. In 1993, the glass industry in The Netherlands expected a weight reduction of 15% in 1995 compared to 1991 [37]. We will use this figure for the possible improvement of small glass bottles in Europe in the period 1995–2010. Several Dutch companies reduced the weight of vegetable jars with 20% in 1993 [14]. Furthermore, some jam and jelly bottles were reduced in weight by 10% in 1995 [14,15]. Based on these projects, we assume that a weight reduction of jars by 15% in 2010 is feasible for western Europe.

[10] Aluminum is also used for non-food packaging. Sprayers are common packages in this category. We did not take the aluminum consumption for these purposes into account because no data were available on both the quantities and the improvement options.

Table 7
Measures for reducing CO_2 emissions related to packaging consumption[a]

	Life cycle costs (ECU)	Material input (kg)	Process energy requirement (MJ)	CO_2 emission (kg)
Glass bottle large	177	500	107	466
Light glass bottle large[b]	147	375	107	358
Glass bottle small	327	833	278	767
Glass bottle small refillable[b]	172	42	611	155
PET bottle one way	85	33	71	230
PET bottle reusable	78	3	138	65
PET bottle reusable recycled[b]	78	3	138	63
PET bottle to be recycled[b]	85	33	71	202
Steel beverage can	162	78	253	223
Steel beverage can light[b]	153	63	253	187
All steel beverage can[b]	168	87	253	244
Aluminum beverage can	179	42	253	288
Aluminum beverage can light[b]	174	39	253	271
Liquid board	74	28	107	83
Liquid board (1.5 liter)[b]	55	25	71	69
Pouch[b]	61	4	107	52
PC bottle[b]	91	3	207	72
PS cup	102	28	167	239
PP cup	92	24	167	164
Glass jar	196	500	167	470
Glass jar light[b]	172	400	167	383
Steel food can	135	94	167	254
Steel honeycomb food can[b]	116	66	167	189
HDPE bottle	152	100	167	649
Recycled HDPE bottle[b]	152	100	167	512
Pouch[b]	69	10	167	86
Liquid board[b]	90	28	167	87
Cardboard box	78	35	90	42
Cardboard box light[b]	73	28	90	38
Cardboard box + bag	83	38	90	58
PVC blister	127	36	90	172
Cardboard blister[b]	128	35	90	42
LDPE film	53	4	107	38
LDPE film thin[b]	52	3	107	36
PP film	52	3	107	33
PP film thin[b]	52	2	107	32
PP laminate	52	3	107	33
PET laminate	53	2	107	31
PP metalized	51	2	107	28
PET metalized	52	1.5	107	27

[a] Expressed per 1000 l of packaging service.
[b] New packages and packages with currently a small market share.

Besides weight reduction, resources can be saved by glass recycling. Two types of recycling are possible: product re-use and material recycling. Currently, the European (material) recycling rate is already 50% [39]. The Swiss recycling rate is the highest in Europe (85%) and can be seen as a technical maximum for Europe. However, due to the large transportation distances in Europe in rural areas this figure will most likely not be reached in practice. Since large improvements are not expected in European glass recycling we focus on product reuse. In The Netherlands beer bottles and some jar types are reused. Average trip numbers of 20 trips are reported [40]. We assume that this system is also an option for western Europe. The success of such a system depends on the willingness of the consumers to return the package (influenced by the height of a deposit fee) and the willingness of the producers to implement such a system. Standardization of packaging is a strong tool to make product reuse work. With standardized bottles it does not matter if the package is returned to producer A or producer B. Standardization for beer bottles is a proven technology in The Netherlands. We will therefore only model this option for these types of bottles for Europe and assume that full penetration is possible before 2010.

5.1.2. PET bottles

PET (Poly Ethylene Terephthalate) bottles were introduced in the soft drink sector to replace the standard 1 l glass bottles. PET bottles are especially suited to pack carbonated soft drinks. PET bottles also replace PVC bottles that are often used in southern Europe for the packaging of mineral water [38]. Fifty percent of the PET packaging in Europe is used to pack soft drinks, 27% is used to pack mineral water, and 5% is used to pack other drinking liquids. The rest (18%) is used for other purposes like food and non-food packaging [41].

Most PET bottles used in Europe are one way PET bottles. Although many different PET bottles exist, the reference bottle can be characterized by a volume of 1.5 l and a weight of 50 g [10].

The reference PET bottle can be improved in several ways. The first improvement is using refillable bottles. In The Netherlands and Germany many PET bottles used are already refillable. This development was possible because new types of PET bottles became available that can be cleaned at temperatures up to 75°C [42]. They weigh 103 g. The refillable PET bottles are designed to make 25 trips during a lifetime of 4 years [19,43]. Many bottles, however, make less trips because of damage during the refill process (scuffing) [43]. We will model the refillable PET bottle as having a volume of 1.5 l, a weight of 103 g, and a trip number of 20 [10].

PET bottles are normally made out of virgin PET. Coca Cola developed a three layer PET bottle with a recycled PET inner layer [44]. We will model this bottle that contains 25% recycled PET as an improvement option for the reference bottle.

5.1.3. Liquid board package

Cardboard as packaging for liquids has been used for several decades. The Tetra Classic was introduced as early as in 1952 [32]. The most important markets for liquid carton board are milk and juice packaging. Less important are wine, water, and soup [32].

In order to hold liquids, liquid board is laminated with other materials, such as PE and aluminum. For example, Tetra Briks for juice packaging contain 75% cardboard, 20% PE and 5% aluminum and the total weight is 28 g for a 1 l package [45]. Cardboard is used as middle layer with a PE and aluminum layer on the inside and a PE outer layer. We use these characteristics to model the reference liquid board package.

The liquid board package is expected to change in the future in order to compete with other packages. More plastics may be used for easier openings and better closures and SiO_x layers may be used for extended shell life [46–48]. These changes are not likely to have a severe inpact on the material use of the liquid board package. Increasing the packed volume can decrease the material use for liquid board packages. Increasing the size of the 1 l package to 1.5 l saves 9% of packaging material per l [14].

5.1.4. Steel and aluminum cans

In Europe there is a strong competition between steel and aluminum for beverage cans. Almost all lids of European beverage cans are made out of aluminum, while 50% of the bodies of the cans are made out of steel and another 50% out of aluminum [33]. For food cans, the situation is entirely different. Tin plated steel commands 100% of the European food can market [49].

We describe three reference cans to cover the entire range of aluminum and steel packaging used for packing of beverages and food: two beverage cans and one food can. The first reference can is the steel can with a volume of 33 ml and a weight of 27 g. The aluminum lid adds another 2.7 g. The reference 33 ml aluminum beverage can weighs about 14 g including the lid [33,38]. Food cans are used in a wide variety of sizes. We will use a 1 l can as the reference can. A 1 l steel can has an average weight of 88 g [50].

The first way to improve the cans is to make them lighter. Many developments aim at reducing the weight of steel beverage cans to save material costs. In the last decade the weight of steel beverage cans has been reduced by 20% [33]. It is already possible to produce a steel can body that weighs 23 g. Hoogovens is developing ultra thin steel that should make it feasible to produce can bodies that weigh 18 g by the year 2000 [33,46,51]. Aluminum producers estimate that an aluminum can in the year 2000 will weigh 13 g (including lid) [52]. Both the aluminum and steel light cans are expected to replace the current aluminum and steel cans completely [52]. Furthermore, there are some developments going on that will influence the weight of food cans. Continental Can is working on a 'honeycomb can'. This can has a honeycomb structure, which makes the can stronger. With this structure, it is possible to produce a can that weighs 30% less [50]. We expect full market penetration of this can to be problematic, since labels can not be attached as easily and the printability is worse than for normal cans.

The 'all steel can' is another improvement option; it is developed by Hoogovens (NL), British Steel (GB), and Rasselstein (D). The difference with the normal steel beverage can is the steel 'push in' lid. The advantage of the all steel can is that it can be recycled entirely. Aluminum lids can not be recycled since they are

incinerated in the recycling process [51]. The lid of the all steel can weighs about 8 g. The total weight of the all steel can in 2000 will be around 26 g. We expect that full penetration of the all steel can is feasible.

5.1.5. PS and PP cups

Polystyrene (PS) and polypropene (PP) cups, made from thermoformed sheets, are used in the liquid food market to pack yogurt and butter. Reference 500 ml cups made from PP and PS weigh 12 and 14 g, respectively [51]. No options to improve these packages have been reported in the literature. As a possible improvement option we suggest replacement of PS by PP cups. PP yogurt cups are lighter than PS cups; 12 and 14 g, respectively. Furthermore, the GER of PP is lower than the GER of PS.

5.1.6. New packaging: pouch and PC bottle

Besides improvements of traditional packages some new packages have been developed for the beverage sector. We will describe the plastic pouch and the PC bottle.

Both Tetra Pak and Elopak introduced the plastic pouch (flexible packaging) for the packaging of milk and juice. Tetrapak uses LLDPE while Elopak uses multiple layer PP laminates [53]. The advantage of using pouches for liquid packaging is that they are extremely light. An empty 1 l pouch from Elopak weighs 10 g whereas an empty 1 l pouch from Tetra Pak only weighs 4 g. The pouches are harder to handle than non-flexible packaging; after opening they need to be emptied into a multiple use can. Although the pouches have a very small cost price, the handling characteristics may prevent the pouch to gain a large market share in Europe.

The polycarbonate (PC) bottle was introduced on the Dutch market in 1996 for packaging of milk. The advantages of the PC bottle is that it is a light bottle (74 g for a 1 l bottle), that is refillable, and that it has a trip number of 30 [39,54]. Moreover, the square shape of the bottle leads to savings of shelf space.

5.2. HDPE non-food bottles

Non-food bottles are used to pack shampoos, detergents and other cleaning liquids, lubricants, and light cleaning chemicals. In contrast to food bottles, only a few different materials are used to pack these liquids, with HDPE as the most common material used. A wide variety of packages are used to pack non-food liquids which vary strongly in shape and size. We define a bottle with a volume of 0.5 l as the reference bottle. Based on the weight of shampoo bottles the weight of the reference bottle is estimated at 500 g [19]. Many projects were performed in the period 1992–1996 to reduce the amount of packaging material for non-food bottles. These projects show that 25% of material can be saved by the use of thinner materials, increase of product quantity, concentration of products, and shape renewal [12–16]. To take these developments into account, we define an improved

HDPE bottle that weighs 375 g, and assume that this bottle can reach full market penetration before 2010.

The HDPE bottle can also be made from recycled material. The use of 20–80% recycled HDPE has been reported in non-food bottles [12,14]. We will model a HDPE non-food bottle that contains 50% recycled material. We expect that full implementation of this bottle should technically be feasible in 2010.

Refill systems are the third option to reduce CO_2 emissions. Refill systems have large material saving potential: material savings up to 80% have been reported [14,16]. Two refill systems are analyzed: the plastic pouch and the cardboard package. In the refill system, a multiple use bottle containing the product is sold. After finishing the product, the consumer saves the multiple use package and buys the new product in a refill package that is advantageous over the reference package in terms of material use. The contents of the refill package are poured in the multiple use bottle. To pack 0.5 l of non-food liquids, 5 g of HDPE is needed if a pouch is used. The cardboard package weighs 14 g, including 1.8 g of LDPE laminate [54]. No technical implementation barriers are expected for a high implementation level of these packages. However, the necessary change in consumer behavior that is needed to implement this packaging may hamper full implementation.

5.3. Boxes

Three types of reference boxes are defined to describe the wide variety of boxes used to pack food and non-food products. The first reference box type is solely made out of cardboard and represents the average cardboard package used for many food and non-food products. Assuming a volume of 1 l, the reference box weighs 35 g [10]. The second reference box has the same characteristics and contains an inner PE bag that weighs 3 g. Inner bags are often used to keep foodstuffs fresh [10]. The third reference box represents blister packaging, which is often used to pack small non-food products. We have modeled this box as a plastic box with a cardboard back (10 g of HDPE and 2 g of board) and a volume of 0.5 l [10].

Three types of improvement options are investigated. The first option is the use of lighter boxes by removal of redundant material, the use of smaller boxes due to more efficient packaging, the increase of the box volume, and the use of thinner material. Based on different projects we estimate that a 20% reduction on packaging board should be feasible in 2010 [13–16,54].

The second improvement option relates to blister packaging. Trends are visible in The Netherlands, especially in the Do It Yourself (DIY) sector, that substitute plastic blister packaging with blisters made from 100% cardboard [13–16,55], which makes complete recycling of blister packaging possible. On average these blisters weigh 17.5 g for 0.5 l packages [10]. No technical barriers are expected that may prevent full implementation.

5.4. Flexible packaging

Material changes possible in flexible packaging (films and bags) depend heavily on the products that are packed. For many food products, barrier properties for moisture and gasses, especially oxygen and carbon dioxide, play a crucial role. Other products do not need high barrier properties. For this reason, we define high and low barrier films as reference packages.

Low barrier films are most often made from LDPE (1225 kt in Europe) and PP (585 kt) [7]. Therefore, we define a LDPE and a PP bag as reference package. Average film thickness is 40 and 30 μm[11] for LDPE and PP films, respectively [10]. A reference LDPE bag weighs 3.7 g and a PP bag weighs 2.7 g assuming a packaged volume of 1 l.

There are three options to reduce material use related to low barrier films before 2010. First, replacement of LDPE films by PP films can lead to material and energy savings. Second, the use of metallocene films can lead to savings of 20% due to improved polymerization control in the production process which make it possible to reduce the thickness of the films without affecting the strength [39,50,56,57]. Third, the use of paper wrappings (8 g) may also be an improvement due to the renewable nature of the feedstock.

High barrier films are typically multilayer films, either co-extruded laminates or coated films. Typical laminates consist of a carrying layer made from PP (25–30 μm) and a barrier layer made from PVdC, a super thin (2–3 μm) layer with excellent barrier properties [58]. We define a reference high barrier film that weighs 3 g for a 1-l package.

The film thickness of laminates can be reduced before 2010. Several methods are possible. The thickness of the carrying layer can be reduced using PET (12–20 μm) [58]. The use of PP metallocene may also result in a thinner carrying layer (15% less) [43]. We will model the latter as the improvement option for the reference laminate.

Coated films consist of a carrying layer made from PP and PET and a coating of aluminum or silicon oxide. Coated films are an improvement compared to laminates, since the barrier layer is extremely thin (0.04 μm), leading to a low weight package. The reference 1-l package weighs 1.6 g. These very thin films can be improved even more by substitution of PP with PET and by the use of PP-metallocene. These options may lead to 1-l packages that weigh 1.3 g in 2010.

5.5. Overview of all measures

In Table 7 life cycle costs, material input, process energy requirements, and CO_2 emission are stated for all reference and improved packages. The values are expressed per functional unit: to fulfill a packaging service of 1000 l of packed products. The process energy requirements are defined as all energy used in the life cycle of packaging materials except material production.

[11] μm = micrometer = 10^{-6} m.

Table 7 shows that for re-use packages (e.g. PET bottle reusable) the process energy requirements are higher than for single trip packaging due to extra transport and cleaning. However, the total CO_2 emissions during the life cycle are lower. This is the result of the low material input of re-use packages. Reusable glass bottles require only 42 kg of glass whereas one way glass bottles require 833 kg of glass. This is also the reason for the lower life cycle costs of reusable glass packaging compared to one way glass packaging. Similar reasoning applies to PET bottles that are used once compared to reusable PET bottles.

Table 7 also shows that a shift from glass to PET (500 kg glass vs. 33 kg PET) saves large amounts of material and thereby saves costs and CO_2 emissions.

When comparing 'PET bottles to be recycled' and 'PET bottles reusable', it becomes clear that material recycling leads to reduced CO_2 emissions compared to reference packages, but is not as effective as product re-use.

Table 7 shows that light packages are cheaper and emit less CO_2 due to material savings.

Liquid board packages and packages made from cardboard have a relatively low CO_2 emission in relation to material use, due to the renewable nature of the feedstock. Therefore, it is advantageous to replace PVC blisters by cardboard blisters.

6. Potential for CO_2 emission reduction

In this section we evaluate the potential of the improved packages that are described above. By implementing improved packages, savings in CO_2 emission can be achieved. Table 8 shows the CO_2 emission reduction potential of the individual improvement measures and the cost efficiency of these options expressed in ECU per t CO_2 saved. The CO_2 emission reduction figures in Table 8 represent savings that are feasible when the packaging technology that is available in 2010 is implemented in 1995. The potential reduction of CO_2 emissions for each improvement measure is not corrected for inter-measure influences in Table 8. This is done in Fig. 2 by assuming that measures are implemented in order of implementation difficulty, with the least complex measures implemented first. In section three we described that, in this paper, we link the difficulty of implementation to the required change in the entire packaging system.

In Table 8 the change in the packaging chain is indicated by a division of the possible measures in three categories. The table discerns measures with small complexity of implementation (S1–S9), medium complexity of implementation (M1–M6), and large complexity of implementation (L1–L4). The measures with small complexity of implementation correspond to the use of less, lighter, and thinner materials. Only changes at the level of the packaging manufacturer are necessary for these measures. Measures with medium implementation difficulty involve measures where material substitution takes place. Material substitution leads to changes in the material production sector and the packaging manufacturing sector. Measures with large complexity of implementation involve re-usable

Table 8
Potential CO_2 emission reduction and costs of improved material management for primary packaging in western Europe

No.	New packaging concept	Old packaging concept	CO_2 emission reduction (%)	Costs ECU/t CO_2 saved
S1	PP film thin	PP film	1.1	−1200
S2	Cardboard box light	Cardboard box	0.5	−1200
S3	LDPE film thin	LDPE film	1.1	−1100
S4	Honeycomb food can	Steel food can	2.0	−360
S5	Light glass bottle large	Glass bottle large	2.4	−280
S6	Glass jar light	Glass jar	0.2	−280
S7	Steel beverage can light	Steel beverage can	0.2	−230
S8	Aluminum beverage can light	Aluminum beverage can	0.2	−190
S9	Light HDPE bottle	HDPE bottle	1.8	−130
M1	PET bottle one way	Glass bottle large	5.2	−470
M2	Steel beverage can light	Aluminum beverage can	1.1	−150
M3	PP cup	PS cup	1.4	−120
M4	PET bottle to be recycled	PET bottle one way	1.0	0
M5	Recycled HDPE bottle	Light HDPE bottle	2.9	0
M6	Cardboard blister	PVC blister	2.2	0
L1	Pouch	Liquid board	14.1	−390
L2	Glass bottle small refill	Glass bottle small	5.6	−230
L3	Pouch	HDPE bottle	4.7	−160
L4	PET bottle reuse recycled	PET bottle one way + PET bottle to be recycled	15.1	−40

packages: changes in all stages of the packaging life cycle are required. Measures that rely on a change in consumer behavior are part of this category as well.

Fig. 2 presents the measures that are stated in Table 8 by means of a supply curve. Contrary to normal supply curves, the order of implementation is included in this figure. Within the categories 'lighter packages', 'material substitution', and 'product re-use' the measures are ordered by cost-effectiveness. This Fig. 2 shows that the total cumulative CO_2 emission reduction that can be achieved amounts to 51%. All measures are cost-effective from a life-cycle point of view. The potential cost effective savings on CO_2 emissions of measures that involve lighter packaging (low complexity) is 9%, and measures that involve material substitution (medium complexity) can add another 10%. The potential for emission reduction is increased by another 32% by implementing measures that involve product re-use. These measures are characterized by a large complexity of implementation. In the analysis only direct costs involved are taken into account. Transaction costs[12] were not taken into account, as no estimates are available. Transaction costs would decrease the cost effectiveness of measures.

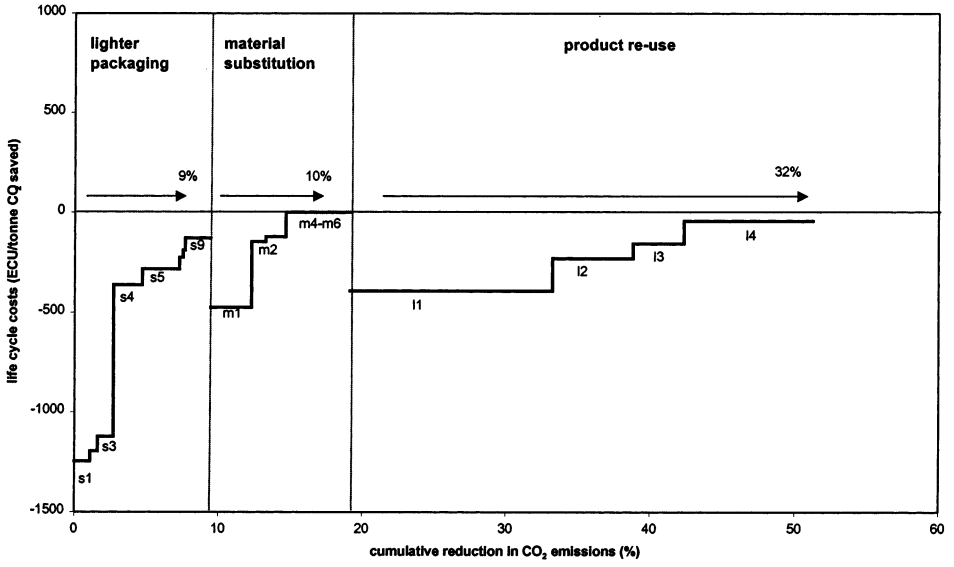

Fig. 2. A supply curve for the reduction of CO_2 emissions by improved use of materials for primary packaging in Europe. The horizontal axis depicts the total reduction in CO_2 emission in %. The three types of improvement measures are also ordered over the horizontal axis. On the vertical axis the specific costs are depicted as a function of the amount of CO_2 reduced (in ECU per t CO_2 saved). The numbers refer to Table 8.

[12] Transaction costs are defined by Williamson (1985) as the costs necessary to make a transaction. Three phases are discerned: a contact, contract and control phase. Costs included in transaction costs are inquiry costs, marketing costs, monitoring costs, costs for enforcement etc. [60].

The order of implementation used to calculate the potentials of the measures may be varied. Changes in implementation order will influence the reduction potential of the specific measures but will not change the cumulative reduction in CO_2 emissions, since we have corrected for inter-measure influences by calculating the potential of measures relative to measures that are implemented earlier.

The total CO_2 emission related to primary packaging is calculated at 78 Mt per year. This is calculated by combining the material requirement and CO_2 emission of reference packages as stated in Table 7 with the total material requirement for primary packaging as stated in Table 6. A reduction of 51% corresponds to a reduction of 40 Mt per year. This is 1.4% of western Europe's anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion; calculated from emission data by [59].

7. Discussion

In this section we will comment on the choices we made, their influence on the results, and on the quality of the input data.

7.1. Influence of choices made

In this study we investigated technical options to improve primary packaging so that it results in reduced CO_2 emissions. Further, we analyzed the impact of these options on CO_2 emission reduction in western Europe. Because of the wide scope of this study, choices were made to limit the level of detail. These choices have several consequences. First, only a limited amount of reference and improved packages were modeled. Increasing this number would certainly improve the accuracy of the CO_2 emission reduction estimates. Second, we did not discern different regions in Europe. By modeling regions, differences in packaging culture and transportation distances can be accounted for. Third, we focused on direct costs only. No information is available on transaction costs. Information on transaction costs might prove that some options are not cost effective and therefore difficult to get implemented. We created insight in possible differences in transaction costs by defining three levels of implementation difficulty. Defining these levels of implementation difficulty is only a first step towards a good understanding of the implementation barriers in the packaging sector. Further research is needed to complete this understanding and make calculations possible about the potential of implementation.

For the economic evaluation, we assumed a specific order of implementation. This choice influences the potential of the individual measures. Fig. 3 shows a new supply curve for a different implementation order. In this case the measures that are difficult to implement are implemented first. By doing so, the supply curve simulates the situation where policy is not focused on incremental changes in the packaging structure but prefers a more radical change in order to reach certain CO_2 emission reduction goals. Fig. 3 shows, in comparison with Fig. 2, that the potential

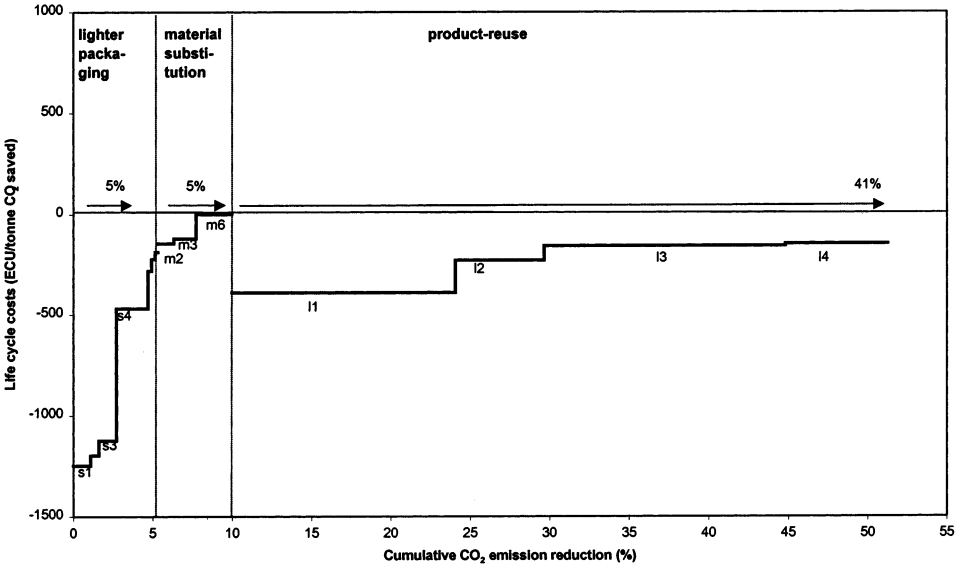

Fig. 3. A supply curve for the reduction of CO_2 emissions by improvement of the material efficiency of primary packaging in Europe. In this supply curve the measures that are difficult to implement are implemented first. The numbers refer to Table 8.

of measures that are difficult to implement increases and that the cost effectiveness of some of these measures also increases.

The supply curves as depicted in Figs. 2 and 3 represent the technical potential of CO_2 emission reduction. Due to many factors it is not likely that the full technical potential will be implemented: the potential of implementation will be lower than the technical potential. We have defined three types of measures to give an indication of the difficulty of implementation and we have used the *number* of life cycle stages in which adaptation to the improved package is needed as an indicator for the difficulty of implementation. Although we believe that this subdivision creates useful insights in the complexity of implementation and therefore in the likelihood of measures to be implemented, it is not the only factor that determines whether improvement measures are implemented. The physical characteristics of improved packages, for example, may prevent them from gaining a large market share. In this study two improvement options are described that have specific characteristics that may prevent full implementation: the pouch and the honeycomb can.

Due to the rules for constructing supply curves as described in Section 2, not all available measures contribute to the technical potential. The PC bottle has a technical potential of 6% CO_2 emission reduction when replacing the liquid board package. However, the pouch is a more cost effective option and is therefore implemented first, thereby reducing the potential of the PC bottle to zero.

For calculation of the potential of CO_2 emission reduction we compared packaging technologies that are available in 2010 with the situation in 1995. We did not take possible energy efficiency improvements in the period 1995–2010 into account. If these improvements would have been taken into account, the potential of CO_2 emission reduction due to improved material management would have decreased. An increase in energy efficiency of material production of 20% in the period 1995–2000 would decrease the CO_2 emission reduction potential to 48%.

To study the effects of technological change in material production and waste management, and the effects of changes in packaging consumption due to variations in relative prices a more integrated analysis is necessary. Such an integrated analysis is carried out for packaging using the MATTER–Markal model [61].

The reliability of the results of this study depends not only on the assumptions made but also on the quality of the data used. The calculations for different measures are based on a variety of data sources. To discuss the reliability of the results we discern the same three categories as in Table 8: measures with low, medium and large implementation difficulty.

7.2. Discussion of results for measures with small implementation difficulty

The costs and CO_2 emission calculations related to measures with low implementation difficulty (light packages) are only sensitive to the costs and energy data on material production, since this is the only parameter where the light packages differ from the reference packages. All these measures have negative costs due to the savings on material costs. For the energy requirements for material production, reliable information was available by means of GER values. The energy requirement of aluminum production is less reliable than the other GER values because the GER of aluminum is very sensitive to the recycling rate. We assumed a recycling rate of 25%, but an increase in the recycling rate to 50% would halve the CO_2 emission related to aluminum production. Because of the small share of this measure in the total savings, the influence on the total savings is negligible. For steel packaging, the recycling rate is also an important parameter but the sensitivity to this parameter is much smaller than for aluminum. The information on market prices is less reliable because the market prices of basic materials have a tendency to fluctuate strongly. For PE, the price increased from \$0.83 to \$1.19/kg in the period 1996–1997; an increase of 43% [30]. The market price for aluminum fluctuates even more because aluminum is a trade metal. In 1994, for example, the price increased from about \$1100/t to about \$2000/t, an increase of 85% [28]. The paper prices are notorious for their cyclical nature. The price of containerboard rose in the period 1993–1995 from \$300/t to \$580/t and fell back to \$250/t in the period 1995–1996 [62].

Besides data reliability, the estimated potential material savings play an important role in the final emission reduction as well. We estimated these savings based on projects carried out in The Netherlands due to the voluntary agreement between the packaging industry and government and activities in other European countries. This approach may have resulted in an underestimation of the potential savings,

because of measures overlooked in the inventory (since they are not reported in the sources used or since the stage of development of the techniques is such that the techniques cannot be treated quantitatively). Therefore, the results should be viewed as an estimate of the lower limit of the technical potential. However, within the timeframe chosen the situation is different. We have often assumed 100% penetration when measures are technically ready to be implemented. In reality, certain measures may take more time to reach full implementation. In this respect the potential of implementation may be substantially lower.

7.3. Discussion of results for measures with medium implementation difficulty

For measures with medium implementation difficulty (often material substitution), the costs and energy requirements of the packaging materials are the most important parameters. Substitution of aluminum cans by steel cans is a measure with large uncertainties in the CO_2 emission reduction potential and cost efficiency, due to the sensitivity of the GER of aluminum to the recycling rate and to the large price fluctuations of aluminum. The total CO_2 savings of this option are calculated at 0.6% of the total CO_2 emission reduction potential for primary packaging and therefore the influence of this measure on the total CO_2 savings potential is minimal.

A change in material is likely to lead to extra investments because packaging manufacturing machines will need to be replaced and packaging lines will need to be adapted to the new packages. We did not take these extra investments into account. We argue that the packaging industry is a fast moving industry that changes packaging design regularly in order to keep up with the consumer's wishes. We assume that the measures will be implemented when packaging machines and filling lines are completely depreciated or when adjustments to the current packaging lines and packaging making equipment can easily be made.

7.4. Discussion of results for measures with large implementation difficulty

Measures with large implementation difficulty (mostly reusable packaging) are sensitive to more parameters than the first two categories, e.g. the costs and energy use of cleaning, (return) transport, and storage. Since material savings compensate the extra costs that are made in the packaging life cycle, the options may also be sensitive to changes in material prices. To determine the sensitivity of the calculations to the input data we will double or halve the value of many parameters individually and re-calculate total CO_2 emission reductions and costs.

Halving the material costs leads to a decrease in the cost effectiveness of reusable packages compared to single use packages. The cost effectiveness of reusable glass bottles decreases with 46%. For refillable PET bottles, the influence is even greater. Halving of the costs for PET resin leads to positive costs for the refillable PET bottle compared to the single trip bottle (+ 60 ECU/t CO_2 saved). This shows that the economic viability of reusable PET bottles strongly depends on market prices of PET resin.

Doubling of the return transport costs increases the total costs for reusable packaging by 30–50%. The total costs of the measures remains negative (− 23 ECU/t CO_2 saved for reusable PET bottles). The two refill packages and the PC bottle are not very sensitive to changes in any of the cost parameters.

Halving of the data on energy use for packaging making, material production, and waste processing leads to lower CO_2 emission reduction, since the reusable and refillable packages are less influenced by the energy requirement of these processes than the reference packages. The decrease in CO_2 emission reduction was small and we can therefore conclude that the sensitivity of the improved packages to these input data is small.

To study the influence of return transport on the CO_2 emission reduction of reusable packages, we increased this parameter from marginal energy costs to the same energy use as for a fully loaded truck. This large increase in energy use for transport had hardly any effect on final calculations. We also increased the average transport distance from 200 to 800 km to find out whether a large distribution area (e.g. the USA) has significant effects on the reduction of CO_2 emissions by returnable packaging. This increase resulted in a decrease of the potential of returnable packaging of 25–30%. The costs also increased slightly but remained negative.

Finally, we studied the effect of cleaning energy on the CO_2 emission reduction of reusable packaging by doubling the energy consumption of the cleaning process. This increase in energy consumption leads to small increases in the CO_2 emission reduction of reusable packaging ($\approx$ 10%). This shows that the CO_2 emission reduction of reusable packaging is fairly insensitive for fluctuations in energy consumption of cleaning processes.

8. Conclusions

We have studied the potential of a large number of technical measures that will be available in 2010 to improve material management of primary packaging. Further, we estimated the potential impact on CO_2 emissions in western Europe when the packaging demand in 1995 was fulfilled with these improved packages. This resulted in nine measures that improve current packaging by using less or lighter materials. Full implementation of these measures would result in a reduction of 9% in CO_2 emissions related to the production and consumption of primary packaging in western Europe, compared to the situation in 1995. We also discerned six measures that improve current packaging by means of material substitution. The potential reduction in CO_2 emissions for these measures amounts to 10% of the CO_2 emissions related to primary packaging in 1995. Finally we discerned five measures that involve re-usable packaging. The potential reduction in CO_2 emissions of these measures is 32% of the CO_2 emissions in 1995 related to primary packaging. These measures require large changes in current packaging practices or require changes in consumer behavior. It is therefore expected that the difficulty of implementation is larger than for the other two categories.

Summation of all investigated measures results in a total technical reduction potential of CO_2 emissions related to primary packaging of 51% compared to 1995. All these measures have negative costs per t CO_2 saved. Therefore, the cost effective potential of CO_2 emission reduction is also 51%. The costs are negative due to the large savings in material costs. In the cost calculations no transaction costs are taken into account, which may influence the cost efficiency of certain measures. Measures that require large changes in the packaging chain are likely to have higher transaction costs than measures that require small changes.

This study presents a *first* analysis of the reduction of CO_2 emissions that can be achieved by improved management of material use for primary packaging. Further research should focus on bringing more detail into the calculations and extend the focus to more product groups like transport packaging, printed matter, and buildings. Possible improvements that will bring more detail into the calculations for primary packaging are:

1. the distinction of different regions in Europe, which will effect parameters as transportation distance, implementation level, and production costs,
2. the distinction of more specific packaging categories, which will bring more detail into the improvement options, and
3. more specific cost calculations, such as taking the transaction costs into account.

Further research should also focus on improvement options on the long term, e.g. new packaging materials as biopolymers. Finally, research that focuses on the barriers of large scale diffusion of new packaging and possible solutions to overcome these barriers is essential.

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