Improving material management to reduce greenhouse gas emissions

Beter omgaan met materialen ter vermindering van broeikasgas emissies

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

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The earth can't withstand a systematic increase of material things.
If we grow by using more stuff,
I'm afraid we better start looking for a new planet.

Robert Shapiro
Monsanto

Cover: Close up of Cypress tree
This thesis is printed using digital printing technology

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Chapter 1

Introduction

1.1 Introduction
This thesis deals with the way we, as society, can improve the efficiency of material use and how this may contribute to mitigation of human induced climate change. The central question that is addressed is:

> *Which greenhouse gas emission reduction can be achieved potentially, by improved management of material use?*[1]

Since it is not possible to answer this question in all its facets, the purpose of this thesis is to make a contribution to answering this question.

This introductory chapter starts with an introduction to climate change and describes the importance of focusing on material use and material management in this context. Then an overview is given of studies that have been published with a focus on material use and management. Next, the focus of this thesis is be addressed. Finally, an outline is presented of how the question raised above will be answered in this thesis.

1.2 Climate change
Human activities can contribute to climate change when these activities lead to increased concentrations of greenhouse gases in the atmosphere. These increased concentrations lead to a perturbation of the energy balance at the earth's surface, also called radiative forcing. In turn, this radiative forcing most probably leads to an increase of the temperatures at the earth's surface. Important greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).
Climate change due to greenhouse gas emissions caused by human actions is regarded as one of the major global environmental problems that we face

[1] Here, material management is defined as all choices made about the type, quantity, and quality of materials that are used to produce a certain product or service and the way these materials are discarded after use.

today. Concerns about the potential risk and consequences of this change led in 1988 to the establishment of the Intergovernmental Panel on Climate Change (IPCC) by the World Meteorological Organization and the United Nations Environmental Program, with the objectives to (i) assess available scientific information, (ii) assess the impacts of climate change, and (iii) formulate response strategies [1]. In 1990 the IPCC published her First Assessment Report and five years later her Second Assessment Report. In the second report the IPCC draws two important conclusions. First, the climate indeed has changed over the past century; the global mean temperature has increased significantly since the late 19^{th} century. Second, the balance of evidence suggests a discernable influence of human activities on the global climate [1].

The second assessment report of te IPCC was accepted by the second Conference of Parties (CoP-2) to the United Nations Framework Convention on Climate Change in 1996[2]. In 1997, targets and timetables Change to reduce the emissions of greenhouse gases were set at the CoP-3 of the UN-FCCC held in Kyoto. At this conference, the member states of the European Union have jointly agreed to a reduction of 8% of the emission of the most important greenhouse gases[3] in the period 2008-2012 compared to the 1990 emissions [2].

1.3 Why focus on materials in the context of climate change?

One of the most important human activities that leads to increased greenhouse gas concentrations is the use of fossil fuels: when fossil fuels are burned to deliver useful energy, carbon dioxide is released to the atmosphere unless it is captured and stored.

To reduce the use of fossil fuels a wide range of options can be applied [3]:

1. improvement of the energy efficiency, leading to a reduction of the energy consumption per unit of activity or product,
2. development and application of renewable energy sources like biomass energy, hydropower, solar, and wind energy,
3. a shift in the use of fuels, from resources with a high carbon content (coal) to resources with lower or even no carbon content (natural gas, uranium),
4. and improvement of material management.

The first two options have been studied intensively in the last 20 years and are already part of many national policies to reduce greenhouse gas emission. The

[2] The Conference of the Parties is established by the United Nations framework Convention of Climate Change (UN-FCCC) with the responsibility to watch over the progress towards the aim of the convention, to adopt future amendments to the convention, to resolve conflicts, etc. The UN-FCCC was drawn up by the International Negotiating Committee established by United Nations General Assembly.

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

third option is currently not part of many greenhouse gas reduction policies partly because requires a large change in the energy infra-structure. Another eason is the (public) resistance against nuclear power in many countries because of the problems involved.
The last option, improvement of material management, is not commonly incorporated in greenhouse gas reduction policies either. This is remarkable since several studies indicate that this option has a large potential and is often economically attractive. Before we will describe the results of these studies in more detail, we will first explain why material efficiency may lead to reduced greenhouse gas emissions.

Figure 1 shows a simplified overview of the life cycle of materials in an economy. Raw material production, material production, and product manufacturing require large amounts of energy.

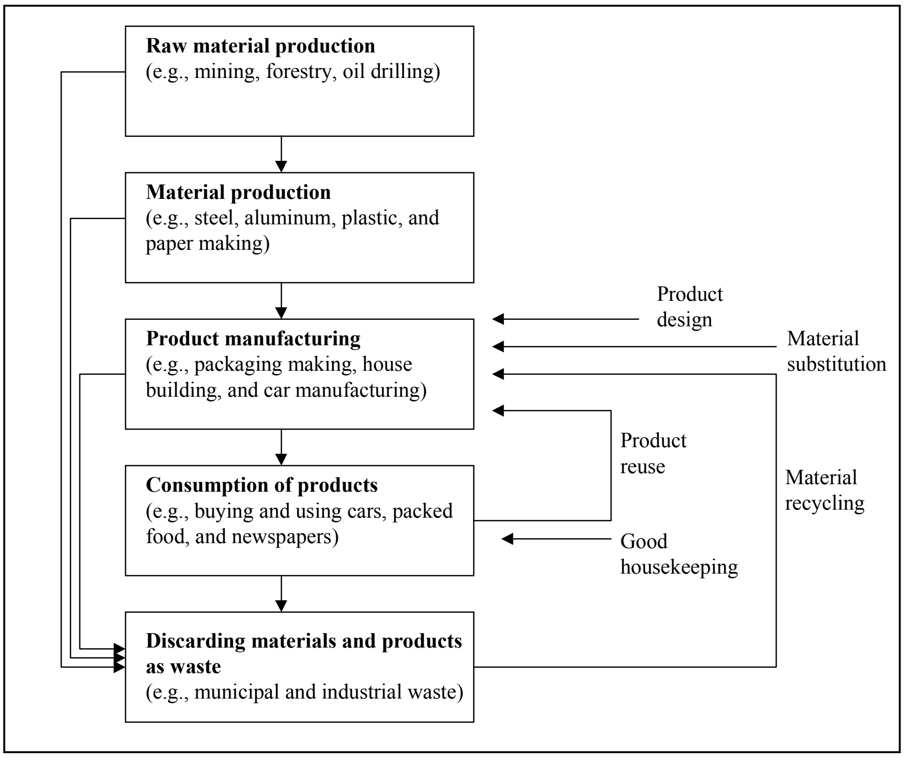

Figure 1: Schematic representation the material life cycle including measures for more efficient material management.

Together, these processes form the industrial sector. In 1995, The industrial sector[4] consumes about 40% of the global total primary energy use [4]. When materials are used more efficiently, either in the product manufacturing stage or in the consumption stage of products, less materials need to be produced and therefore less energy is needed in the raw material and material

[4] Excluding refineries

production stage[5]. Consequently, more efficient material management is likely to lead to reduced emissions of greenhouse gases. In this thesis, more efficient material management is defined as taking those measures that lead to a reduced emission of greenhouse gases by a different use of materials without substantially affecting the function of material use. In Figure 1 several of these measures are depicted. See Worrell et al. (1995) for a description of these measures [5].

Before exploring other studies that have focused on more efficient material management to reduce greenhouse gas emissions, we start with an overview of the literature on material use in general.

1.4 What aspects of material use have been studied before?

Several themes can be discerned in literature on material use. First, trends in material use over time are studied. Second, the impact of material use on the environment is studied. Third, studies are done to investigate options to improve material use.

Studies on trends in material use

In 1972 the club of Rome published 'limits to growth', where they expressed their concern about the adequacy of material supplies. This was coupled with growing concern about the effects of material wastes on the health of people and ecosystems. They stated that these effects would limit the growth of society as we know it within 100 years. In other words, they stated that the way society was using materials was not sustainable and could not continue without having large environmental impacts [6].

In 1978 a study was published that posed a less negative view about the sustainability of material use. In this study Maulenbaum (1978) examined the demand for metals in the U.S in the period 1951 - 1975. More specifically, for metals he studied the *intensity of material use*, which can be expressed as the demand for materials in kg per dollar gross domestic product (GDP). Maulenbaum (1978) showed that for many metals the intensity of use declined in the 60ies and 70ies. This led him to state that this development "...constitutes strong support for the argument that man's knowledge, skill and aspirations have served to slacken his need for industrial materials" [7].
Williams et al. (1987) continued the work of Maulenbaum (1987) and studied the use of several basic materials over long periods [8]. They concluded that the intensity of use of many materials declined over the time periods studied. These developments can be depicted by means of a bell shaped curve or inverted U curve (see Figure 2). The bell shaped curve can be seen as a de-

[5] It is also possible that other materials need to be produced in case of material substitution. This leads to reduced greenhouse gas emissions when in the production process of the substitutes less greenhouse gases are emitted.

linking of material use and economic growth. In this context, de-linking means that the intensity of material use declines while GDP keeps growing. This relation is also called *dematerialization*. The believe that the material intensity of use follows this kind of pattern made them to state that "..these trends mark the passing of the era of materials-intensive production and the beginning of a new era in which economic growth is dominated by high technology products having low material content" [8]. The results of Williams et al. (1987) are supported by Jänicke et al. (1989) who show a de-linking of material consumption (for selected materials) and economic growth for many nations [8,9]. In studies of Roberts (1988 and 1990) the same kind of results are presented for global and U.S. metal use respectively [10,11]. In this period many other studies, mostly on metals, showed similar results. See Cleveland and Ruth (1999) for an excellent overview of these studies [12].

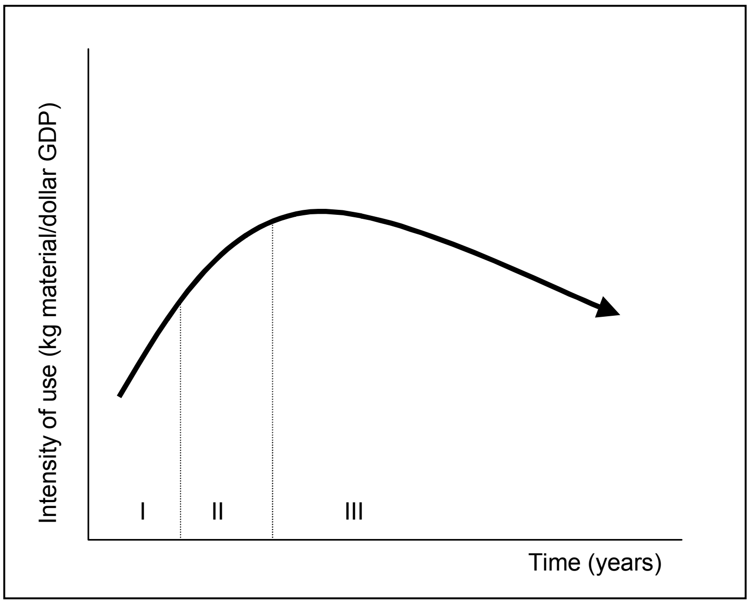

Figure 2: Bell shaped "intensity of use curve", including a subdivision in three phases of economic development

The theory on the reason why material use shows a bell shaped pattern over time is the following. When economies start to develop, material use is low and there are vast potential markets (phase I, see Figure 2). In this phase, material use grows rapidly for building up an infrastructure (more rapidly than GDP). This growth leads to advances in processing technology, leading to improved materials quality and further increases in demand (phase II). In the next phase (phase III), the ratio of value-added to kilogram of material increases as more sophisticated materials are produced and innovations lead to more efficient use of materials. Now, the demand for materials in kilograms per unit GDP peaks and begins to decline. Later in this phase, markets for bulk materials become saturated and shifts take place in consumer preferences at high-income levels to less material-intensive goods and services [8].

These insights in the development of the material intensity of use over time inspired Bernardini and Galli (1993) to present a theory about dematerialization. They postulated that the intensity of use of a given material follows the same pattern for all economies and that the maximum intensity of use declines the later it is attained by a given economy (see Figure 3). In other words: dematerialization of the economy takes place autonomously at certain levels of economic development and developing countries will not require the same amount of materials in their development as developed countries did.

These optimistic results about the dematerialization of economies are not shared by the entire scientific community. Cochran (1988) shows that the "era of materials" has not passed at all because the volume (instead of weight) of materials has increased dramatically over time. He states that expressing total material use in volume rather than weight shows in correct proportions the switch from high density materials like steel to low density materials like plastics and aluminum [13]. De Bruijn and Opschoor (1997) also warn for these substitutions between materials. They call this *transmaterialization* instead of dematerialization [14]. Matos and Wagner (1998) also noticed transmaterialization in U.S. material use in the 20th century: the share of renewable materials decreased from 45% in 1900 to 8% in 1995. De Bruijn and Opschoor (1997) also find that dematerialisation may have taken place in the last 20 years but that current trends show a re-linking[6] of material use and economic growth.

It is important to notice that it is completely plausible for the intensity of use for a particular material or for aggregate material use to decline, while total use of materials increases due to rising affluence. In other words, less materials are used relatively to GDP but more materials are used in absolute terms. De Bruijn and Opschoor (1997) distinguish therefore between *weak dematerialization* (a decline in intensity of use) and *strong dematerialization* (decline in total material use) [14]. Wernick (1994) notes that population growth and rising affluence leads to increased material use, offsetting substitution, technical change and other forces that promote dematerialization [16]. Janicke et al. (1997) showed for several countries that the demand for various materials did not decline even though the intensity of use generally declined [17]. Matos and Wagner (1998) also showed for the U.S. that total material intensity dramatically declined over the 20th century while the absolute total material use strongly increased [18]. Thus, even though modern economies use materials more efficiently, the continuous growth of these economies leads to an absolute increase in material use and therefore it is also likely that environmental impacts increase.

The overview of material use studies by Cleveland and Ruth (1999) shows that a majority of the studies agree that the weight-based material intensity of developing economies is falling but that the absolute use of materials still increases [12].

[6] Here, re-linking means that the material intensity is growing with GDP after a period where material intensity has been declining with growing GDP (de-linking).

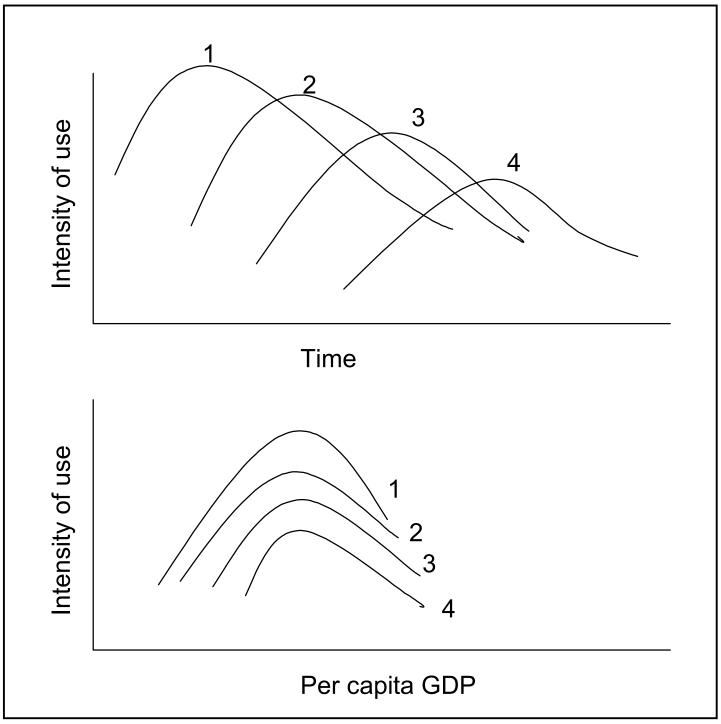

Figure 3: Figurative description of the theory of dematerialization. Countries 1-4 complete development in subsequent periods of time at around the same value of per capita GDP. The intensity of use of a given material declines the later in time each country reaches certain stages of development. Taken from [15].

Many studies on material use implicitly argue that a reduced intensity of material use automatically leads to reduced environmental impacts. Is this a correct assumption? To answer this question, in the next section we will describe several studies that explicitly link material use to environmental impacts.

Before we do so, it is important to remark that a large flaw in all the studies mentioned above is the use of apparent consumption data. Apparent consumption means that the material consumption in a country is calculated by adding *material* production and *material* import data and subtracting *material* export data. No data on the production, import and export of *products* is used while these *products* are important carriers of *materials*. To illustrate this with an example: to estimate steel consumption in a country, the production and imports of steel are added and the amount of steel that is exported is subtracted. However, the import and exports of, for example, cars are not taken into account. Therefore the actual consumption of materials in an economy can be over- or under estimated based on the import/export characteristics of the economy. In this thesis we will contribute to a methodology to take these product flows into account.

Studies on material use and environmental impacts

Many environmental impacts are associated with material use. To name a few: the energy use for material production leads to greenhouse gas emissions, resource mining often leads to serious deterioration of the local environment, natural resource production may lead to a loss of forest area and biodiversity, and discarding materials leads to waste production of which part is toxic. To estimate the environmental impacts of material use, indicators are used.

Much work on the environmental impacts of material use is done at the Wuppertal institute in Germany [19]. They introduced the indicator called MIPS (material-intensity per service-unit). MIPS is the total material use that is necessary to produce a certain service unit, e.g., to pack a product or to carry a load. To calculate MIPS all material flows are added based on weight, whether they are tons of copper mined, tons of water used, or tons of CO_2 released to the atmosphere. In this calculation no weighting system is applied to aggregate the environmental impact of materials, since the authors do not "…see any practical and convincing superior suggestion to weighting materials in a more differentiated way" [20] (p.9). Due to this method of aggregation, there is no scientific consensus about the applicability of the MIPS indicator. In Hinterberger et al. (1997) the indicator is defended by stating that MIPS is the "only measure introduced to date that can be used to compare relative environmental demands, and which can translated directly to realm of economics" [20] (p.8).

In Adriaanse et al. (1997) also the weight of all materials is added to calculate the indicator "total material requirement (TMR) of economies" [21]. The difference with MIPS is that MIPS is a measure for material consumption per service unit and TMR is an indicator for a total economy. Part of the total material requirement are hidden flows. These flows represent the portion of the total material requirement that never enters the economy like the disturbance of natural resources that occurs when producing those commodities that do enter the economy.

The indicators MIPS and TMR are ways to *communicate* that material use leads to environmental impacts. They are especially suited to communicate that often much more resources are used than may be expected when studying the production process of the material involved (hidden flows). However, these indicators are not well suited for *policy making:* they are not suitable to compare the environmental impacts of different means of material use since the environmental harm of a material has little to do with its mass. Due to this reason, these indicators are also not suitable to rank improved material management measures according to their environmental impact. To do so, more policy relevant indicators are needed.

Therefore in this thesis we will relate material use to one type of environmental impact (climate change) and we will use the amount of emitted greenhouse gases related to material use as indicator.

Studies on influencing the future impact of material use

The understanding that material use is still increasing in absolute terms, has led to studies that do not look back but look into the future. Instead of studying historical trends they actively search for solutions to reduce material use and the environmental aspects associated with material use. A distinction can be made between conceptual studies that focus on rearranging material use in all parts of society and specific studies that are focused on solving specific problems or optimizing specific inefficiencies.

Studies on rearranging material use

One well-known example of these conceptual studies is Factor Four by Weizsäcker et al. (1998). In this book they state, founded by means of 50 examples of technological improvement, that it should be possible to double wealth while halving resource use in absolute terms. To reach this goal they plea for a change in technological progress - towards greater resource productivity instead of greater labor productivity. The Factor 10 club even goes a few steps further. They advocate that it is necessary, and possible, to increase resource productivity with a factor 10 [22].

Besides these initiatives with their simple[7] but appealing messages, a new scientific discipline emerged in the beginning of the nineties that has a less simple message but a more holistic view. This scientific discipline focuses on the subject of industrial ecology. This discipline seeks to optimize the total industrial materials cycle from virgin materials to finished products to ultimate disposal of wastes [23,24]. Natural ecosystems are used as a model of how materials can be used efficiently and can be re-used in small and large cycles [25]. The metaphor of industrial ecology is intended to stimulate imagination and enlarge the sense of the possible with regard to industrial innovation and social organization [26]. Figure 4 shows how energy and materials should be used according to the industrial ecology philosophy in contrast to the way of using and discarding materials and energy in the classic industrial system. The figure shows that the classic industrial system requires a large input of materials that are converted into large waste flows that leave the economy. In the industrial ecology system only small inputs of energy and materials are needed to make the systems work. Large amounts of materials are recycled in the economy, which results in small volumes of waste production.

To reach the desired industrial system, changes in all parts of society are needed. Therefore, studies of the industrial ecology community cover a wide range of subjects and scientific methodologies [27]. Important areas are material and substance flow analyses where the flows of materials and chemical substances through economies are mapped, e.g., [28]. The aim of

[7] Simple in this context means easy to communicate. The actions necessary to reach their goals are not simple at all.

many of these studies is to present information that can be used to optimize these flows. Other studies focus on creating local industrial 'ecosystems' by interconnecting the energy and waste flows of several industrial activities, see e.g. Cote and Hall (1995) [29]. Life Cycle Assessment (LCA) is often used as a tool to determine and compare the environmental impacts of specific products. Besides technical studies to track and optimize flows also more policy and strategy-oriented studies are of interest to this scientific discipline.

Studies on (optimizing) specific problems

Many studies have been done that focus on specifically defined aspects of the advocated changes in material use. Waste management problems created large attention for improved material management. Many studies address the possibilities of measures like prevention, improved product design, material and product recycling, good housekeeping, resource cascading, and material substitution in order to reduce the amount of waste, e.g., [30-38]. However, much less studies have been done that relate these measures to the subject of climate change.

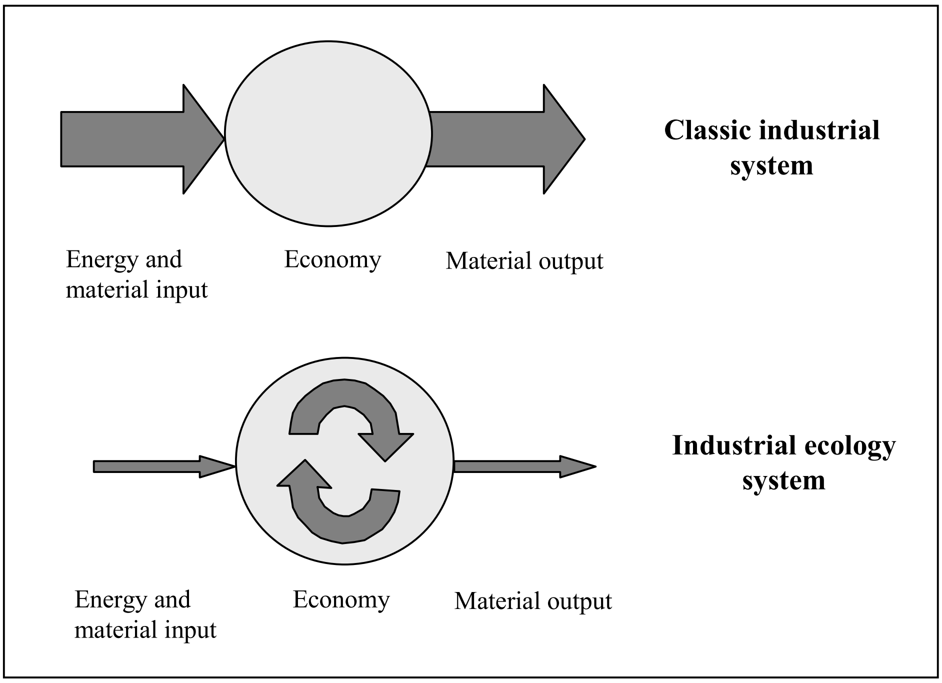

Figure 4: schematic representation of material and energy throughput in classic industrial system and industrial ecology system.

Case studies by Worrell et al. on plastic packaging and fertilizers show that a significant greenhouse gas emission reduction is possible by more efficient material use [5,39]. Patel (1999) studied a number of material management options for the plastics sector in Germany. He showed that these options may lead to a 24% reduction of the CO_2 emissions from the German plastics producing industries [40]. Furthermore, EPA (1998) showed that management of waste materials presents many opportunities to reach greenhouse gas emission reduction [41]. Elliott (1994) showed that recycling, an improved material management option, may lead to large savings in industrial energy use [42]. In The Netherlands, in 1995, a project[8] was started to model both the Western European energy and materials system and determine, based on technological improvement options, the greenhouse gas emission reduction potential in these systems in the period 1990 - 2050. Gielen (1999) concluded, based on the results of this modeling, that "… the potential for emission reduction in the materials system seems to be of a similar magnitude as the emission reduction potential in the energy system"[43]. The importance of these studies, in order to understand the potentials for greenhouse gas emission reduction, is stated in a report commissioned by the United Nations Department of Policy Coordination and Sustainable Development [44]. Based on these studies one may conclude that the potential of improved material management on greenhouse gas emission reduction seems to be significant. Consequently, creating more insights in the exact potential and the ways to utilize this potential is important. This is the subject in this thesis.

1.5 Focus of this thesis

To give an answer to the question: "*Which greenhouse gas emission reduction can be achieved potentially, by improved management of materials?*", all material management options and all greenhouse gas emissions for all materials that are used in our society need to be studied. Since, this is not comprehensible to study in a reasonable timeframe, this focus of thesis is limited to

(I) a few product groups,

(II) the geographical area's Western Europe and The Netherlands, and

(III) the greenhouse gases: CO_2 and CH_4.

The emphasis is more on CO_2 than on CH_4 since CO_2 is the most important greenhouse gas (see Chapter 5, Table 1).

Studying product groups instead of materials has the advantage that trans-materialization processes are not overlooked. We have selected three product groups for which large amount of materials are used: packaging, buildings and publication paper.

The first product group that is studied is *"packaging'*. This is an interesting product group to study since large quantities of materials are used in this sector and it has a significant contribution to greenhouse gas emissions. About 40% of all municipal solid waste in Western Europe consists of packaging materials [45] and the production and consumption of packaging materials is good for

[8] This project is called the MATTER project. Several studies presented in this thesis were done to provide input in this project. The Matter project team consisted of ECN, IVEM-Groningen University, CAV-Free University of Amsterdam, Bureau B&G, NW&S - Utrecht University.

about 4% of Western Europe's CO_2 emissions [46]. A second reason for choosing packaging materials as subject of study is that much attention has been paid to packaging in terms of waste prevention. Therefore, many initiatives have taken place to use packaging materials more efficiently. These initiatives can be evaluated with respect to their greenhouse gas emission reduction potential. Finally, a wide range of materials is used for packaging, which gives us the opportunity to study the potentials of material substitution.

"Buildings' is a very important product category since it can be seen as a representative product group for the construction sector. In this sector large flows of materials are used. It even is the number one sector in terms of material use: about 50% (344 Mtonne) of the most significant material flows in Europe are used for construction purposes [47]; mostly concrete, bricks, iron, and wood. Furthermore, these materials stay in society for a long time due to the long life-time of construction works. In terms of building materials we focus on wood. The focus on wood is interesting since the use wood does not lead to large CO_2 emissions, contrary to other building materials. Therefore, it may be used as a substitute for other building materials. Improved use of wood implies both substitution of traditional materials like concrete, steel and bricks by wood, and reuse of wood to reach optimal resource efficiency.

The product group 'Communication papers' consists of both Newsprint and Printing & Writing paper. This product group is interesting to study for a number of reasons. First, the production of paper consumers large amounts of energy; paper is one of the most energy intensive materials [48]. Therefore, improved material management in this sector is likely to have significant effects in terms of energy reduction. Second, the category communication papers is the largest consumer of paper with a share of about 48% [49]. Third, paper consumption does not seem to follow the same dematerialization trends as other traditional bulk materials [17]. It seems that with increasing GDP, paper is not used more efficiently. Moreover, since GDP is generally growing in developed countries, so is paper consumption. An interesting aspect of this trend is the way developed economies currently develop. Large economic growth takes place in the information sector. This has even led to the introduction of the term 'information society'. The fact that the amount of information that is digitally available to in offices and homes rises in a dramatic manner is likely to have significant effects on paper consumption. Some argue that paper consumption will drop dramatically since information will be exchanged in digital manners. Others believe that paper consumption will rise strongly since the amount of information that is used by people is much larger than the increase in paper efficiency - expressed in paper use per unit of information.

Since we focus on three specific product groups to answer the question as stated in paragraph 1.1, the specific question that is focused on in this thesis is: *Which greenhouse gas emission reduction, especially CO_2, can be achieved potentially in Western Europe or The Netherlands, by improved management of materials in the product groups 'packaging', 'residential buildings', and 'publication paper'?*

1.6 Outline of this thesis

The most important materials studied in this thesis in terms of improved material management are paper (used for packaging and publication papers), wood (used for packaging and for construction purposes), and plastics (used for packaging). Many of these materials enter economies in the shape of products or packaging. Earlier we noted that these product flows are generally not taken into account in material analyses studies.

In *Chapter 1* a contribution is made to the methodology of material flow analysis. More specifically, in Chapter 1 a method developed by Joosten et al. is refined and tested. The method can be used to track material flows -both direct and indirect flows- through an economy [50]. Indirect flows are defined as material flows that are not visible in statistics since they are incorporated in products. The material flow analyses is carried out for the paper and wood flows in the Dutch economy. The choice to study the paper and wood flow is based on the fact that these are important materials in the product groups studied in this thesis. The central question is this chapter is: Is STREAMS a good method to analyze material flows and does it provide new insights in the paper and wood flows in the Netherlands
In *Chapter 3 and 4* the focus is on the technical CO_2 emission reduction potential of improved material management for *primary and transport packaging* respectively. Primary packaging is all packaging that is in direct contact with the product that is packed. Transport packaging is defined as all packaging that used to bundle and transport the primary packages and their content. In these chapters technical measures to improve the current management of Western European packaging materials are studied for their CO_2 emission reduction potential. The time horizon is set at 2010 which implies that measures are only taken into account that are currently available or will be so in the near future. A methodology is used to calculate the total possible CO_2 emission reduction potential. Attention is paid to the difficulties that may be expected when implementing these technical options. The central question in these chapters is how much greenhouse gas emission reduction can be achieved technically, by improved management of packaging materials.

In Chapter 5 the focus of the previous 2 chapters is extended. First, all greenhouse gas emissions that are emitted in the life cycle of packaging materials are considered instead of only carbon dioxide. Furthermore, next to material management options, also improvements in the energy sector are taken into account. In the analysis, an integrated dynamic energy and materials model - called the MATTER-MARKAL model - is used.

Chapter 6 deals with *communication papers.* In this chapter the focus is on an exploration of the technical opportunities to increase paper efficiency for publication paper use and to calculate the potential greenhouse gas emission reduction. A dynamic model is used to determine the impact of the measures in the period 1995 – 2015.

In Chapter 7 the focus is on improved use of wood in the Dutch residential construction sector. Contrary to the packaging chapters the focus extends beyond the calculation of technical CO_2 emission reduction potentials. Based on innovation characteristics of wood technology and characteristics of the implementation environment, the implementation barriers that can be expected when implementing the technical options are discussed. The reason for this is that insights in the implementation barriers will make it possible to get some grip on the actual CO_2 emission reduction that may be expected on short and longer term. Also, policy recommendations are made to overcome the implementation barriers.

This thesis ends with Chapter 8 where a summary of the previous chapters is given, final conclusions are presented and suggestions for further research are made.

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Chapter 2

Analysis of the paper and wood flow in The Netherlands[9]

Abstract.
Current production structures require large amounts of primary materials and are not likely to be sustained without large implications for the environment. A good understanding of societal metabolism is likely to contribute to more sustainable production and consumption. Material Flow Analysis (MFA) intends to support this understanding by providing insight in material flows. In this article a new method for analyzing materials flows, called STREAMS, is tested. The method is applied to analyze the paper and wood flow through the economic system of The Netherlands. The method is based on data available from the so-called supply and use tables; these tables are made available by Statistics Netherlands and describe the economy of a country in terms of annual supply and use of goods and services by industries and consumers. The method proves to be very useful in analyzing the paper and wood flow in The Netherlands. The method provides detailed information about the final consumption of paper and wood, even for packaging materials and product parts made out of paper and wood. Trends are visible that statistical offices collect less physical data about material flows. This will make the construction of material flow analyses like this one more difficult in the future.

Key words: material flow analysis, paper and wood flows, final consumption, indirect consumption

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[9] Published as M.P. Hekkert, L.A.J. Joosten, E. Worrell, 2000, Analysis of the Paper and Wood Flow in The Netherlands, Resources, Conservation and Recycling, Vol. 30, Issue 1, pp 29-48.

2.1 Introduction

Industrial economies are characterized by their massive throughput of materials and energy. Current production structures require large amounts of primary materials which are processed into products, transported, consumed and finally discarded as waste. This way of creating economic growth is not likely to be sustained without large implications for the environment in which production takes place.

A good understanding of societal metabolism is likely to contribute to more sustainable production and consumption. Material Flow Analysis (MFA) intends to support this understanding by providing insight into the volume, the structure, and the regulating mechanisms of anthropogenic material flows [1].

MFA refers to accounts in physical units (usually in terms of tons) comprising the extraction, production, transformation, consumption, recycling and disposal of materials [2]. Various MFA methods exist which cover approaches such as substance flow analysis, product flow accounts, material balancing and bulk material accounts.

MFA is a fairly new and rapidly growing research field. Accounting of material flows at firm level have been established in many places but similar efforts on the European, national and regional level are still at the beginning.

In Joosten et al. (1999) a new method for analyzing material flows through society is proposed [3]. The method, called STREAMS[10], is based on statistical make and use tables. In the Netherlands these tables are published annually by Statistics Netherlands [4]. The emphasis of the method is at providing detailed information about the *final consumption* of material flows, especially those material flows that are normally hard to trace like packaging material and product parts. This is valuable information because final consumption data of products and materials are very hard to find. Often, apparent consumption data are used as an estimate of the final consumption. However, this estimate is only reliable for final products that are not processed any further. For materials and intermediate products, apparent consumption rather means "the use in industry" which is not a very good estimate for final consumption. Especially for open economies, the difference between imports and exports of materials and products made out of these materials influence the reliability using apparent consumption data as final consumption data.

In Joosten et al. (1998) the STREAMS method is tested successfully on the plastic flows in The Netherlands [5]. The aim of this study is to test the method on the paper and wood flows and providing insights in the paper and wood flows in The Netherlands. We will also refine the method where necessary. We have chosen for analyzing the paper and wood flow because it is an important material flow in The Netherlands in terms of weight and the final consumption is widely spread over many final consumers. Moreover, the STREAMS method is

[10] STREAMS is an acronym for STatistical REsearch for Analysing Material Streams

very suitable for tracing packaging materials through the economy and paper products are used in large quantities for packaging purposes [6].
The analysis described here is executed for the reference year 1990. This reference year was chosen since it enabled us to make use of the work of Blauwendraat and van Dalen as a starting point [7]. Furthermore, after 1990 the amount of physical data collected by Statistics Netherlands declined.
In section 2 we will describe the method shortly and propose some refinements. In section 3 the results of the analysis are described which results in a discussion about the method and results in section 4. We will end with conclusions and recommendations.

2.2 The STREAMS Method

The STREAMS-method makes use of the supply and use tables of The Netherlands, published by Statistics Netherlands [4]. The supply and use tables give an integral view of the material flows (expressed in monetary units) in the economy in which in principle every product, producer and consumer are taken into account[11]. These tables show the annual supply and use of goods and services by industries in monetary terms (in million Dfl.[12] (1990)). They have the form as shown in Figure 1. The supply table gives the production value of about 800 commodity groups produced by 250 industries. The imports of the goods and services are also given. The use table presents the purchases of commodities by industries, final demand categories for those commodities (e.g. exports, consumption by households and government) and the value added of the industries [8]. In the supply and use tables of The Netherlands 37 paper products and 26 wood products are discerned.
To analyze the physical flows of paper and wood products through the Dutch economy we need to convert the monetary supply and use data for paper and wood products to physical terms (i.e. ktons). Joosten et al. (1998) have done this for plastics by dividing all rows by the mean export prices of the plastic products [5]. For paper products the conversion to physical data has been done by Statistics Netherlands [8]. These data are available on an aggregated level [7]. We disaggregate these data by assuming uniform prices within industrial categories. We will use the method of Statistics Netherlands instead of the approach used by Joosten et al. (1999) to obtain physical data. This will be described in paragraph 2.1.
At this stage in the analysis a physical supply and use table for paper and wood products is available which tells us how much paper and wood is produced, consumed, imported and exported and by whom. However, all use-data are only related to direct purchases of paper and wood products. Many types of paper and wood products are used as packaging material and some wood products are widely used as components in the manufacturing of

[11] Only the products that are sold onto the market are recorded in the statistics, so it excludes non-traded products.
[12] 1 Dutch Guilder (Dfl.) is approximately 0.5 U.S.$ (1990).

commodities. This means that the physical supply and use tables do not yet give any information about the final destination of these paper and wood products but only about the direct use. For products that are not regarded as packaging material or product parts, the supply and use tables give the final destination and therefore the final consumption. In order to calculate the final consumption of packaging products and product parts we need to do further calculations.

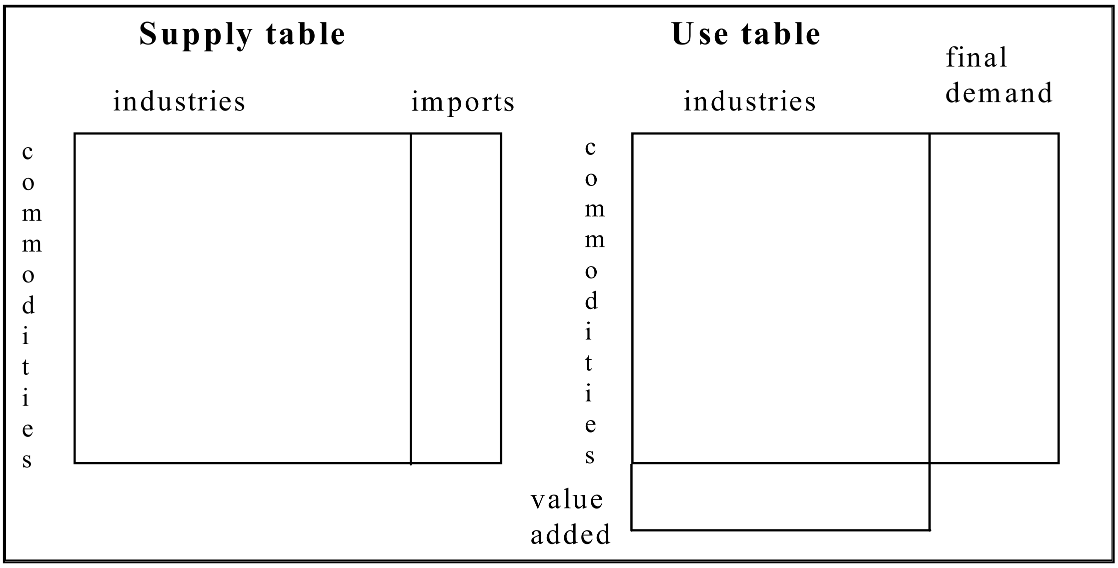

Figure 1. Schematic representation of supply and use tables as published by Statistics Netherlands [8].

The relation between the physical supply and use tables and further calculations is shown in Figure 2. In Figure 2 cardboard boxes and books are taken as an example. It shows that the physical supply and use tables state the amount of boxes that are purchased directly by a publishing house (direct use). This industry produces books which are packed in the cardboard boxes. The supply and use tables also show the amount of books purchased by libraries (direct final consumption). Further calculations result in insights in the amount of boxes and the amount of packaging material that actually end-up at the final consumers (indirect final consumption).
Calculation of the indirect final consumption is a complicated process. Starting with the physical supply and use tables a lot of matrix multiplication has to be carried out, different cross-cuttings of tables have to be used as starting point for other calculations etc. We will now describe the method as used for the analysis of the indirect final consumption of paper and wood products shortly but refer to Joosten et al. (1999) for a detailed description of the general method.
For all paper and wood products in the supply and use tables it is estimated whether they are used as packaging material, product component or as final

product. The paper and wood products that are applied as packaging material or product component are listed in Table 1 and are used in further calculations. For all 800 commodities in the supply and use tables we determine if these paper and wood products are used in the manufacturing process. This is possible because the use table states which industries purchase the paper and wood products and the supply table states the output of these industries. We allocated the amount of paper and wood products that are purchased by the industries over the output of the industries[13]. At this stage all commodities that are manufactured by the industries have a packaging or component share expressed in kilogram paper or wood product per million guilder commodity output.

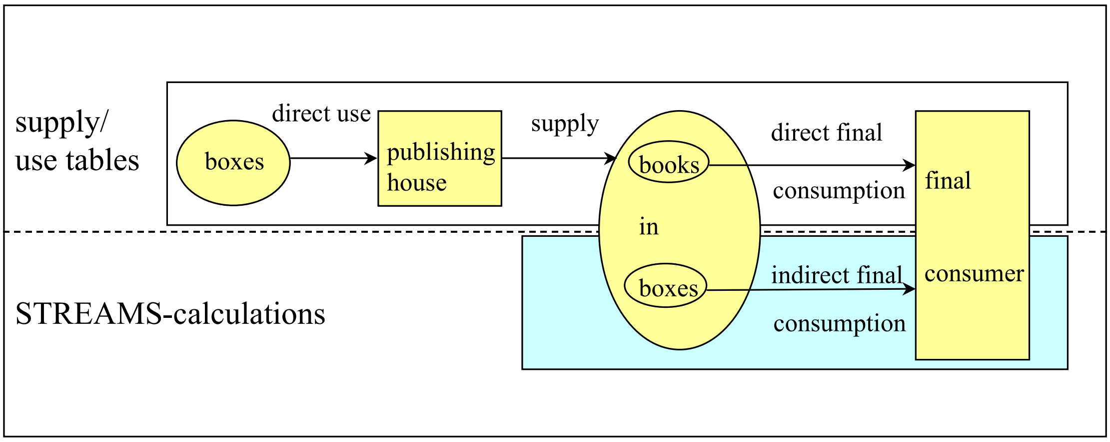

Figure 2. Schematic relationship between supply and use tables and further calculations.

The average packaging or component share of all commodities is calculated, also in kg paper or wood product per million guilder of commodity output. This is necessary because different industries may produce the same products but use different packaging technologies.

We use the packaging and component shares to determine where the packaging material and the components end up. The use table states the amount (in million guilders) of commodities that are purchased annually by the industries and final demand categories. By multiplying all these purchases with the packaging or component shares of the commodities we allocate the packaging material and product components over the final consumers of the commodities.

[13] Some industries however manufacture several commodities of which some are likely to be packed with paper or wood products or contain wooden components and others are not. Joosten et al. (1998) did not distinguish between these commodities and assigned the same packaging or component share to all commodities produced by an industry. In our analysis we will make this distinction by making by estimating for all 800 commodities if they are likely to be packed or not or if they are likely to contain wooden products components. This analysis makes it possible that some commodities are packed and others are not while they are all produced by the same industry.

Combining these results with the physical supply and use tables, which present the direct use of paper and wood products, both the direct and indirect final consumption of paper and wood products are calculated.

Table 1. Paper and wood products that are likely to be consumed indirectly (as packaging material and product part).

paper product type	paper products	wood product type	wood product
packaging	packaging paper	pallets	pallets
	packaging print		
	paper packaging products	other packaging	crates
	corrugated card board		other packaging products
	packaging board		
	other card board	semi-finished product	sawnwood
			plywood
			particle wood
			intermediate wood products

Price calculations

We have stated a short description of the methodology to calculate the direct and indirect final consumption of paper and wood products. An important step in the calculations is the conversion of the monetary make and use data for paper and wood products into physical terms. This conversion is difficult because a large variety in quality exists for paper and wood products which has a direct effect on the prices. Statistics Netherlands has developed a method for conversion of monetary data into physical data that we use in the conversion process of the wood product data [8].

Before doing so, we separate the rows containing the wood data from the original supply and use tables. This results in a use table and a make table containing 26 rows (wood products) and 250 columns (industries). We will call these make and use tables together: the balance. All the numbers in the balance that represent the amount of wood products that are purchased and produced by the industries (in million guilders) we call items.

For every item in the balance prices are collected. Import and export prices are derived from the foreign trade statistics. In some cases production statistics provided data on produced or used quantities. Sometimes this information covers the whole industry while in other cases it only refers to part of the industry, mainly large firms. In the latter case it is assumed that the derived price is representative for the whole industry. In most cases, however, direct data on product prices are not available and have to be derived in an indirect way. In this case export prices from the foreign trade statistics are used for the

conversion of monetary domestic production data while import prices are assumed to be representative for the domestic consumption prices.
After conversion from monetary terms to physical terms for each item in the balance, the tables are tested. First, it is analyzed whether the total supply of one product is equal to the total consumption of that product using the following equation [8]:

$$\sum P_i + I = \sum C_i + E + \sum C_{h,g} + \Delta \text{ stocks} \quad (1)$$

where:
$\sum P_i$ = total production of wood product by industries, I = import of wood product, $\sum C_i$ = total consumption by industries of wood product, E = export of wood product, $\sum C_{h,g}$ = total consumption by households and government of wood product, Δ stocks = changes in stocks of wood product

Inconsistencies are removed by solving the equation for all wood products, where items for which no direct information is available are adjusted using other sources which contain direct physical information on production or consumption of wood products [9, 10].

Secondly, it is analyzed whether the total output of an industry in physical terms is equal to the total input in physical terms [8]. So for the production of wood products equation 2 holds:

$$\sum P_w = \sum C_w + \sum C_o - \sum W_{w,o} \quad (2)$$

where:
$\sum P_w$ = total production of wood products per industry, $\sum C_w$ = total consumption of wood and intermediate wood products per industry, $\sum C_o$ = total consumption of other materials per industry, $\sum W_{w,o}$ = total amount of waste of wood and the other materials, generated per industry.

This equation provides an instrument for testing the reliability of the estimated output of an industry. By doing so the price estimates that seems the least reliable are adapted by using other data sources [9, 10]. The adaptations influence equation 1 and therefore the testing process has to start all over. After many iterations both equations hold and the physical supply and use tables are ready.

2.3 The paper and wood flows in The Netherlands

For every paper and wood product that is analyzed, the STREAMS-analysis results in a table that presents the *indirect* final consumption by industries, service industries and other final consumers. The tables have the same shape as the original use tables: 800 commodities by 250 industries. Different types

of information can be read from the tables. The *direct* final consumption follows directly from the physical make and use tables. The results of the analysis are presented in a very aggregated way in the Tables 2 till 8.
Table 2 shows the direct and indirect (packaging) final consumption of the paper products. We categorized the 36 paper products into 6 categories, which will be used in later tables. The table shows that more than a third (1250 ktons) of the paper used in the Netherlands (3550 ktons) in 1990 is used as packaging material. Corrugated board is used mostly for packaging purposes (600 ktons). Other large product categories are newspapers (350 ktons), advertisement printing (350 ktons), magazines (200 ktons) and hygienic paper (200 ktons)[14].
In Table 3 the direct and indirect final consumption (packaging and product components) of wood products is presented. The 26 wood products are also categorized into 6 categories. The table shows that the amount of packaging wood and wooden components used in the Netherlands is relatively small compared to the direct final consumption.
Table 4 and Table 5 show the foreign trade of paper and wood products. It is shown that 750 ktons paper products and 650 ktons wood products are imported indirectly as part of (other) commodities (21% and 17% respectively of the total final consumption).
Table 6 shows the final consumption of paper products by different consumer categories. To create this table the 300 industries and other demand categories in the make and use tables are aggregated into 9 categories. Households are the major consumers (1450 ktons). A considerable part of this is the indirect consumption of packaging material (700 ktons or 48%). Table 7 shows the final consumption in The Netherlands of wood products by different categories of consumers. Here the households are also the major consumers (1400 ktons wood products or 39%) followed by construction industries (850 ktons or 24%).
Table 8 shows for which category of commodities the paper and wood products are used. It shows the amount of wood and paper products that are 'attached' to or incorporated in the commodities, as packaging material or product component. To create this table the 800 commodities in the make and use tables are aggregated into 9 categories.
In the tables 2 till 8 the *final* consumption of paper and wood products in The Netherlands is stated. To do so the paper and wood purchases of the paper and wood industries have been eliminated in order to prevent double counting[15]. Table 9 presents the purchases and the production of paper and wood products of the paper and wood industries.

[14] We present rounded numbers because the uncertainties in the calculations do not justify a higher accuracy . In the tables we do present the exact outcomes of the calculations.
[15] If the purchases of the paper and wood industries would not have been set to zero the following situation would have occurred: both wood based panels purchased by the furniture manufacturing industries and the furniture that contain these panels would have been counted in the total consumption. The wood based panels would have been counted twice.

Table 2. Direct and indirect final consumption of paper products as calculated for The Netherlands in 1990 [ktons].

paper products	direct	as packaging material	total
basic paper types	**319**	**0**	**319**
pulp	41	0	41
recovered paper	25	0	25
basic paper	94	0	94
graphical paper and board	130	0	130
special paper	23	0	23
other paper products	6	0	6
office paper	**269**	**0**	**269**
paper rolls and graph. paper	48	0	48
envelopes	72	0	72
correspondence paper	11	0	11
chain forms	79	0	79
labels	59	0	59
books	**141**	**0**	**141**
books	1	0	1
schoolbooks	31	0	31
encyclopedias	25	0	25
other books	28	0	28
bind products	57	0	57
magazines	**648**	**0**	**648**
magazines	150	0	206
newspapers	341	0	341
television magazines	38	0	38
professional magazines	49	0	49
other magazines	14	0	14
other categories	**777**	**0**	**777**
hygienic paper	188	0	188
cartographic print	3	0	3
cigarette paper	9	0	9
securities, money	102	0	102
wall paper	15	0	15
postcards	2	0	2
calendars	9	0	9
advertisement printing	340	0	340
flyers	109	0	109
paper packaging	**140**	**1254**	**1394**
paper packaging products	14	122	136
corrugated board	31	584	615
packaging card board	20	368	388
other card board	51	13	64
packaging paper	23	80	103
packaging print	1	87	88
total	**2294**	**1255**	**3548**

Table 3. Direct and indirect final consumption of wood products as calculated for The Netherlands in 1990 [ktons].

wood products	direct	indirect as product components	indirect as packaging	total
basic wood	**1093**	**103**	**0**	**1196**
wood	347	0	0	347
sawnwood etc.	746	103	0	849
board	**574**	**114**	**0**	**688**
board (no veneer)	283	43	0	325
plywood	205	72	0	277
other board	86	0	0	86
interior	**875**	**18**	**0**	**893**
stairs	33	0	0	33
closet, cupboard etc.	23	0	0	23
kitchen elements	67	0	0	67
other carpentry	39	0	0	39
furniture parts	67	18	0	85
parquet	35	0	0	35
wood based beds	31	0	0	31
special furniture	135	0	0	135
furniture	410	0	0	410
furniture buildings	33	0	0	33
building	**376**	**0**	**0**	**376**
doors	118	0	0	118
window-frames	95	0	0	95
assembly constructions	157	0	0	157
scaffoldings	7	0	0	7
packaging	**122**	**0**	**427**	**549**
other packaging wood	15	0	92	107
crates	29	0	124	153
pallets	78	0	212	289
other products	**155**	**105**	**0**	**260**
coffins	18	0	0	18
other final wood products	7	0	0	7
other intermediates	113	105	0	218
brush products	17	0	0	17
total	**3194**	**340**	**427**	**3961**

Table 4. Foreign trade of paper products by The Netherlands in 1990 [ktons]

paper products	export direct	export indirect	import direct	import indirect
basic paper types	2395	0	3291	0
office paper	55	0	108	0
books	72	0	70	0
magazines	42	0	23	0
other categories	240	0	228	0
paper packaging	586	600	1062	741
total	**3390**	**600**	**4782**	**741**

Table 5. Foreign trade of wood products by The Netherlands in 1990 [ktons]

wood products	export direct	export indirect	import direct	import indirect
wood	873	40	2644	77
board	76	45	1339	96
interior products	181	5	414	11
building products	53	0	37	0
packaging products	96	260	72	327
other products	58	34	61	106
total	**1337**	**384**	**4568**	**617**

Table 6. Final consumption of paper products as calculated for The Netherlands in 1990, by final demand category [ktons]

	direct	as packaging	total
agriculture and fishing	3	22	26
industry	307	290	597
buildings	23	46	69
trade	377	25	402
other services	743	132	875
households	744	681	1425
investments	1	46	46
stock increase	61	12	73
other categories	33	2	35
total	**2294**	**1255**	**3548**

Table 7. Final consumption of wood products as calculated for The Netherlands in 1990 by final demand category [ktons]

categories	direct	indirect as packaging	indirect as product component	total
agriculture and fishing	34	5	0	39
industry	154	198	18	371
buildings	913	39	0	953
trade	48	12	0	60
other services	199	46	10	255
households	1230	95	219	1544
investments	415	25	89	529
stock increase	-13	7	4	-3
other categories	159	0	0	160
total	**3140**	**427**	**340**	**3908**

Table 8. Indirect final paper and wood consumption as calculated for The Netherlands in 1990 by commodity categories [ktons]

commodity categories	packaging wood products	wooden components	packaging paper products	total indirect consumption
food and tobacco products	103	0	556	660
textiles and fashion articles	3	7	102	112
paper and printing products	31	0	33	64
construction materials and interior	32	81	75	188
chemical products	70	0	162	232
metal products and machinery	105	32	128	265
transportation	20	0	12	33
other products	63	219	201	484
Total	**428**	**340**	**1269**	**2037**

Table 9. Purchases and production of basic paper and wood products by the paper and wood industries in The Netherlands in 1990 [ktons]

	purchases	production
wood	679	650
sawnwood	2067	361
board (no veneer)	476	78
plywood	411	66
other board	582	61
total	**4215**	**1217**

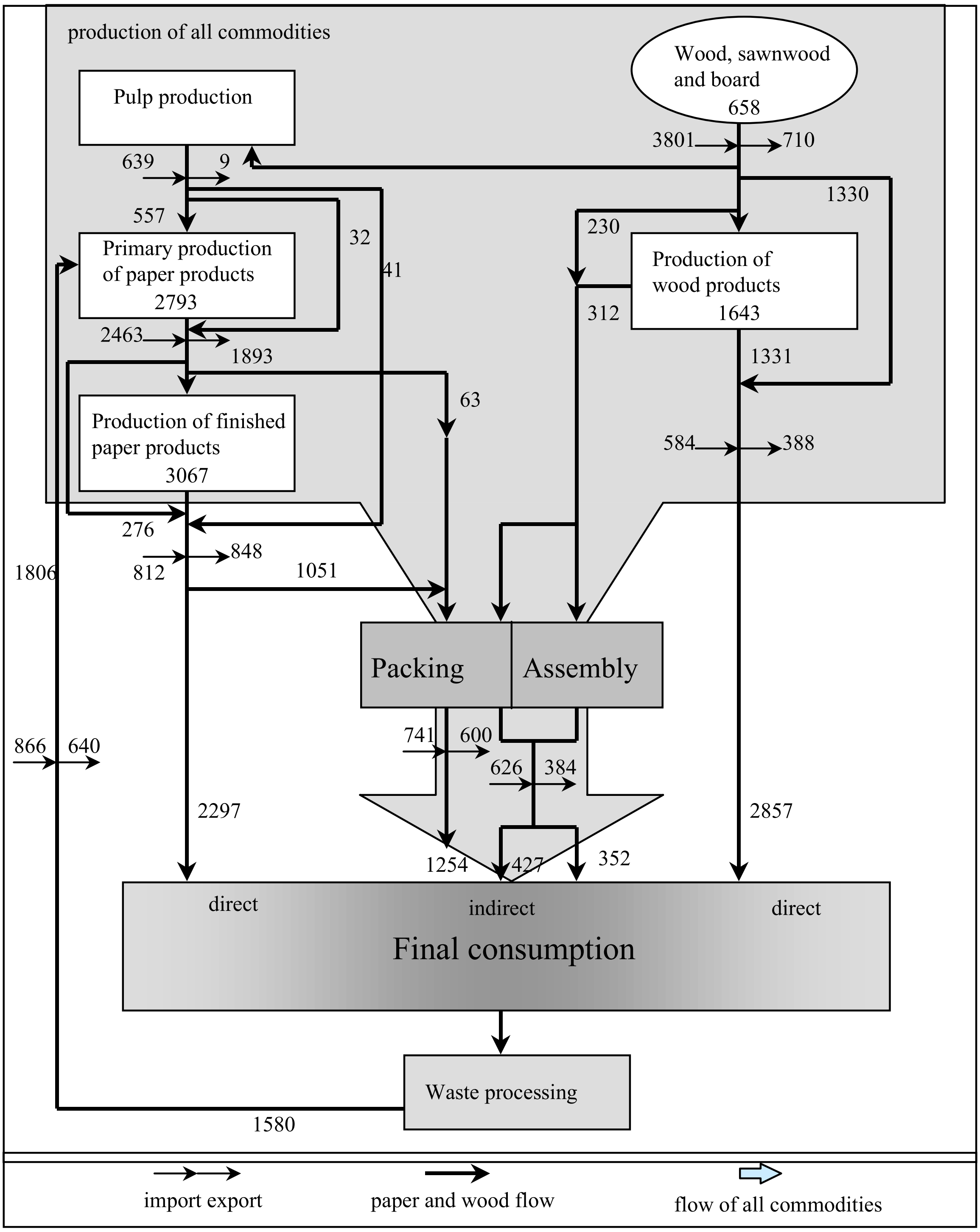

Figure 3. Schematic presentation of results of STREAMS-calculations for the paper and wood flows in the Netherlands in 1990 (in ktons).

The tables 2 till 9 are used to construct a flow chart (Figure 3) of the paper and wood products through the economy of The Netherlands in 1990. The figure shows the paper and wood flow in the Dutch economy from primary production to waste processing. To keep the picture readable all wood and paper products have been aggregated to one wood and one paper stream respectively. Figure 3 is not a mass-balance. It shows the ktons of paper and wood *products* instead of solely the ktons of paper and wood. Besides recovered paper no waste streams have been depicted because the supply and use tables do not give any information about these streams. The same holds for the production of wood pulp for the paper industry. Figure 3 demonstrates the open character of the Dutch economy (large import and export flows in all steps of the life cycle), especially for primary materials. Furthermore it shows that most paper and wood resources are imported (pulp and wood).

2.4 Discussion

Methodological aspects

In this chapter we will focus on the shortcomings of the STREAMS method and the ways that they influence the results. Furthermore we will discuss aspects in the calculations that affect the reliability of the results.
The first shortcoming of the method is that the supply and use tables that are used as starting point for the material flow analysis present transactions only when they have economic value. This might create problems when analyzing the material flow. Waste streams for example are not stated in these tables. In order to get a complete view of the material flow, adequate information about the waste streams is required. In addition, no data are available for recycling streams unless there is an economic value related to it, like recovered paper. If a material flow can not be traced in the supply and use tables, other information sources must be used in order to complete the material flow analysis. This process may lead to problems as other data sources often use other definitions to describe products and industries.
Statistics Netherlands monitors only companies that employ more than 10 employees. Extrapolation methods are used to estimate the total figures for a certain sector. Since the wood industry in The Netherlands consists of many small companies, errors may be introduced in the supply and use tables.
A second shortcoming is that the methodology is not very suitable for creating a mass balance of the material flows as done in Ayres et al. (1989) because not enough insight in the production processes, waste flows and waste treatment is generated [11]. Joosten et al. (1998) try to solve this problem by calculating all plastic products back to their primary plastics content [5]. In the analysis of paper and wood flows, we decided not to do these calculations for two reasons: firstly, it would introduce more uncertainties because an average primary material content for different products is assumed. Secondly, the primary material content of the different products can be added later without too much trouble if more research has been done towards the amount of process waste and additives needed for manufacturing the products.
The reliability of the results is related to the uncertainties that are introduced with the different calculation steps. Introduction of uncertainties starts with the

transformation of monetary data into physical data. Even though we followed the methodology of Statistics Netherlands, which is a very thorough method, uncertainties are definitely created. The main reasons are the estimated prices. Most prices are derived from the foreign trade statistics, which discern a wide variety of products. Due to publications of Statistics Netherlands we know exactly which products that are discerned in the foreign trade statistics are part of the categories stated in the supply and use tables [4]. However, it is hard to obtain a good indication of the material qualities that industries purchase and therefore it is difficult to calculate an exact price per demand category based on the foreign trade statistics.
For packaging material and product parts the STREAMS-calculations introduce other uncertainties as well. One of the first assumptions that have to be made in the STREAMS-method is whether a paper or wood product will be used as packaging material, product part or final product. Fortunately, for most paper and wood products it is quite obvious for which purposes they are used. For cardboard, however, this is not always the case. Cardboard can be used for cardboard boxes (packaging product) but also for advertisement purposes (like billboards). At first sight this may lead to large uncertainties. We reduced these uncertainties by treating service industries (where this problem occurs most) as final consumers of paper and wood products.
Other uncertainties are introduced when allocating the purchased packaging material and product components over the industrial output. This is not a statistical calculation process but is largely influenced by the researchers knowledge of packaging technologies. In most cases it is quite obvious which commodities are packed and which are not. If this is not the case all purchased paper and wood products are divided over all commodities produced based on their relative output. This allocation method proved to be more functional than the allocation method in Joosten et al. (1999), which is completely based on the relative outputs per industry, because with the latter method commodities for which it is obvious that no packaging material is used in the production still got a packaging share.
In the last steps of the calculations unavoidable errors are introduced because two assumptions were made. Firstly, we assume an average packaging or semi finished product intensity per commodity. Even though large differences in intensity are leveled out this way we follow this procedure because the use-table does not differentiate between the same commodities but produced by different industries. Therefore also the difference in packaging intensity cannot be taken into account. Secondly, we assume that commodities that are imported have the same packaging and semi-finished product intensity as domestically produced commodities. Even though this assumption is not very likely in the case of packaging we use this estimate because no information was available on the differences in packaging intensity of commodities between The Netherlands and other countries.

Comparison of results with other studies

We will now evaluate the results of our analysis using the STREAMS method with FAO-statistics and several studies done in The Netherlands. The latter is needed because it is not possible to compare the final consumption data from our analysis with the FAO statistics. This is due to the fact that the FAO statistics do not discern *final* but only *basic* paper and wood products. In other words: the FAO determines the paper and wood flow at the level of the paper and board mills and the wood industries while most of our data is about products manufactured by industries like the paper converting, printing, publishing, wooden furniture and other wood products industries.

In Table 10 we compare our results at the level of the paper and board industry and the wood industry with FAO and PPI data [6, 13]. The comparison is at an aggregated level because the sub-categories as stated by the FAO were not comparable to our results due to different definitions of the categories. Table 10 shows that our results are within an 11% range when compared to the FAO and PPI data.

Comparison of the results of our analysis using STREAMS with the results of other studies is difficult for various reasons. The first obstacle is a difference in aggregation. In most studies it is not clear which paper and wood products are part of a certain category. The second obstacle is the low consistency of most studies. Fraanje and Lafleur (1994) present a total picture of the paper and wood flow in the Netherlands based on numerous sources, showing that a lot of data about the consumption are not known and that estimates about total consumption therefore may be on the low side[16] [14].

The third obstacle is related to the way the information is collected. Examples are the paper waste studies where the amount of recovered paper generated in the Netherlands is estimated [15]. Since not all paper products are purchased and converted into waste within the same year no direct comparison can be made with the paper consumption data of households resulting from the STREAMS analysis. For some paper products however, like newspapers and packaging paper, a reasonable comparison can be made.

In Table 11 results of other studies are compared with results of our analysis. The first row shows a comparison between the cardboard consumption of households according to the STREAMS analysis and the amount of cardboard waste produced by households [15]. Fraanje and Lafleur (1994) estimated this quantity based on sorting experiments done in 1989 and extrapolated this quantity with the production growth between 1989 and 1990. The next row shows a comparison of packaging paper and cardboard use by households and service industries as calculated with the STREAMS-method and waste data for the same paper categories by the same consumers based on Knol (1991) [16].

[16] For example, Fraanje and Lafleur (1994) state that, based on literature, only 20% of the total wood consumption is traced back to the construction industries [15]. This low estimate is due to a lack of wood consumption data in the construction industry.

Table 10. Comparison of production, foreign trade and apparent consumption data from our analysis with FAO and PPI statistics for The Netherlands in 1990 [ktons]

	source	production	imports	exports	app. consumption
paper + paperboard	FAO	2770	2420	2099	3091
basic paper and board	CBS	2757	2498	1893	3362
deviation (%)		-0.5	3.1	-10.9	8.1
recovered paper	PPI	1567	861	635	1820
recovered paper	CBS	1580	866	640	1806
deviation (%)		0.8	0.6	0.8	-0.8
basic wood products[17]	FAO	1217	3983	949	4252
basic wood products	CBS	1334	3698	897	4135
deviation (%)		8.8	-7.7	-5.7	-2.8

The last comparison for paper products is the consumption of newspapers by households resulting from our analysis with the newspaper waste by households in 1990 based on Nagelhout (1991) [15]. Table 11 shows that our results deviate between 5 and 9% with other studies. The lower rows show the comparison of the consumption of different wood products by households. The results of the supply/use analysis correspond well (within 1 - 4%) with Fraanje and Lafleur (1994) who estimated these data based on production and foreign trade statistics and production data from the DIY-sector [14].

Even though just a small selection of the results is compared with other studies, these examples suggest that the methodology results in a representative picture of the actual situation. Furthermore the methodology offers advantages compared to other studies considering detail, consistency and type of information that can be read from the analysis i.e. final consumption, indirect consumption, aggregation per commodity, aggregation per final consumer etc.

Discussion of results

The analysis of the paper and wood flow in The Netherlands showed that paper packaging is a substantial part of the total paper flow (about 35% of the total paper consumption). Wood packaging and wooden parts in products have a smaller share in the total wood flow (about 11% and 9% respectively). A large part of the indirect consumption of paper (packaging) is imported with other products (approximately 60%). For wood products this share is even larger (approximately 80%).
The total final consumption of paper products is calculated at about 3600 ktons. The apparent consumption of paper that results from our analysis is

[17] The FAO presents its wood data in cubic meters. For the comparison we used the densities as stated in FAO (1995)

about 3400 ktons. The difference between the apparent consumption and the final consumption is relatively small (about 5%).

Table 11. Comparison of results of other studies with results of supply/use analysis

type, other studies	amount ktons	type, supply/use analysis	amount ktons	difference (%)
cardboard waste, households	379	cardboard use, households	397	5
packaging paper and cardboard waste, households and service industries	740	packaging paper and cardboard use households and service industries	706	5
newspaper waste, households	345	newspaper consumption, households	315	9
furniture consumption, households	372	furniture consumption, households	368	1
wood board consumption, households	278	wood board consumption, households	290	4

The reason for this small deviation is that the imports and exports of final paper products are about the same magnitude. The calculated final consumption of paper products is larger than the apparent consumption as stated by the FAO [13]. The difference is 13%.
For wood products the difference between final consumption (about 3900 ktons) and apparent consumption (about 4300) is about 9%. The reason for this is that the imports of final wood products are substantially larger than the exports, about 600 ktons and 400 ktons respectively. The difference with the apparent consumption as stated by the FAO is smaller (about 6%) [13].
For the paper flow we are able to calculate the recovery rate of paper because the supply and use tables contain recovered paper data. The recovery rate, the amount of recovered paper that is collected in The Netherlands in 1990 divided by the amount of paper products that is consumed in The Netherlands in 1990, is calculated at 45%. Based on PPI (1997) statistics the recovery rate is be calculated at 51%. The difference in recovery rate is due to the use of final consumption figures in this study compared to the use of apparent consumption figures in the PPI statistics. This shows the value of generating better insights in the final consumption of economies.
The amount of recovered paper that is used by the paper industry amounts to 76% of the feedstock used. The large difference between the recovery rate and the recovered paper input is related to large imports of recovered paper and

basic paper products in The Netherlands.
The calculations resulted in a good overview of the final consumers of the paper and wood products. Households are the major consumers of paper and wood products, 1400 ktons and 1500 ktons respectively in 1990. Especially the amount of paper packaging is very large (700 ktons) compared to the other final demand categories. The largest consumers of packaging wood are the industries (200 ktons).
The consumption of food and tobacco products leads to the largest indirect consumption of packaging paper and packaging wood (600 ktons and 100 ktons respectively in 1990) compared to the consumption of other final demand categories. Furthermore the consumption of metal products and machinery leads to a large consumption of packaging material made out of paper and wood (300 ktons in total).
Based on the total final paper consumption in The Netherlands in 1990, the consumption per capita can be calculated at 237 kg/capita. This is substantially higher than the 204 kg/capita as stated by PPI (1997) [6]. We explain this difference by the fact that we calculated the final consumption of paper products including the indirect consumption of packaging material and that PPI (1997) makes calculations based on apparent consumption figures.

Application of STREAMS-method

Application of the STREAMS method results in data that are categorized according to the definitions compiled by Statistics Netherlands. These category definitions differ from the ones used in the international statistics. These different definitions make data comparisons difficult. We propose that more uniform definitions are used by the different statistical offices.
A shortcoming of the STREAMS method is that only little insight is created in waste flows. This is directly related to the fact that these flows are only recorded in the make and use tables when these flows are subject of trade and represent a monetary value. This shortcoming can only be improved if the focus of statistical offices will shift towards physical flows instead of monetary flows. By doing this also waste statistics may be incorporated in physical make and use tables.
The use of the STREAMS-method for analyzing material flows in other countries than The Netherlands or in future years depends on the quality and availability of statistics. First of all, disaggregated supply and use tables should be available. Secondly, detailed price statistics are needed. In our case, most prices were derived from the foreign trade statistics. Recent developments within Statistics Netherlands resulted in foreign trade statistics where only monetary values are presented. Due to these developments, price calculations become very difficult. Furthermore, due to trade liberalization within the European Union future foreign trade statistics might be of a different quality. If these trends will continue, material flow analysis based on (national) statistics will become more difficult and less accurate.

2.5 Conclusions and recommendations

The paper and wood flows in The Netherlands in 1990 have been calculated using the STREAMS method. The method resulted in a better overview than existing methods, because: (i) a consistent overview of the material streams is obtained because one uniform source is used for the analysis; (ii) the results are more detailed than other methods; and (iii) insight is gained in the material flows that are not visible in statistics i.e. packaging materials and parts (attached to or incorporated in other products). Disadvantages are that the methodology requires some assumptions that are based on the researcher's knowledge of the subject and that it is elaborate (due to numerous price estimates and large numbers of matrix multiplication). Furthermore, case studies need to be performed to assess whether the methodology is also applicable to other countries than The Netherlands.

The application of the methodology to the paper and wood streams showed that the total final consumption of paper products in The Netherlands in 1990 was 3600 ktons. The final consumption of wood products is calculated at 3900 ktons. Paper packaging is a substantial part of the total paper flow (about 35% of the total paper flow). Wood packaging and wooden parts in products have a smaller share in the total wood flow (about 11% and 9% respectively). A large part of the indirect consumption of paper (packaging) is imported with other products (approximately 60%). For wood products this share is even larger (approximately 80%). The results of the analysis also point out that the consumption of food and tobacco products and metal products/machinery leads to the largest indirect consumption of paper and wood packaging. Households consume most paper and wood products compared to other final demand categories. The construction industry is the second most important consumer of wood products and the other industries are the largest consumer of packaging wood. The paper consumption per capita in The Netherlands in 1990 is calculated at 237 kilograms. PPI (1997) calculated the consumption per capita in The Netherlands in 1990 at 204 kg/capita. This indicates that end-use calculations provide other insights in the paper and wood flow than apparent consumption calculations. This effect is also visible for the analysis of the recovery rate of paper. This study shows a recovery rate of 45% in The Netherlands in 1990 while PPI statistics suggest a recovery rate of 51%.

Trends are visible that statistical offices collect less physical data about material flows. We are concerned about these developments because it will make material flow analysis based on national statistics more difficult and almost certainly less accurate.

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Chapter 3

Reduction of CO_2 emissions by improved management of material and product use: the case of primary packaging[18]

Abstract

About 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 about 3% of Western Europe's CO_2 emission. 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 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.

Key words: material use, packaging material, primary packaging, material management, CO_2 emission reduction

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3.1 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 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 6 most important greenhouse gases[19] 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[20] [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[21]. 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 fulfil a specific function. Examples of a function are: to pack an amount of food or to carry a load. Material substitution 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 (about 40%) is packaging [7-9]. The production and consumption of packaging materials is good for about 4% of Western Europe's CO_2 emissions [10].

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

[20] Excluding refineries

[21] 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.

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[22], 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.

3.2 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 Figure 1, a simplified picture of the life-cycle is depicted[23]. 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 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 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.

[22] Western Europe is defined as Norway and Switzerland plus the European Union (15) which includes Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and United Kingdom.
[23] The life cycle is defined as the combination of processes needed by a product to fulfil 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]

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.

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.

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.
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 Figure 1). The energy consumption during material production ($E_{material}$) is obtained by multiplying the GER[24] by the amount of packaging material needed to pack 1000 liters of product. The latter is the specific function that all reference packages need to fulfil, also called the *functional unit* (f.u.). The energy consumption for manufacturing the package ($E_{manufacturing}$) is obtained by multiplying the specific energy consumption of the manufacturing process (in GJ/tonne material) by the amount of materials

[24] 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]

needed per functional unit. The transportation energy ($E_{transport}$) is obtained by multiplying the transportation energy for transporting 1000 liters of product per kilometer by the transportation distance. The transportation energy is allocated on a weight basis over packaging and products. The energy consumption of recycling ($E_{recycling}$) and waste processing ($E_{waste\ processing}$) is obtained by the specific energy consumption of these stages (in GJ/tonne) multiplied by the amount of materials discarded after packaging 1000 liters of product. $E_{waste\ processing}$ can be negative if material is incinerated with energy recovery. The total energy use during the lifecycle 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.

$$E = \sum E_{material} + \sum E_{manufacturing} + \sum E_{transport} + \sum E_{collection} + \sum E_{recycling} + \sum E_{waste\ processing} \qquad (1)$$

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 ($C_{manufacturing}$) is obtained by means of formula 2.

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

In which:

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

I = the initial investment

OM = operation and maintenance cost

CAP = capacity of manufacturing plant expressed in number of packages per year.

The transport costs ($C_{transport}$) are obtained by multiplying the time to deliver 1000 liters 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 tonne material by the volume that was necessary to pack 1000 liter 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 ($C_{waste\ processing}$) are obtained by multiplying waste treatment costs (ECU/kg) by the amount of waste per functional unit. The total costs of the lifecycle are expressed by Formula 3.

$$C_{lc} = \sum C_{material} + \sum C_{manufacturing} + \sum C_{transport} + \sum C_{recycling} + \sum C_{waste\ processing} \qquad (3)$$

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

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

In which:

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

$CO_{2\ lc\ new}$, $CO_{2\ lc\ old}$ = Emission of CO_2 in new and old life cycle, respectively

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 Figure 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 proven technology. Therefore, the time horizon in this study is set at 2010. We use 1995 as the reference year.

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 tonne CO_2 saved are depicted first. The CO_2 reduction potential and the costs of the individual measures per tonne 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.

3.3 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[25], and volume. These data are presented in the next

[25] 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.

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.

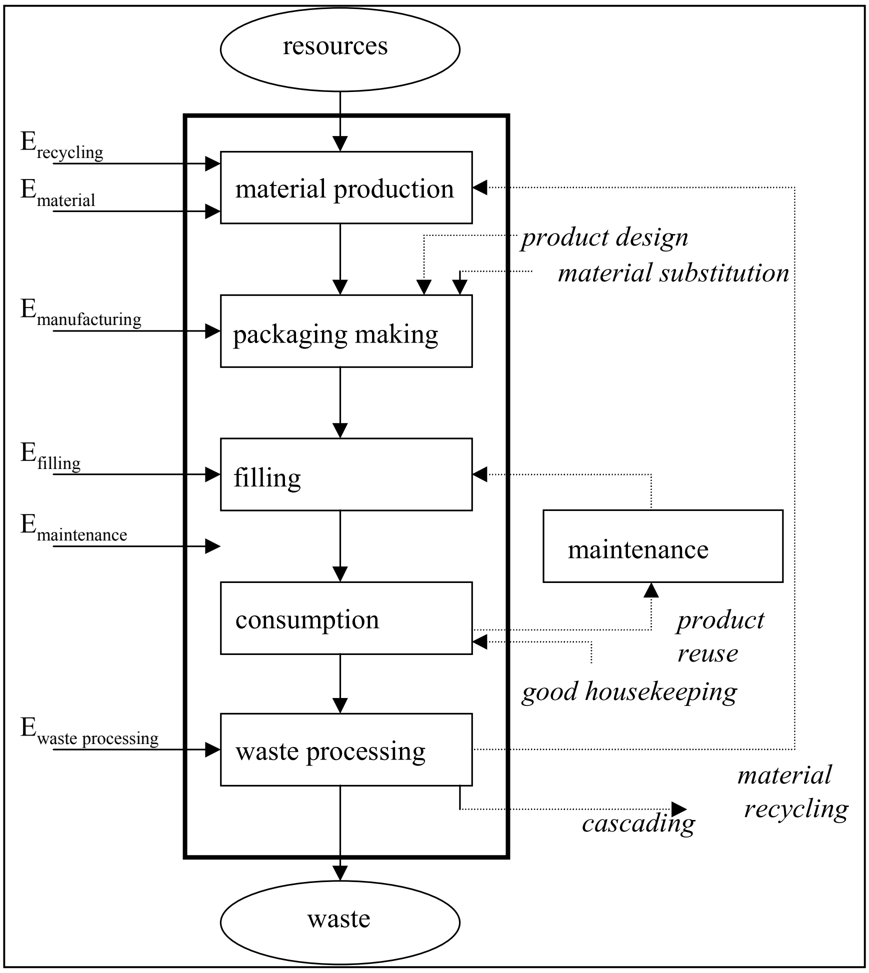

Figure 1: Life-cycle of primary packaging. The simple life-cycle is depicted in the box, improvement options are depicted as dashed lines. On the left side the separate energy requirements of the processes are stated.

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. 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.

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

	feedstock GJ_{prim}/ton	primary energy GJ_{prim}/ton	Electricity GJ_{el}/ton	total GJ/tonne
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

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 kilograms 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 liters of diesel per km for a fully loaded 20 tonnes 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 liters 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, 11520 large (1.5 liter) bottles can be loaded in a truck (24 pallets, carrying 40 crates that contain 12 bottles) compared to 16800 small (0.3 liter) 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.
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[26] 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].

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

	packaging making	**Filling**	**Cleaning**	**transport**	**return transport**
	MJ_{el} /kg pack	MJ_{el} /ton prod	MJ_{prim} /1000 pack	MJ_{prim} /1000 pack	MJ_{prim} /1000 pack
Blowmoulding	12.2				
Thermoforming	5.5				
Film making	2.6				
Can making	2.3				
Plastic bottle (1.5 liter)		202	426	107	0.01
Plastic bottle (0.5 liter)		202		83	
Aluminum/steel can (0.33 liter)		202		83	
Glass bottle (1 liter)		202		107	
Glass bottle (0.3 liter)		202	426	83	0.07
Film (1 liter)		202		90	
Cardboard box (1 liter)		202		90	
Plastic box (0.5 liter)				45	

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.

[26] Final waste is waste that is left after recycling

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

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 approximately 1.3 US$ (1995) [23].

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 hours. Furthermore, we assume that 1 hour is needed for loading or unloading a truck [19]. A total cost (truck + labor) of ECU 22 per hour 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 per tonne) and costs for incineration (156 ECU per tonne) [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.

3.4 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 [7,33,34]. 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 [35]: 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 [36]. This shows that 65% is used for non-susceptible food packaging, 23% for susceptible food packaging, and 12% for non-food packaging.

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	[33]
Cardboard	0,75	[34]

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 (17250 ktonnes[27]) followed by cardboard (4051 ktonnes) and steel (2329 ktonnes). The PE and aluminum use for non-carbonated packaging refers to liquid board packaging that contains aluminum[28] and PE for packaging of juices and milk.

[27] ktonne = 1000 tonne = million kilograms

[28] 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 5: Costs of packaging making, filling, transport, storage, waste treatment

	Unit	PET Bottles	Cans	Glass Bottles	Other Bottles	Boxes	Flexibles	All Pack.
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/tonne product							95
Incineration [26]	ECU/tonne product							156

Table 6: Use of packaging materials per packaging category in Europe

Packaging category	**Material**	**Amount (ktonne)**	**Packaging category**	**Material**	**Amount (ktonne)**
Beverages/	Glass	7500	Dry food /	cardboard	2475
Carbonated	PET	570	non susceptible	PP	756
	Steel	329		LDPE	735
	Aluminum	283		metallocene	220
Beverages/	Glass	6500	Dry food /	LDPE	0
Non-carbonated	Cardboard	751	susceptible	PP	270
	PET	530		aluminum	160
	PE	200		PET	110
	Aluminum	41		metallocene	65
				HDPE	45
Dairy products/	PS	448			
No milk	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			

3.5 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.

Bottles

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 liter bottle that is used to pack soft drinks and milk. The average weight of this bottle is estimated at 500 grams [12]. The second reference bottle is the 0.3 liter bottle that is often used to pack beer. The average weight of this bottle is estimated at 250 grams [37]. 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 liter and a weight of 250 grams; the volume of the glass jar is in between the often-used 37 and 72-centiliter jars [37]. The weight of the reference bottles is calculated based on the weights of several types of bottles that are sold on the Dutch market [38].

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 with 33% and in two projects the weight of liquor bottles was reduced with 20% and 22%, respectively [14,39]. 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 [38]. 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.

Besides by 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% [40]. 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 [41]. 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 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.

PET bottles

PET (Poly Ethylene Terephthalate) bottles were introduced in the soft drink sector to replace the standard 1 liter glass bottles. PET bottles are especially suited to pack carbonated soft drinks. PET bottles also replace PVC bottles that are often used in South Europe for the packaging of mineral water [39]. 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 [42].

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 liters and a weight of 50 grams [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 [43]. They weigh 103 grams. The refillable PET bottles are designed to make 25 trips during a lifetime of 4 years [19,44]. Many bottles, however, make less trips because of damage during the refill process (scuffing) [44]. We will model the refillable PET bottle as having a volume of 1.5 liters, a weight of 103 grams, and a trip number of 20 [10].

PET bottles normally are made out of virgin PET. Coca-Cola developed a three layer PET bottle with a recycled PET inner layer [45]. We will model this bottle that contains 25% recycled PET as an improvement option for the reference bottle.

Liquid board package

Cardboard as packaging for liquids has been used for several decades. The Tetra Classic was introduced as early as in 1952 [33]. The most important markets for liquid carton board are milk and juice packaging. Less important are wine, water, and soup [33].

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 grams for a 1 liter package [46]. 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 SiOx layers may be used for extended shell life [47,48,49]. 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 liter package to 1.5 liters saves 9% of packaging material per liter [14]

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 [34]. For food cans, the situation is entirely different. Tin-plated steel commands 100% of the European food can market [50].
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 grams. The aluminum lid adds another 2.7 grams. The reference 33 ml aluminum beverage can weighs about 14 grams including the lid [34,39]. Food cans are used in a wide variety of sizes. We will use a one liter can as the reference can. A 1 liter steel can has an average weight of 88 grams [51].
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% [34]. It is already possible to produce a steel can body that weighs 23 grams. Hoogovens is developing ultra thin steel that should make it feasible to produce can bodies that weigh 18 grams by the year 2000 [34,47,52]. Aluminum producers estimate that an aluminum can in the year 2000 will weigh 13 grams (including lid) [53]. Both the aluminum and steel light cans are expected to replace the current aluminum and steel cans completely [53]. 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 [51]. 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 [52]. The lid of the all steel can weighs about 8 grams. The total weight of the all steel can in 2000 will be around 26 grams. We expect that full penetration of the all steel can is feasible.

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 grams, respectively [52]. No options to improve these packages have been reported in literature. As possible improvement option we suggest replacement of PS by PP cups. PP yogurt cups are lighter than PS cups; 12 and 14 grams, respectively. Furthermore, the GER of PP is lower than the GER of PS.

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 [55]. The advantage of using pouches for liquid packaging is that they are extremely light. An empty 1 liter pouch from Elopak weighs 10 grams whereas an empty 1 liter pouch from Tetra Pak only weighs 4 grams. The pouches are harder to handle than non-flexible packaging; after opening they need to be emptied in 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 grams for a 1 liter bottle), that is refillable, and that it has a trip number of 30 [40,56]. Moreover, the square shape of the bottle leads to savings of shelf space.

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 liter as the reference bottle. Based on the weight of shampoo bottles the weight of the reference bottle is estimated at 500 grams [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 grams, 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 an 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 liters of non-food liquids, 5 grams of HDPE is needed if a pouch is used. The cardboard package weighs 14 grams, including 1.8 grams of LDPE laminate [56]. 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.

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 liter, the reference box weighs 35 grams [10]. The second reference box has the same characteristics and contains an inner PE bag that weighs 3 grams. 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 grams of HDPE and 2 grams of board) and a volume of 0.5 liter [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 [13-16,56].
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 [13-16,58], which makes complete recycling of blister packaging possible. On average these blisters weigh 17.5 grams for 0.5 liter packages [10]. No technical

barriers are expected that may prevent full implementation.

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 ktonnes in Europe) and PP (585 ktonnes) [7]. Therefore, we define a LDPE and a PP bag as reference package. Average film thickness is 40 and 30 μm[29] for LDPE and PP films, respectively [10]. A reference LDPE bag weighs 3.7 grams and a PP bag weighs 2.7 grams assuming a packaged volume of 1 liter.

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 [40,51,59,60]. Third, the use of paper wrappings (8 grams) may also be an improvement due to the renewable nature of the feedstock.

High barrier films are typically multilayer films, either coextruded laminates or coated films. Typical laminates consist of a carrying layer made from PP (25-30 :m) and a barrier layer made from PVdC, a super thin (2-3 μm) layer with excellent barrier properties [61]. We define a reference high barrier film that weighs 3 grams for a one-liter 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) [61]. The use of PP metallocene may also result in a thinner carrying layer (15% less) [44]. 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 one-liter package weighs 1.6 grams. 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-liter packages that weigh 1.3 grams in 2010.

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 fulfil a packaging service of 1000 liters of

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[29] μm = micrometer = 10^{-6} meter

packed products. The process energy requirements are defined as all energy used in the life cycle of packaging materials except material production.

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 versus 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.

3.6 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 tonne 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 Figure 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.

Table 7: Measures for reducing CO_2 emissions related to packaging consumption expressed per 1000 liters of packaging service. New packages and packages with currently a small market share are stated in italic.

	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	147	375	107	358
Glass bottle small	327	833	278	767
Glass bottle small refillable	172	42	611	155
PET bottle one way	85	33	71	230
PET bottle reusable	78	3	138	65
PET bottle reusable recycl.	78	3	138	63
PET bottle to be recycled	85	33	71	202
Steel bev can	162	78	253	223
Steel bev can light	153	63	253	187
All steel bev can	168	87	253	244
Aluminum bev can	179	42	253	288
Aluminum bev can light	174	39	253	271
Liquid board	74	28	107	83
Liquid board (1.5 liter)	55	25	71	69
Pouch	61	4	107	52
PC bottle	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	172	400	167	383
Steel food can	135	94	167	254
Steel honeycomb food can	116	66	167	189
HDPE bottle	152	100	167	649
Recycled HDPE bottle	152	100	167	512
Pouch	69	10	167	86
Liquid board	90	28	167	87
Cardboard box	78	35	90	42
Cardboard box light	73	28	90	38
Cardboard box + bag	83	38	90	58
PVC blister	127	36	90	172
Cardboard blister	128	35	90	42
LDPE film	53	4	107	38
LDPE film thin	52	3	107	36
PP film	52	3	107	33
PP film thin	52	2	107	32
PP laminate	52	3	107	33
PET laminate	53	2	107	31
PP metalised	51	2	107	28
PET metalised	52	1.5	107	27

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/tonne 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 recycl.	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 recycl.	PET bottle one way + PET bottle. to be recycl.	15.1	-40

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 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.

Figure 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 Figure 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[30] were not taken into account, as no estimates are available. Transaction costs would decrease the cost-effectiveness of measures.

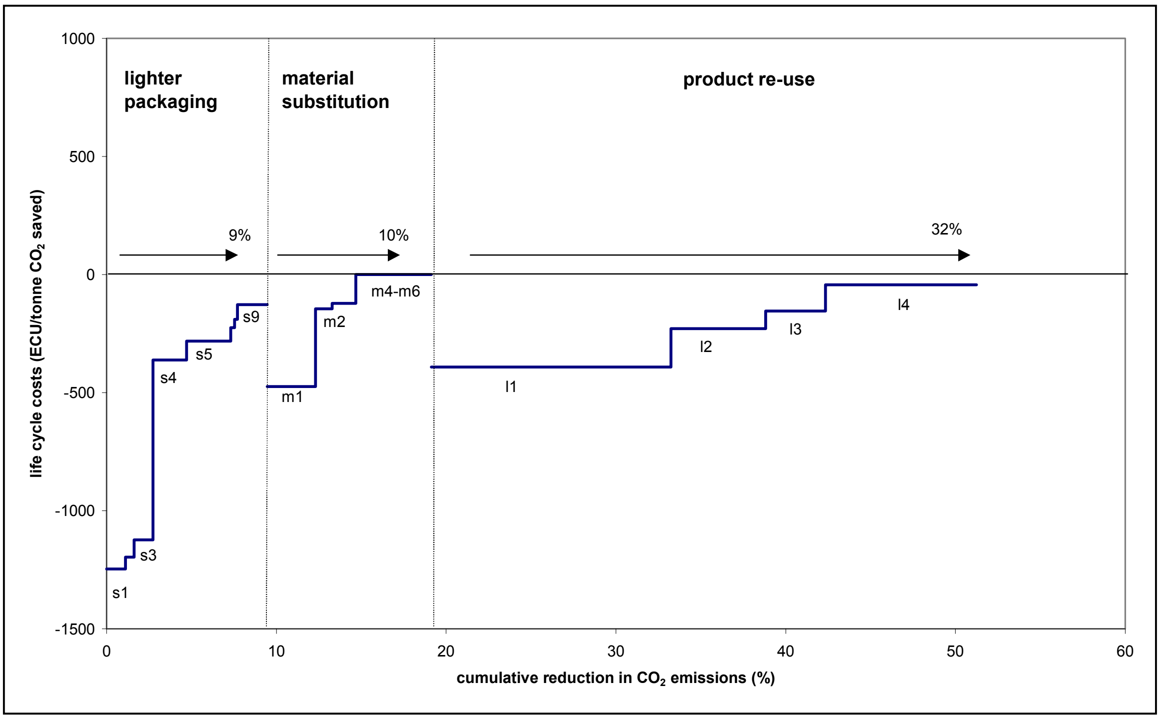

Figure 2: A supply curve for the reduction of CO_2 emissions by improved use of materials for primary packaging in Europe. The horizontal axis depicts the total reduction in CO_2 emission in %. The three types of improvement measures are also ordered over the horizontal axis. On the vertical axis the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

[30] 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 Mtonnes 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 Mtonnes 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 [62].

3.7 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.

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. Figure 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. Figure 3 shows, in comparison with Figure 2, that the potential 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 Figures 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 [64].
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.

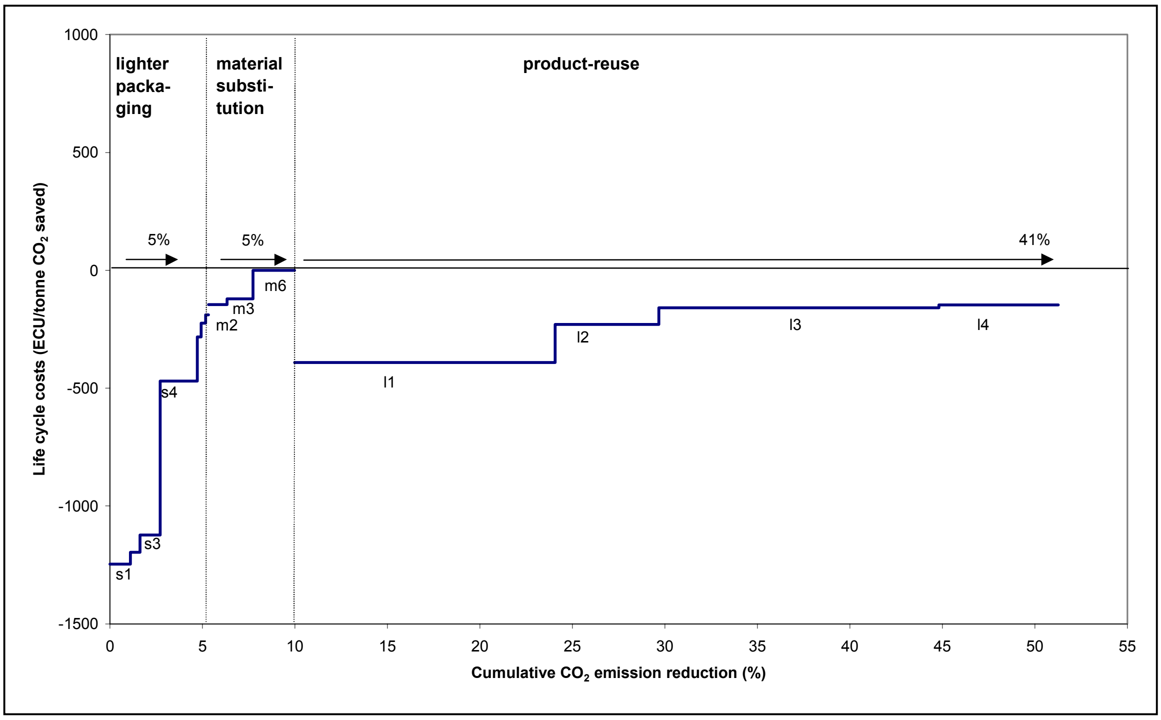

Figure 3: A supply curve for the reduction of CO_2 emissions by improvement of the material efficiency of primary packaging in Europe. In this supply curve the measures that are difficult to implement are implemented first. The numbers refer to Table 8.

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/kg 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/tonne to about $2000/tonne, 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/tonne to $580/tonne and fell back to $250/tonne in the period 1995 - 1996 [65].
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.

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.

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/tonne 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/ tonne 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 of final calculations. We also increased the average transport distance from 200 km to 800 km to find out whether a large distribution area (e.g., the United States) 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 (about 10%). This shows that the CO_2 emission reduction of reusable packaging is fairly insensitive for fluctuations in energy consumption of cleaning processes.

3.8 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 tonne 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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Chapter 4

Reduction of CO_2 emissions by improved management of material and product use: the case of transport packaging[31]

Abstract

About 40% of the global primary energy use and emission of CO_2 is related to the production of materials. In this study we investigate the potential and cost-effectiveness of CO_2 emission reduction by means of improved management of material use for transport packaging in Western Europe. Measures for improved use of transport packaging material are identified and evaluated. A supply curve for CO_2-emission reduction is presented based on data about the use of transport packaging in 1995. We show that technically it seems possible to reduce the CO_2 emissions related to the production and use of transport packaging in 1995 by 40% when new packaging technology is implemented that is expected to become available between 1995 and 2010. In this reduction figure, improvement of energy efficiency in material production processes and changes in packaging demand are not taken into account. Most evaluated measures can be implemented cost-effectively, when taking life-cycle costs into account. This would result in a CO_2 emission reduction of 34%. Evaluation of the measures shows that 12% reduction of CO_2 emissions related to transport packaging is possible by using lighter packages. Material substitution can lead to a reduction of also 12%. From a CO_2 emission reduction point of view, the most promising improvements are large changes in the packaging system like substitution of single use packaging by re-usable packaging. This may lead to 16% reduction in CO_2 emissions. However, large scale introduction of this option may be hindered by the complexity of implementation.

Key words: material use, packaging material, transport packaging, material management, CO_2 emission reduction

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4.1 Introduction

For the production of packaging many types of materials are used like glass, plastics, paper and steel. The production processes of these materials are energy intensive. The energy requirements for production of these materials vary from 20 GJ/tonne for packaging paper to 70 GJ/tonne for plastics and 187 GJ/tonne for aluminum [1]. The energy consumption and CO_2 emissions that are related to the production of these materials can be reduced by energy efficiency improvement in the production route and by improved material management.

To reduce the energy consumption and emission of CO_2, many studies focus on improvement of the energy efficiency of production processes. Improved management of materials, however, has had much less attention. Most material management studies that evaluate measures like material recycling, material substitution and product design focus on the effects on waste reduction.

There are a few studies that focus on the relevance of material use to reduce CO_2 emissions. In [2] the importance of materials as sources and sinks of CO_2 emissions is discussed. Less attention is given to ways and means to reduce the related CO_2 emissions. In [3] the same author concludes that "..the potential for emission reduction in the materials system seems to be of a similar magnitude as the emission reduction potential in the energy system". In 1998, EPA published a study on greenhouse gas (GHG) emissions from management of materials in municipal solid waste [4]. The study shows that management of materials presents many opportunities for GHG emission reduction. However, the focus of the study is on waste management; a detailed investigation of options for more efficient material management in the production and consumption stage is not carried out. Two studies from Utrecht University describe how more efficient management of materials may lead to reduction in energy use. In [5] the potential of energy savings due to more efficient use of fertilizer is investigated for The Netherlands. In [6] an approach is described for analyzing the potential of material efficiency improvement which is subsequently tested on plastic packaging in The Netherlands. Both studies show that there is a significant potential for reduction of CO_2 emissions by more efficient use of materials in those specific cases. Finally in [7] the United Nations Department of Policy Coordination and Sustainable Development state the importance of material efficiency research in order to understand the potentials for emission reduction.

In an earlier study we already showed that more efficient use of *primary* packaging may result in significantly lower CO_2 emissions [8]. The objective of this study is to investigate options for more efficient use of all materials related to *transport* packaging in Western Europe and to calculate the CO_2 emission reduction potential when these options would be implemented. Information on the total material use and CO_2 emissions related to transport packaging in Europe has not been published in literature and is therefore part of the objective of this study.

In the next section we describe the method we use to investigate the options: The method is derived from an approach presented by Worrell et al. [6]. In section 3, we present the general input data we use in this study. In section 4 the demand for transport packaging materials in Western Europe is analyzed. Section 5 elaborates on current packaging technology and possible measures to improve materials management. In section 6 the potential reduction in CO_2 emissions is calculated and evaluated. We end with a discussion and conclusions.

4.2 Method

The method that we used for calculating the potential and cost-effectiveness of CO_2 emission reduction by improved management of materials used for transport packaging is identical to the method that we used for similar calculations on primary packaging. We will describe the method shortly. For a detailed description we refer to [8].

The method consists of 6 steps. First the current consumption of transport packaging is analyzed. Because many different packaging products exist, with a large variety in packaging characteristics, we cluster them in a number of categories. For the analysis we have selected the following 6 categories: (1) carrier bags, (2) industrial bags, (3) transport boxes, (4) grouping films, (5) pallets, and (6) transport films. We differentiate between transport films and grouping films because transport films are used to bundle packages on a pallet while grouping films are used to bundle smaller amounts of rigid packaging. For this reason, the strength requirements for grouping films are different than for transport packaging. We differentiate between carrier bags (for transport of final products by consumers) and industrial bags (for transport of intermediate and bulk products) for the same reason. The strength requirements for carrier bags are smaller than for industrial bags.

Second, reference packages are defined to model the wide variety of packages that exist within the defined categories.

Third, the lifecycle CO_2 emissions and the life cycle costs are calculated for the reference packages. This is done by summation of the CO_2 emissions and costs of the individual life cycle stages and transport between these stages. We discern the following stages: material production, packaging making, filling, unpacking, maintenance, waste collection, and waste management (see Figure 1). All CO_2 emissions and costs are calculated per specific function that all packages need to fulfil, also called the functional unit (f.u.). For all categories, except the category 'industrial bags', the functional unit is defined as 1000 transport trips. A transport trip is defined as the transport of a package (e.g. a transport box or pallet) plus packaged goods from the filling stage to the unpacking stage (see Figure 1). For industrial bags the CO_2 emissions are calculated for transportation of 1000 kilograms of products in order to be able to compare packaging concepts with different volumes.

Fourth, we identify measures that lead to an improved use of materials in the life cycle of the reference packages. Improved use of materials considers all measures that lead to a reduction of CO_2 emissions in the life cycle of the package. In Figure 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. Options are only taken into account if they are technically feasible in the short term or are already proven technology. The time horizon in this study is therefore set at 2010. 1995 is used as reference year.

In this study only improvements in *packaging* technology are taken into account. Other improvements that could reduce the CO_2 emission related to the production and use of packaging are not studied, e.g., improvement of energy efficiency of material production processes, energy efficient transportation systems, and changes in waste management technologies.

Fifth, the CO_2 emissions and the life cycle costs of the improved packages are calculated and compared to the standard packages. The CO_2 emission reduction potential is calculated by multiplying the difference in CO_2 emission between the improved and the reference package per functional unit by the number of functional units that correspond to the actual packaging consumption in the reference year.

Sixth, the cumulative CO_2 emission reduction is calculated for the situation where all measures are implemented. The measures are also evaluated in terms of cost-effectiveness. A supply curve is used for this evaluation[32]. Choices about the order of implementation are important because measures can influence the potential savings of each other, or even prevent the application of a specific measure. In [8] we partly based the ordering of improvement measures on the difficulty of implementation. A first assessment of the difficulty of implementation was made by assuming that the most critical factor that determines the difficulty of implementation, is the necessary change in the packaging system. This way of ordering proved to be helpful to create insights in the CO_2 emission reduction potential of a wide variety of improvement measures. In this paper we will also order the improvement measures by implementation difficulty. For construction of the supply curve the measures with low implementation difficulty are implemented first and measures with high implementation difficulty are implemented later.

The quality of the input data and the influences of the choices made in different stages of the method, e.g., definition of reference and improved packages and

[32] See [6] for a detailed description about the construction of a supply curve for reduction of CO_2 emissions by improved material use of packaging materials.

evaluation of measures, is discussed by means of a sensitivity analysis in the discussion.

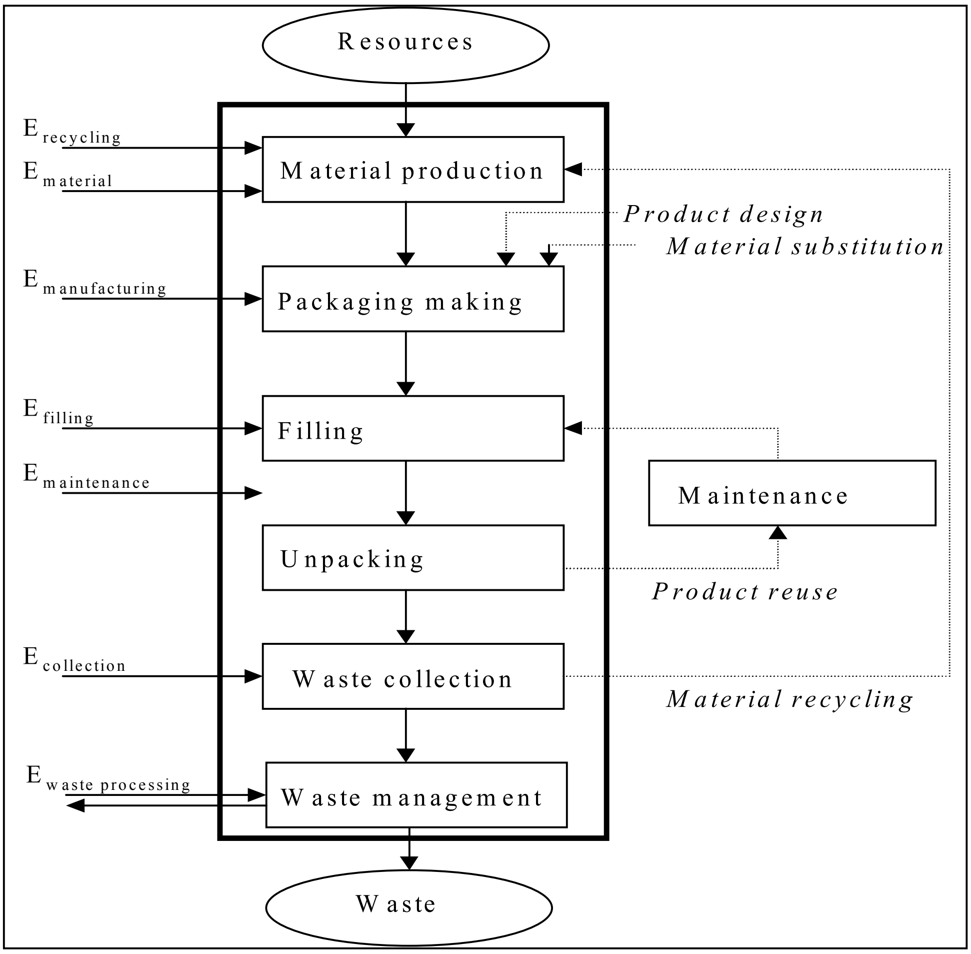

Figure 1: Life-cycle of transport packaging. The simple life-cycle is depicted in the box, improvement options are depicted as dotted lines. On the left side the energy requirements of the different processes are stated. Unpacking is assumed to require no energy since it is not a mechanical procedure.

4.3 General Input data

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

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 making, filling, transport, maintenance, waste collection and waste management.
To calculate the energy consumption for material production we use the gross energy requirements (GER) for the materials involved. The GER value of products is equal to the embodied energy (feedstock) plus the amount of energy that is used for the production and transportation of feedstocks, semi-finished products and the final product. In Table 1 these GER values are stated for the materials used in this study.
The energy use for manufacturing depends on the type of package and the production processes involved, e.g., injection moulding for pallet and crate production, extrusion of plastics film for production of shrink covers and stretch films, and production of boxes from corrugated board. In [9] the energy requirements of these processes are presented in MJ_{el}/kg package. The results are summarized in Table 2. From this table one can see that the energy requirements for packaging making are sometimes negligible compared to the energy requirements of the production of the materials involved [9].
After producing the package, it also needs to be filled. For the investigated improvement measures, the energy requirements for filling transport packaging does not differ significantly. Therefore, data for filling transport packages are not part of the calculations. However, there is one exception, which is the use of shrink covers. For this type of packaging extra energy is needed for heating the cover to make it shrink. The energy requirements for this process are taken into account.

Table 1: GER values for materials used for transport packaging per tonne packaging[1] [9-11]

	Feedstock $GJ_{primary}$/tonne	**Primary energy** $GJ_{primary}$/tonne	**Electricity** $GJ_{electricity}$/tonne	**Total GER** $GJ_{primary}$/tonne
PE	47.7	30.1	7.9	97.6
Recycled PE	0.0	0.6	0.6	2.1
PP	47.7	25.5	6.9	90.3
Recycled PC	0.0	0.6	0.6	2.1
PET	45.8	29.0	9.0	97.3
Corrugated board	18.6	6.0	8.2	45.1
Packaging paper	0.0	11.5	0.6	12.9
Sawn wood	15.6	5.3	0.8	22.8
Pressed wood fibers	17.3	7.4	0.3	25.6
Glue	40.0	40.0	0.0	80.0

[1] The GER values in Table 1 are broken down in feedstock energy that is embodied in the final product and both electricity and primary energy that are used in various production and transportation processes in the production of the final product. Recycled materials have zero feedstock energy by definition. To be able to add the $GJ_{primary}$ and $GJ_{electricity}$ we have assumed an efficiency of 40% to convert primary energy into electricity.

The energy that is necessary for transportation of the packed products to the stores is allocated to primary packaging [8]. To avoid double counting, in this study we do not take these energy requirements into account. However, we do take the extra transport into account that is necessary when multiple use transport packaging is used. In many cases, multiple use transport packaging is part of so-called 'packaging pools'. A packaging pool refers to a service organization that owns returnable pallets and crates. These pallets and crates are rented by the distributors. The advantage of such a pool system is that the individual distributors need to keep less pallets and crates in storage for sudden demand fluctuations. We will model a system where crates and pallets are returned to the pool-owner after each product delivery for cleaning. We will assume average transport distances of 100 km between pool-owner and distributor and between pool-owner and customer[33].

Cleaning of transport packaging is only needed for multiple trip packaging. We will use average energy requirements for large cleaning facilities [12].

Packaging waste is either landfilled or incinerated. Incineration plants can produce heat and electricity. In Western Europe 75% of the final packaging waste[34] is landfilled and 25% is incinerated [13]. Thirteen percent of the waste is incinerated with energy recovery, either heat (54%), power (12%) or combined heat and power (34%) [13, 14]. 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 17% and a thermal efficiency of 60% [15].

Table 2: General energy use data for several packaging processes and packages[1] [9, 11, 13]

	Packaging making	**Filling**	**Cleaning**	**Transport**
	MJ_{el} /kg pack	**MJ_{el} /kg pack**	**MJ_{el} /1000 pack**	**MJ_{prim} /1000 trips**
Plastic crate	3.1		270	4590
Stretch film	2.6			
Corrugated box	0.1			
Shrink cover	2.6	7.56		
Paper bag	neg.			
PP bag	2.6			
Wooden pallet	neg.			
Plastic pallet	3.1		270	5048

[1] The abbreviation neg. is used to indicate that the energy use for packaging making is negligible to the energy use for materials production. Empty cells indicate for filling that the energy use is the same for all packaging concepts, for shrink covers extra energy is needed.

[33] This is based on the fact that a large Dutch pool owner has two central facilities in The Netherlands [41]

[34] Final waste is waste that is left after recycling

The empty cells for cleaning and transport indicate that no energy is required for the packaging concepts.

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 life cycle can be calculated. For emissions from electricity production and primary energy use we use average CO_2 emission data for Western Europe [16, 17]. CO_2 emission factors for incineration of plastics are derived from the oxidation reactions. For paper, board and wood 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.

Table 3: CO_2 emission factors for electricity, primary energy carriers and packaging materials as used in this study [16, 17].

	Electricity	**Coal**	**Oil**	**Gas**	**Wood**	**PC**	**PE**	**PP**	**Corrugated board**
kg CO_2/GJ	123.6	94.6	73.3	63.1	0.0				
kg CO_2/kg					0.0	2.8	2.8	2.8	0.0

Data on costs

The life-cycle costs of reference and improved packages are calculated by summation of the costs for material production, packaging manufacture, transport, recycling, and waste 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 approximately 1.3 US$ (1995) and 2.1 Dfl (1995) [18].

The costs of packaging manufacture depend on the investments for the packaging line and the costs of operation. No detailed data on investment and operation costs are available for the different packaging concepts. We therefore calculate the production costs by subtraction the material costs from the average prices of the packaging concepts and taking a 10% profit margin into account [19]. The data on prices, material costs and production costs per 1000 packages are stated in Table 5. In Table 6 the production costs are also stated per 1000 packaging trips.

The costs for filling the transport package do not differ significantly between different transport packages and are therefore not included in the calculations.

Table 4: Material costs for several packaging materials [11, 20-22]

Material	Market-price (ECU/kg)
LDPE (film) [20]	1.14
HDPE (film) [20]	1.23
HDPE (injection moulded) [21]	1.01
Recycled PE (film) [21]	0.60
Recycled PE (injection moulded) [21]	0.49
PP [20]	0.70
Paper [22]	0.47
Corrugated board [22]	0.30
Wood [11]	0.25
Recycled PC [21]	2.09

Table 5: Prices, material costs and production costs of transport packages [19, 23-28]

	Prices ECU/1000 pack	Material costs[1] ECU/1000 pack	Production costs ECU/1000 pack
Multiple use PE pallet [23]	75000	30400	40100
Multiple use recycled PE pallet [23]	25000	14600	9400
Multiple use recycled PC pallet [23]	75000	30800	39900
Single use wooden pallet [23]	5000	4300	680
Multiple use wooden pallet [23]	20000	6300	12400
Corrugated pallet [24]	6000	1800	3800
Pressed wood pallet [24]	5000	4000	900
Plastic crate [25]	3000	2000	875
Wooden crate [26]	1000	550	400
Corrugated box [27]	700	250	400
Pallet covers [27]	2100	1500	550
Pallet shrink film [27]	850	600	250
Grouping film [27]	40	25	10
Carrier bag [19]	70	25	40
Paper bag [19]	110	25	75
Reusable bag [19]	509	170	300
Industrial bag [19]	360	120	220
Industrial paper bag [19]	390	130	240
FIBC [28]	3700	1200	2200
Returnable FIBC [28]	6360	2100	3800

[1] calculated by combining the packaging characteristics as described in section 5 with Table 4

The costs for extra transport of the returnable packages as stated in Table 6 are estimated by assuming an average transport distance of 100 km and a total delivery time of 3 hours. Furthermore we assume that 1 hour is needed for

loading or unloading a truck. A total cost (truck + labor) of ECU 22 per hour is assumed [12]. For returnable transport packaging, extra costs for storage 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 [12] and that empty pallets and crates are stored for one week before they are returned to the producer.
When returnable packages are used, extra costs have to made for organizing a system where pallets and crates are returned after usage (see section 4.5). In Table 6 these 'pool costs' are based on the tariffs that are used by pool organizations in The Netherlands [29]. Returnable packages are often cleaned before they are used again. The costs as stated in table 6 are based on the use of large cleaning facilities [29].
Waste management costs are differentiated between costs for landfilling (95.3 ECU per tonne) and costs for incineration (156.3 ECU per tonne) [30].
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.

4.4 Material use for transport packaging in Europe

To estimate the potential of material efficiency improvement for transport packaging information is needed about the current material input[35].
The plastic demand for production of carrier bags is estimated at 430 ktonnes [13, 31]. Carrier bags are most often made out of PE. The amount of plastic (PE) industrial bags is estimated at 460 ktonne [31].
Industrial bags can also be made out of paper. The amount is estimated based on the cement production in Europe because these bags are used mainly for cement packaging. Ten percent of the European cement production is packed in bags [32]. The amount of paper is estimated at 85 ktonnes and due to the PE layer in these bags the PE demand is estimated at 15 ktonnes [32]. Transport boxes can either be made out of corrugated board (11700 ktonnes) or PE (884 ktonnes) [13, 22]. The amount of grouping films amounts to 290 ktonnes in 1990 [31]. We estimate the 1995 demand at 310 ktonnes based on the average growth of PE consumption in Europe [13, 31].
The demand for pallets in Europe is 280 million per year [33]. The majority of these pallets is made from wood (96%). Taking into account that a single use pallet weighs 17 kg and a multiple use 25 kg and that 66% of the pallets are single use. The total wood use is calculated at 4956 ktonnes [33, 34]. The remainder of the pallets is assumed to be made from PE which adds 336 ktonnes to the material use when an average weight of 30 kg is assumed [35]. Transport films can be subdivided in shrink covers (380 ktonnes of PE) and stretch film (320 ktonnes of PE) [31][36]. An overview of the total material use per

[35] No information was found on efficiency improvements for steel barrels. In the material use analysis steel consumption is therefore not taken into account.
[36] 1990 data from [28] extrapolated to 1994 with growth rate of PE consumption

category is stated in Figure 2. The figure suggests that the plastics demand is totally satisfied by PE. This is not the actual situation. Division of total European packaging films by resin shows that 81% of the resins used is PE, 14% is PP, and 4% are others [13]. In Figure 2 no differentiation is made between PE and PP because no information is available on the PP shares for the various categories.

Table 6: Costs of packaging making, transport, organization, storage and cleaning [12, 19, 23-29][1]

	production ECU /1000 trips	transport ECU /1000 trips	Organization ECU /1000 trips	storage ECU /1000 trips	cleaning ECU /1000 trips
Multiple use PE pallet	535	675	500	49	3
Multiple use recycled PE pallet	130	675	500	49	3
Multiple use recycled PC pallet	530	675	500	49	3
Single use wooden pallet	680				
Returnable wooden pallet	300	675	500	49	3
Corrugated board pallet	3800				
Pressed wood pallet	200	340	500	49	3
Plastic crate	10	370	150	22	3
Wooden crate	80	370	150	22	3
Corrugated box	400				
Pallet cover	550				
Pallet shrink film	250				
Grouping film	10				
Carrier bag	40				
Paper bag	75				
Reusable bag	300				
Industrial bag	220				
Industrial paper bag	240				
FIBC	2200				
Returnable FIBC	750				

[1] Empty cells indicate that no transport, pool organization, storage or cleaning is necessary for these packaging concepts.

Figure 2 shows that the corrugated board is used most for transport packaging (11.7 Mton), followed by wood (about 5 Mton) and plastics (about 3.5 Mtonne). Only a small amount of paper is used (about 0.1 Mtonne).

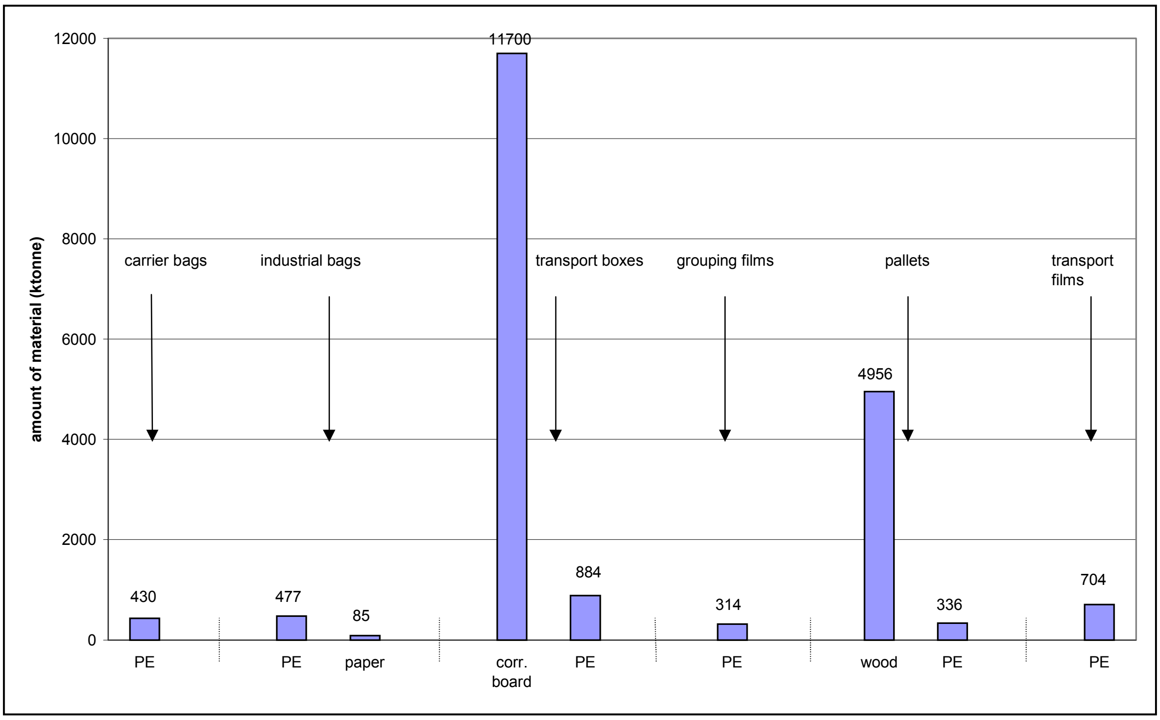

Figure 2: material demand for transport packaging in Europe in 1994

4.5 Reference and improved packaging concepts

In this section we describe both the reference and the improved packages. Reference packages are model packages that have characteristics that correspond to the average characteristics of types of transport packaging in Europe. We will describe the packages per packaging category and per material type used.

Carrier bags

Carrier bags are most often made out of plastics, more specifically, most bags are made from LDPE [36]. The thickness of the films used for the production of carrier bags varies between 10 to 200 micron. The average carrier bag in The Netherlands weighs 20 grams and has dimensions of 40x35 cm [37]. Based on this we have defined a reference carrier bag that is made out of LDPE, weighs 20 grams, has dimensions of 40 cm by 35 cm, and a thickness of 66 micron.
Several measures can be applied to reduce the material demand and related CO_2 emissions for carrier bags. The first measure is to reduce the weight of the carrier bags. Substitution of LDPE by HDPE reduces the weight of carrier bags by 20% [38]. Co-extrusion of plastic films also leads to weight savings of 20%[37]

[37] Tables 1 and 2 show that the energy use for packaging making is small compared to the energy use for plastics production. We have therefore assumed that an increase in energy use for co-extrusion compared to normal extrusion is negligible for the total energy use related to the production of carrier bags.

[37]. We will model these developments by defining a light bag that weighs 20% less.
Another possible measure to reduce material related CO_2 emissions is substitution of the material types used. PE can be substituted by paper. Paper bags are heavier than the average plastic bag. An average paper bag with the same dimensions as the PE bag weighs 56 grams [37]. We assume that full penetration of this option is technically possible.
Most carrier bags are made from virgin PE. Besides virgin PE also recycled PE can be used. The recycled PE content can be 15-20% without changes in the appearance and strength of the bag [19]. If carrier bags are made from 100% recycled resin the weight increases by 50% [19]. We model a bag made from 100% recycled resin that weighs 30 grams as an improved package. We assume that full penetration is technically possible.
The last option is to reduce the amount of bags. In The Netherlands the government and retailers agreed that plastic bags should not be handed out for free [38]. This resulted in a reduction of the amount of carrier bags because consumers started to reuse bags or make use of durable carrier bags. We will model this option by defining a bag that can be re-used. The model re-usable bag is made from PP straps, weighs 240 grams and has a lifetime of 100 shopping trips [39]. Technically, full penetration seems to be possible. However, this will require large behavioral changes of the European consumers.

Industrial bags

Industrial bags are used to pack products like plastic granulate, animal feed, fertilizers, soda, and cement. A large variety in size and thickness is used. We define a reference plastic industrial bag that is capable of carrying 25 kg which is an often used size due to the handling characteristics of 25 kg bags [32] The bags, made from HDPE, have a thickness of 150 :m and weigh 105 grams [40, 41]. Besides plastic bags also paper bags are used to pack products like cement and fertilizer. The bags are often multi-wall paper with a PE moisture-proofing layer. We have defined a reference paper bag that weighs 262 grams (252 grams paper and 10 grams LDPE) and has the same size as the plastic industrial bag [41].
Unlike carrier bags we do not expect that much savings on the bag weight is possible because strength characteristics are very important for industrial bags and reduced performance of industrial bags leads to large costs due to product loss.
The only improvement option that we will model is the substitution of PE bags by the Flexible Intermediate Bulk Container (FIBC). The FIBC is made from woven PP straps (200 gram/m^2) and weighs around 1.5 – 2 kg. The carrying capacity is 1000 kg. In principle this bag is only used once. Multiple use bags are also delivered even though they are not used very often. These bags are made from heavier material (240 gram/m2) and have reinforced carrying straps [28]. We assumed that implementation of this option is only technically

possible when it is used for professional purposes. We estimate that the majority of industrial bags are used for industrial purposes (90%).

Transport boxes

The most common transport boxes are the boxes made from corrugated board. These boxes are suitable to transport dry food and non-food products. In fresh-products sectors, e.g., fruit and meat sector, the most common transport box is the crate. A crate is an open transport box (no top or lid) with generally a larger floor surface and a smaller height. In the fruit sector crates from corrugated board are common while in the meat sector plastic crates are standard.

Corrugated box

We define the reference corrugated box as having a volume of 40 liters (40x60x17 cm) and a weight of 800 grams [27]. Boxes of 40 liter are used often for transport of food products and for this size boxes, 800 grams is an average box weight [27].
Several options are available to improve the standard corrugated box. New box making machines have been introduced to the market that make for example better use of corrugated board due to improved gluing techniques (less overlap of corrugated board is needed). Savings of 15% corrugated board have been reported [42]. Shape-renewal of boxes also has led to the use of less corrugated board, e.g., in some cases it is possible to remove the top flaps of the boxes which leads to savings of 20-30% [42, 43]. In other cases it was possible to reduce the box height [43, 44]. Also projects demonstrated the potential of improving the packaging operation itself. Standardization of primary packages, for example, saved 20% corrugated board by a milk producer since only one type of box was required that is smaller than the average size of the boxes used before [42, 43]. Also more efficient stacking of primary packages and changing the primary packaging design resulted in smaller transport box sizes [42, 43, 44]. Concentration of the product or a smaller primary package can lead to major savings in transport packaging. Savings of 16 – 30% have been reported in the period 1992-1996 by the use of smaller primary packaging and concentration [36, 42, 43]. Based on all these experiments where savings in the range of 15-30% are reported we assume that 20% less corrugated board is needed to fulfill the same packaging need. We model this as a lightweight box that weighs 20% less.

Crates

Crates are normally used to pack loose products like fruit and vegetables, meat and product parts[38]. The crates can be used for one-way shipping or function as a returnable package. The one-way crate is mostly made out of wood or corrugated board and is normally used to pack fruit and vegetables. No information is available on the market shares of wooden and corrugated

[38] Crates are also used for transportation of bottles. No improvements for these crates have been modeled.

crates. Corrugated crates have better printability properties and need less storage after being used since they can be pressed together. Therefore, we will model the corrugated crate as the reference 'single use' crate. The standard corrugated board 'single use' crate weighs 6oo grams and has a volume of 40 liter[39] [27].
Instead of one-way crates, multiple trip plastic crates can be used. These crates can compete with both the corrugated crate and the corrugated box. The plastic multiple use crate is made from HDPE, weighs 2 kilograms and has a volume of 40 liter [44]. Using plastic returnable crates requires a closed loop transport system. A third party often manages the logistics of this transport system. The crates currently used have a lifetime of 5 - 10 years and the average trippage rate is 25/year [25, 45]. We will model a trip number of 150 trips per life cycle.

Grouping films

We defined 'grouping films' as all plastic films that are used to group or bundle multiple packed products. As such they compete with corrugated boxes. To group multiple primary packages mostly shrink film is used. In many cases the primary packages are placed on a tray from corrugated board, and shrink film is winded loosely around the packages. The film is subsequently heated in order to shrink and thereby bundling the packages. Shrink films are generally made out of LDPE and have an average thickness of 30 - 80 :m before shrinking. The most used thickness is 50 :m [40]. In this study shrink films are compared to corrugated boxes and therefore the standard dimensions of these industrial packages are chosen as the standard dimensions for shrink films (40x60x17 cm, 40 liters). For packing this volume, 200x25 cm LDPE is needed (23 grams) and 150 grams corrugated board.
Several projects in the period 1992-1994 show that shrink films are often over-designed. The thickness of shrink films for packing cans was reduced from 60 :m to 45 µm and the thickness of films to pack cardboard boxes was reduced from 50 :m to 40 :m [34, 40]. Based on these projects we assume that a reduction of 10% is technically feasible before the year 2010.
Replacement of corrugated boxes by grouping films is only possible when the primary package is rigid and offers enough protection to the contents when transported without a corrugated box. This is the case for about 20% of the primary packages currently transported in boxes [39].

Pallets

A vast majority of the pallets used in Europe is made out of wood. Wooden pallets are popular because they are cheap, have a large carrying capacity, and are easy to repair when broken. Moreover, they are very suitable for production of small series with deviating sizes. About one third of the pallets is

[39] When modeled, crates and corrugated boxes only differ in weight. In reality their appearance is quite different and they are used for different purposes.

returnable [33]. We will therefore define two reference pallets: a single use wooden pallet and a multiple use wooden pallet. A single use pallet weighs about 17 kg and a multiple use pallet weighs about 25 kg [34]. On average returnable wooden pallets make 20 trips [33]. The most used wood types are spruce, pine and poplar. Three pallet types are on the market that may be an improvement for the wooden pallet: plastic pallets, corrugated fiberboard pallets and pressed wood fiber pallets.

Plastic pallets

Plastic pallets are used a lot in the food industry because they are easy to clean due to the smooth surface. Furthermore, no liquid can be absorbed by the pallets [46]. The most common material for plastic pallet production is PE but in some cases also recycled PC is used. Pallets made out of PC are stronger than PE pallets. Plastic pallets are especially suitable as multiple use pallets. They weigh around 30 kilograms [23, 35]. There is no consensus about the number of trips that can be made with a multiple trip plastic pallet. In [35] the trip number is estimated at 34 trips while in [24] a lifetime of 100 trips is assumed. In several other publications it is stated that plastic pallet is much more durable than wooden pallets [23, 33]. We will therefore use a trip number of 50.

The shift from one way pallets to returnable pallets requires a large shift in pallet administration and management. The use of multiple trip pallets requires a pallet pool. A pallet pool is an organization that manages the transit of the pallets between the various users. As a result of pallet pools, standard sizes for pallets are introduced to make the pallet applicable for many users. In Europe several organizations are active in the management of pallet pools of which Europool and Chep have the largest market shares [47].

Corrugated fiberboard pallets

Pallets made from corrugated fiberboard are an option to replace single trip wooden pallets. Some types are made from solid corrugated board and are capable of making more than one trip but most pallets made from corrugated board will be used for single trips. The pallet is cheap compared to wooden and plastic pallets and weighs about 6 kg which makes it a very light-weight pallet [24]. This already has been a reason for some companies to use this pallet since it reduces the weight in the trailer [48]. A large disadvantage of these pallets is that they are not resistant to water.

Pressed wood fiber pallets.

Pallets can also be made from pressed wood fibers. The advantage of these pallets is that they can save a lot of space if they are used for multiple-trip purposes because they use a fourth of the space of piled wooden pallets when stacked empty. Pressed wood fiber pallets are made out low-grade fibers, mostly from bark and thinnings. The fibers are molded into a pressed wood pallet with the use of synthetic organic resins (glue). The average weight of the pallet is 16 kg [24]. Pressed wood fiber pallets are designed for one trip but are often used more often [24, 33]. We use a trip number of 5 trips per pallet [24].

Transport films

Transport films are used to bundle secondary packages, e.g. corrugated boxes, on a pallet. Two kinds of transport packaging are used: shrink covers and stretch films. Shrink covers are winded loosely around the boxes and are subsequently heated in order to shrink and form a tight bundle. Stretch films are winded tightly around the boxes. Thereby they are stretched for about 30% and are normally wrapped ca. 3 times around the load to be bundled [40]. Stretching is less energy consuming than shrinking. Furthermore, stretching can be mechanized more easily. Shrink and stretch films are generally made of LDPE. HDPE has poor shrinking and stretching properties and is therefore not usable as a transport film.

In 1990 the average shrink cover in The Netherlands had a thickness of about 200 :m [49]. Since then, partly because of the Packaging Covenant[40], it has dropped to an average of 100 :m [49]. Because in The Netherlands more actions have been taken to reduce the amount of packaging waste compared to the European average we expect that the average shrink cover in Europe weighs more than the Dutch average. We therefore assume that the average shrink cover in Europe has a thickness of 125 :m. To cover a standard pallet (1.2x1.0x1.6 m) a shrink cover of 1.25x1.05x2.20 m is needed [19]. This results in a weight of 1.31 kg for a reference shrink cover[41]. Improvement of the shrink film is possible by reducing the thickness to 100 :m, resulting in a weight of 1.04 kg [50].

Stretch films have an average thickness of 25 - 40 :m [40]. We assume a mean thickness of 35 :m for the standard stretch film. The weight of the stretch film needed to pack one standard pallet is calculated at 513 grams, assuming that 32 meters of foil with a wideness of 0.5 meter is needed [19]. Improved stretch film is 20% lighter [50].

In Table 7 the above is summarized by stating the life-cycle costs, material consumption and CO_2 emissions for all reference and improved packages. The values are expressed per functional unit.

[40] The Packaging Covenant is an agreement between the Dutch government and the Dutch packaging industry to reduce the amount of packaging waste.

[41] Based on a surface of 11.4 m2, a thickness of 125 micrometer, and a density of PE of 930 kg/m3.

Table 7: Measures for reducing CO_2 emissions related to transport packaging expressed per functional unit. New packaging concepts and concepts with currently a small market share are stated in italic[1].

Packaging category	Packaging concept	Total CO_2 emission kg/f.u.	Total costs ECU/f.u.	Total material kg/f.u.
Carrier bags	LDPE	101	73	20
	Light HDPE	81	68	16
	Recycled LDPE	6	68	30
	paper	42	116	56
	Reusable bag	11	5	2
Industrial bags	HDPE	213	153	42
	Paper	49	113	52
	FIBC	83	39	18
	FIBC returnable	29	14	6
Transport boxes	Corrugated box	729	776	800
	Light corrugated box	583	717	640
	Corrugated crate	547	703	600
	Wooden crate	190	240	440
	Plastic crate	472	668	20
Grouping films	LDPE	253	87	173
	Light LDPE	227	80	156
Pallets	Wood one way	7255	6527	17000
	Wood returnable	670	1782	625
	HDPE returnable	2441	2292	400
	Recycled HDPE return	493	1604	400
	Recycled PC return	493	2293	400
	Corrugated one way	5439	6569	6000
	Pressed wood mult.	2412	2513	3200
Transport films	Shrink cover	6615	2333	1305
	Light cover	5292	2019	1044
	Stretch film	2595	942	512
	Light stretch film	2078	819	410
	No stretch film	284	467	50

[1] In this table all described reference and improved packages are listed. The possible substitutions for CO_2 emission reduction are listed in Table 8.

4.6 Potential for CO_2 emission reduction

In this section we assess the consequences of implementing the selected improvement options.

By implementing the improved packages savings in CO_2 emission can be achieved. In the reference system the total CO_2 emissions related to transport packaging in Europe are calculated at 29 Mtonne per year. This figure is found by combining the material requirement and CO_2 emission of reference packages as stated in Table 7 with the total material requirement for transport packaging as stated in Figure 2. The CO_2 emissions related to transport packaging correspond to 1% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion; calculated from UN-FCCC emission data [52].

Table 8: Potential savings and costs of packaging efficiency improvement measures in Europe for the reference year 1994. A division is made between the options with small complexity of implementation (S1-S5), the measures with medium complexity of implementation (M1-M6) and the measures with large complexity of implementation (L1-L7).

no.	New packaging concept	Old packaging concept	Degree of substitution (%)	CO_2 emission reduction (%)	Costs (ECU /tonne CO2)
S1	Light corrugated box	Corrugated box	100	-6.9	-400
S2	Light LDPE grouping film	LDPE grouping film	100	-1.2	-288
S3	Light shrink cover	Shrink cover	100	-1.3	-238
S4	Light stretch film	Stretch film	100	-1.1	-238
S5	Light HDPE carrier bag	LDPE carrier bag	100	-1.5	-238
M1	LDPE grouping film	Corrugated box	20	-4.8	-160
M2	No stretch film	Stretch film	100	-1.9	-32
M3	One way corrugated pallet	One way wooden pallet	100	-1.1	-3
M4	Recycled LDPE carrier bag	LDPE carrier bag	100	-5.5	0
M5	Recycled HDPE returnable pallet	Returnable wooden pallet	100	-0.6	31
M6	Paper carrier bag	HDPE carrier bag	100	-2.9	67
L1	Reusable carrier bag	Recycled LDPE carrier bag	100	-4.9	-440
L2	Reusable carrier bag	Paper bag	100	-2.8	-270
L3	Recycled HDPE returnable pallet	One way corrugated pallet	100	-3.0	-89
L4	FIBC	HDPE industrial bag	90	-5.2	-79
L5	Recycled HDPE returnable pallet	One way wooden pallet	100	-4.2	-66
L6	FIBC returnable	FIBC	100	-2.1	-43
L7	Plastic crate	Corrugated box / crate	50	-12.3	16

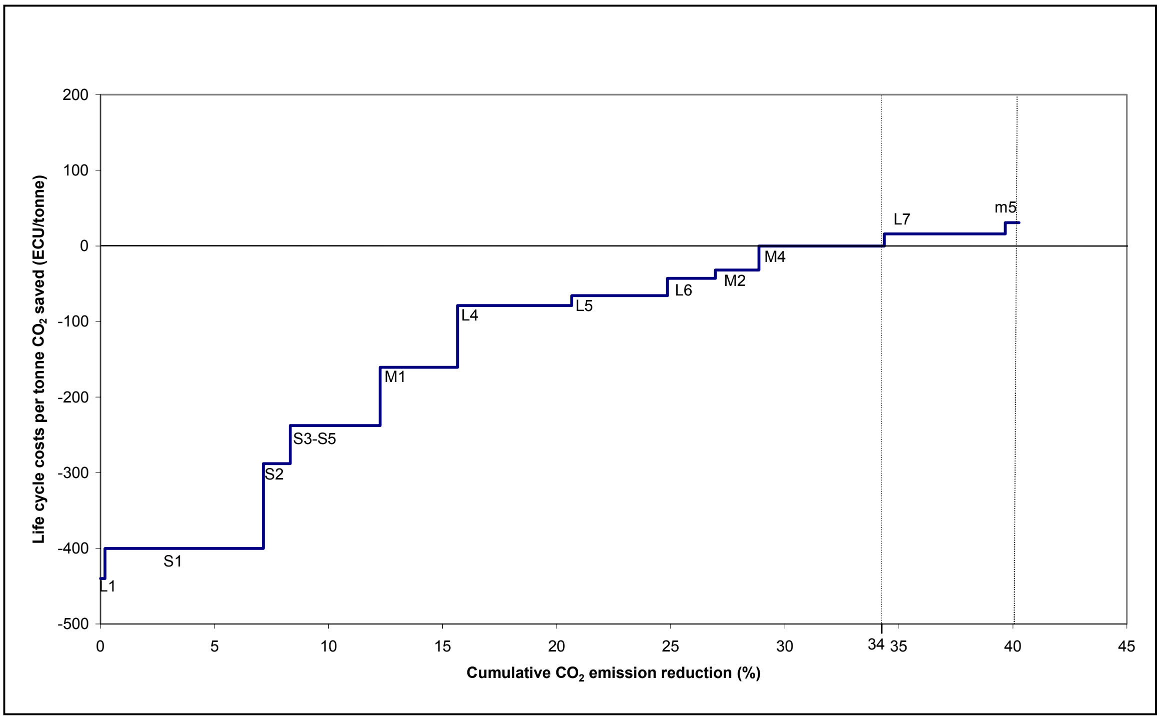

Figure 3: Supply curve of CO_2 reduction measures for the manufacturing and use of transport packaging. The horizontal axis depicts the cumulative reduction in CO_2 emission (in %) that can be achieved. The vertical axis depicts the life cycle costs per tonne abated CO_2 emissions. The numbers refer to Table 8.

Table 8 shows the CO_2 emission reduction potential of the individual improvement measures (replacing reference packages by improved packages) and the costs of these options measured in ECU per tonne CO_2 saved. The total reduction potential identified in table 8 adds up to 63%. The CO_2 emission reduction figures in Table 8 represent savings that are possible when packaging technology that is available in 2010 would already have been implemented in 1990.

In Table 8 the anticipated change in the packaging system is indicated by a division of the possible measures in three categories. The table discerns measures with small complexity of implementation (S1-S5), measures with medium complexity of implementation (M1-M6) and measures with large complexity of implementation (L1-L7). 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. 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 a large complexity of implementation involve returnable packages where changes in all stages of the packaging life cycle are necessary. Also measures that rely on a change in consumer behavior are part of this category.

Figure 3 and Figure 4 depict the cumulative savings of all measures by means of a supply curve. Contrary to Table 8, the potential reduction of CO_2 emissions for each improvement measure is corrected for inter-measure influences.

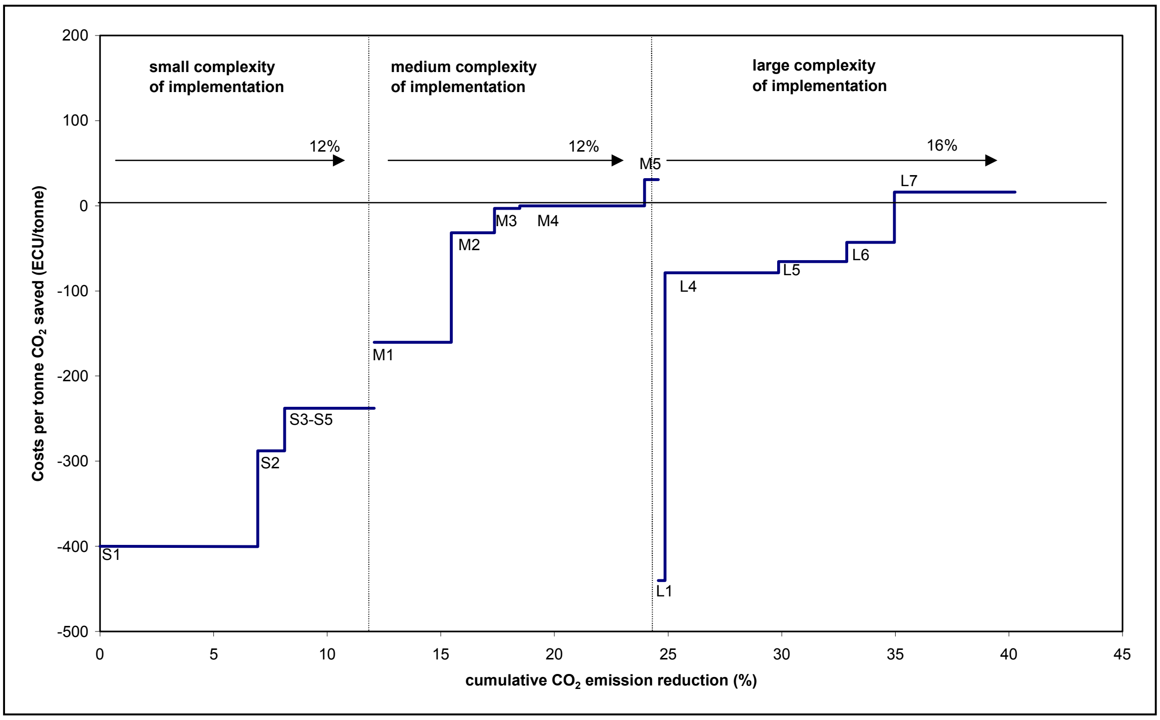

Figure 4: Supply curve of CO_2 reduction measures for the manufacturing and use of transport packaging. The different sections refer to different levels of complexity of implementation.

In Figure 3 all measures are depicted in order of cost-effectiveness. The numbers of the measures correspond to the numbers in Table 8. The supply curve obtained shows that the total cumulative CO_2 emission reduction that can be achieved amounts to 40%. The absolute savings in CO_2 emission can therefore be calculated at 12 Mtonne per year. This is 0.4% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion. The main part of this potential (33%) is calculated to be cost-effective based on a life cycle approach.

Figure 3 does not give any information about the potentials of the measures in relation to the degree of implementation difficulty. In Figure 4 this relation becomes visible. Here, we assumed that measures are implemented in order of implementation difficulty where the least complex measures are implemented first. In section three we already described that in this paper we link the difficulty of implementation to the anticipated change in the entire packaging system. The potential savings on CO_2 emissions of measures with low implementation complexity is 12% and measures that are more difficult to implement can add another 12%. The potential for emission reduction is

increased by another 16% by implementing measures with a large complexity of implementation.
The order of implementation influences the potential of the individual measures due to inter-measure influences. Therefore the improvement potential that is depicted in the supply curves (40%) is smaller than the addition of the individual savings as stated in Table 8 (60%). This effect is visible in two ways.
First not all measures listed in Table 8 are part of the supply curves because the order of implementation prevents them from being implemented. Figure 3 shows that measures M3 and M6 are not implemented since all wooden pallets are replaced earlier by returnable plastic pallets and LDPE carrier bags are replaced earlier by reusable carrier bags. In Figure 4 measures M6 and L5 are not part of the improvement potential. In this case the paper bag is not introduced due to an earlier introduction of the recycled PE bag. The wooden pallet is not replaced by returnable PE pallet since the wooden pallet is replaced earlier by the corrugated pallet.
Second, the potential of some measures in the supply curves are smaller than the potential in Table 8 because in the supply curves the potential is calculated in relation to earlier implemented measures. An example of this effect is measure M4 where the LDPE carrier bag is substituted by the recycled LDPE carrier bag. In the supply curves measure L5 is taken first which corresponds to implementation of a light LDPE bag. Therefore the potential of measure M4 is smaller in the supply curves than in Table 8.

4.7 Discussion

In this study we calculate for all transport packaging in a large geographical area (Western Europe) the CO_2 emission reduction that can be achieved by more efficient management of materials. To do so, it is inevitable to make assumptions regarding production, use and waste management of transport packaging in Europe. In this section we will discuss the reliability of the data used and assumptions made in this study.
Of the energy data used in this study, the energy requirements for material production proved to be the largest contributors to the total energy requirement for single use packaging. We used GER values from a Swiss study as an estimate for these energy requirements. These values are based on a number of European sources [9]. We therefore expect that these GER values are representative for the average European situation.
For returnable packaging also energy requirements for transport are important for the total result. The most important assumption for the calculation of the energy requirement of transport is that extra transport activity of 200 km is necessary for returnable transport packaging. The results of the calculations are very sensitive for this assumption. Replacement of the corrugated box by returnable plastic crates adds currently about 5% to the total reduction

potential. When the transportation distance is 50% less, then the use of plastic crates adds 14% to the total reduction potential, thereby adding 9% to the total CO_2 emission reduction. This is the result of the large influence of corrugated boxes in the total material use of transport packaging (see Figure 2). However, when the transportation distance is doubled, the plastic crate is no longer an improvement option. Depending on the density of population the average transportation distance will differ between European regions. However, in many cases no extra transport will take place for returnable transport packaging because the crates and pallets are not returned to the pool-owner but directly to the distributor. In that case the same truck that is used for the transport of the packed products is also used to return the packaging. Based on this we expect the extra transport of 200 km to represent the upper limit. Therefore, for this option the results should be viewed as an estimate of the lower limit of the technical CO_2 emission reduction potential.

Energy efficiency improvements in material production processes are not taken into account. Improvements in energy efficiency will lower the potential for CO_2 emission reduction due to more efficient material management.

For the costs calculations of single use packaging the most important parameters are costs for material and packaging production. We estimated the packaging production costs by subtracting material prices from packaging prices. Material market prices vary strongly over time. For PE the price increased from \$830/tonne to \$1190/tonne in the period 1996-1997; an increase of 43% [20]. Paper prices are notorious for their cyclical nature. The price of containerboard, for example, rose in the period 1993-1995 from \$300/tonne to \$580/tonne and fell back to \$250/tonne in the period 1995 - 1996 [51]. Also the prices of packaging products are likely to change over time and are likely to be sensitive for the geographical region where it is produced. Price fluctuations have large effects on the calculated costs per tonne CO_2 saved. For example, a decrease in corrugated board costs by 50% results in an increase in costs of measure L7 from +15 ECU/tonne CO_2 to +100 ECU per tonne CO_2 saved. Based on this the cost efficiency of the measures should be interpreted with care.

For returnable packaging also costs for transport and administration are a substantial part of the total costs. Because we assumed in the calculations that all packages are returned to the pool owner after being used these costs are likely to represent the upper limit. When for example packages are returned to the pool owner after being used twice the costs of measure L7 decrease to -50 ECU per tonne CO_2 saved.

To model current and improved packaging practices in Western Europe we defined reference and improved packages. The definitions of the reference packages do not influence the reduction potential of the measures in the first category (low complexity of implementation) because all improvements are stated as relative changes. However, the measures in the second and third category are strongly influenced by the definition of the reference packages because the savings in CO_2 emissions are related to the difference between two reference packages. When reference corrugated boxes for example are modeled to be 10% lighter the CO_2 emission reduction potential of substituting corrugated boxes by shrink foils would decrease from 5.3% to 2.5%. We expect this effect to be strongest for measures related to corrugated boxes because this packaging category is very diverse in shape and weight. A reference corrugated box is therefore more difficult to determine than reference packages in other more homogenous categories.

The potential of measure S1 (light corrugated box) is uncertain. We estimated a possible reduction in corrugated board use of 20% to be possible. This reduction is based on many different measures that can be taken in the field of corrugated board packaging. These measures are individually proven but the total potential of the sum of these measures for all corrugated packaging in Europe is difficult to determine. The reductions realized by the individual measures range from 15% to 30%. This range leads to a range in a CO_2 emission reduction potential of measure L1 of 5.2% - 10.4%.

The potential reduction in CO_2 emission for returnable packaging is strongly dependent on the assumed trip number. In this study we assumed a trip number for plastic crates of 100 trips. A reduction of this trip number by a factor 2 would diminish the reduction potential of this measure from 5.3% to zero. When the trip number is doubled, the potential increases with a factor 1.5 to 7.7%.

To improve the reliability of the results more detailed data on the use of packaging are necessary. Also more insight in the differences in packaging culture and tradition for all European countries would certainly improve the results. More regional or national studies on packaging are necessary in order to increase detailed data availability.

We used the term complexity to take implementation difficulties into account. Figure 4 shows that measures with a large complexity of implementation have the highest potential to reduce CO_2 emissions. If the measures with small and medium complexity of implementation were not implemented first the potential would even be greater[42]. The large complexity of implementation suggests that for successful implementation high transaction costs need to be made. However, these high transaction costs make it possible for specialized companies to enter new markets. For transport packaging, the pool organizations are good examples. The presence of these specialized companies lower the transaction costs of measures with a large complexity drastically.

4.8 Conclusion

Several materials are used for transport packaging. Corrugated board is used most (11.7 Mton), followed by wood (about 5 Mton) and plastics (about 3.5 Mtonne). Only a small amount of paper is used (about 0.1 Mtonne).

[42] In [6] the effect of changes in the implementation order is shown for primary packaging.

The total CO_2 emissions related to transport packaging in Europe is calculated 29 Mtonne per year. This corresponds to 1% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion.
We have studied the potential of a large number of technical measures that can be applied till the year 2010 to improve material management of transport packaging. Also we estimated the potential impact on CO_2 emissions in Western Europe when the packaging demand in 1995 would be fulfilled with these improved packages. This resulted in five measures that improve current packaging by using less or lighter materials. Full implementation of these measures might result in a reduction of the CO_2 emissions related to the production and consumption of primary packaging in Western Europe of 12% 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 is calculated at 12% of the CO_2 emissions related to primary packaging in 1995. Finally we discerned seven measures that involve large changes in current packaging practices or require changes in consumer behavior. The potential reduction in CO_2 emissions of these measures might be 16% of the CO_2 emissions in 1995 related to transport packaging. Implementation of these measures would 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 transport packaging of 40% compared to 1995. The cost-effective potential of CO_2 emission reduction is calculated at 33%. Measures are considered to be cost-effective when the total life cycle costs of the improved package is lower than for the reference package. The reason that many measures are cost effective (result in lower life cycle costs than in the reference situation) are the large savings in material costs.
This study presents a *first* analysis of the reduction of CO_2 emissions that can be achieved by improved management of material use for transport packaging. Further research should focus on bringing more detail into the calculations to improve the reliability of the results. 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 like taking the transaction costs into account. Further research should also focus on improvement options on the long term like 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 necessary.

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Chapter 5

Wrapping Up Greenhouse Gas Emissions[43]

An Integrated Assessment of Greenhouse Gas Emission Reduction Related to Packaging

Abstract

The use of packaging materials results in greenhouse gases (GHG) emissions. In this paper we investigate the potential reduction of GHGs that are related to packaging. We also study the relation between current European waste prevention policies and GHG emission reduction. For this purpose we use the dynamic MATTER MARKAL model in which the Western European energy and materials system is modeled. The results show that GHGs related to packaging can technically be reduced by up to 58% in the period 1995-2030. Cost effective efficiency improvement of materials use contributes to a 32% GHG emission reduction. An additional 13% reduction becomes cost-effective when a GHG emission penalty of 100 ECU/t is introduced. Generally speaking, improved material management dominates the gains that can be achieved without or with low GHG emission penalties, whereas the reduction of emissions in materials production and waste handling dominate when high GHG penalties are applied. The results suggest that more attention should be paid to material efficiency improvement in climate change policy due to the technical potential and the low life cycle costs of material efficiency improvement compared to other GHG emission reduction measures.

Keywords: Packaging, GHG Emission Reduction, CO_2 emissions, Material Efficiency Improvement, Material Management, Waste Reduction

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5.1 Introduction

Greenhouse gas (GHG) emission reduction is one of the key environmental problems for sustainable development in the 21st century. In 1997 targets and timetables were set at the third Conference-of-the-Parties to the United Nations Framework Convention on Climate Change in Kyoto to reduce the emission of GHGs. The member states of the European Union have jointly agreed on a reduction of 8% of the emission of the six most important greenhouse gases[44] in the period 2008 - 2012 compared to the 1990-emissions [1]. Further reductions will be required beyond this period in order to reach stabilization of global GHG concentrations at acceptable levels as called for by the UN Climate Convention. Most probably, a reduction by 50-80% in the next 50-100 years will be required in industrialized countries in order to stay at acceptable concentration levels [2,3].

Table 1 shows the cumulative GHG emissions of Western Europe for the reference year[45][46], expressed in CO_2-equivalents. CO_2 constitutes approximately 80% of the total GHG emissions. Methane (CH_4) and Nitrous oxide (N_2O) constitute the bulk of the non-CO_2 GHG emissions in the reference year. The emissions of both gases are expected to decline autonomously until 2010 due to changing agricultural activities, decreasing coal mining, and decreased landfilling of waste. The relevance of Hydrofluorocarbons (HFCs) will increase in the next decade due to the ongoing substitution of Chlorofluorocarbons (CFCs) with HFCs. Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) emissions remain relatively insignificant. Consequently, in order to reach a significant GHG emission reduction, GHG policies should focus largely on reducing CO_2 emissions.

Table 1: Emissions in the reference year, western Europe [4]

Category		Emission in reference year ($Mt\ CO_2$ eq.)[47]
CO_2	Carbon dioxide	3323
CH_4	Methane	500
N_2O	Nitrous oxide	350
HFCs	Hydrofluorocarbons	42
PFCs	Perfluorocarbons	13
SF_6	Sulphurhexafluoride	15
Total		4243

[44] The greenhouse gases considered in the Kyoto Protocol are CO_2, CH_4, N_2O, HFCs, PFCs and SF_6

[45] Western Europe is defined as the European Union plus EFTA (Norway, Switzerland, Iceland and Liechtenstein)

[46] The reference year is 1990 for CO_2, CH_4 and N_2O, 1995 for HFCs, PFCs and SF_6.

[47] Megatonnes CO_2 equivalents. 1 Mt = 10^6 metric tonnes

There are several options for GHG emission reduction. One of these is improving the efficiency of energy use. Other options are, for instance, increasing the use of energy from clean, renewable resources, and applying end-of-pipe techniques for the removal and storage of CO_2 from energy conversion processes. A large part of the primary energy use, globally about 40%, is related to the production of materials [5]. A limited number of materials constitutes the bulk of this energy use and the associated GHG emissions. Table 2 provides an overview of these materials and the associated emissions for production and waste handling for the year 1995 related to the Western European situation. Comparison of Table 1 and Table 2 shows that approximately one quarter of the total Western European GHG emissions can be attributed to the production of these bulk materials[48].

Table 2: The annual emissions of GHG's in Western Europe in 1995 due to the production and waste handling of materials, calculated following accounting guidelines given by IPCC [7]

	CO_2 (Mt CO_2 equiv. p.a.)	**Non-CO_2 GHG (Mt CO_2 equiv. p.a.)**	**Total (Mt CO_2 equiv. p.a.)**	**Fraction (%)**
Metals	244	11	255	26
Synthetic organic materials	167	53	220	22
Natural organic materials	93	130	223	22
Inorganic materials	49	60	109	11
Ceramic materials	191	-	191	19
Total	744	254	998	100

The emissions related to the consumption of materials can be reduced through implementing emission reduction options in the production process of these materials. However, they can also be reduced through changes in the use of materials. Improved management of material use has been studied and practiced mainly from the perspective of waste reduction. Little attention has been given to material management strategies focused on GHG emission reduction.

Only a few studies have been published dealing with this issue. In [6] the importance of materials as sources and sinks of CO_2 emissions is stated. However, in this study the focus was on the role of materials in CO_2 emissions and storage and not on ways to reduce the CO_2 emissions. In 1998 an EPA study was published on greenhouse gas (GHG) emissions from management of materials in municipal solid waste [8]. The study shows that management of materials presents many opportunities for GHG emission reduction. Although this study focuses on the relation between material use and GHG emissions, it emphasizes waste management. A detailed investigation of options for more

[48] This excludes transport to consumers and product manufacturing from materials

efficient material management in the production and consumption stage was not carried out.

Two studies describe how more efficient use of materials may lead to a reduction in energy use. In [9] the focus is on energy savings due to more efficient use of fertilizer, and in [10] an approach is described for analyzing the potential of material efficiency improvement which is tested on plastic packaging in The Netherlands. Both studies show that there is a significant potential for reduction of CO_2 emissions by more efficient use of materials in those specific cases. Many studies are available that focus on the potential for increased efficiency of materials use from an environmental perspective, for example [11,12]. However, these studies have a generic product design perspective and do not specifically focus on GHG emission reduction.

To provide more insight into the potentials to reduce GHG emissions in Western Europe through changes in the life cycle of materials, a project was started called MATTER (MATerials Technologies for greenhouse gas Emission Reduction), coordinated by the Netherlands Energy Research Foundation[49]. One of the product groups studied in the MATTER project is packaging. This has two reasons. First, packaging materials constitute a significant section of the total materials market; in 1995 about 75 Mtonnes per year of material is used for packaging purposes in Western Europe which equals about 10% of the total Western European material volume [13,14]. Second, changes in material use for packaging are an interesting study object because packaging is already subject to waste management policies such as the European Packaging Directive [15]. These policies will have an impact on GHG emissions, and it is interesting to investigate what this impact could be. Therefore, the effect of existing packaging legislation on Western European GHG emissions can serve as a case study to investigated the impact of existing environmental policies on GHG emissions.

Earlier studies that have been carried out within the MATTER project have already shown that improved management of packaging materials can reduce the CO_2 emissions related to packaging by about 40 - 50% (see [14, 16]). However, these studies focused solely on improved material management in the product stage; changes in energy use for material production, clean energy technologies, and improved waste management technologies have not been considered.

In this paper we present an *integrated* analysis of GHG emission reduction measures in all stages of the material life cycle for packaging materials. Integrated analysis refers in this case to an investigation of the full materials life cycle “from cradle to grave”, taking into account all categories of GHGs, and considering the potential impact of a broad variety of improvement options (see Section 3). We focus on the following four questions:

[49] The MATTER project involves three Dutch Universities (Utrecht University (STS), Free University in Amsterdam (CAV) and Groningen University (IVEM)), Bureau B&G and the Netherlands Energy Research Foundation (ECN) and is carried out in the period 1995-1999.

- What is the potential GHG emission reduction that can be reached through both material and energy related measures in the life cycle of packaging materials in Western Europe in the period 1995 - 2030?
- How do the costs of material management options compare with the costs of other GHG emission reduction options?
- What shifts in material use occur when more or less stringent GHG emission reduction goals are reached?
- What is the impact of current packaging waste prevention policies on GHG emission reduction?

To answer these questions we first present an overview of the relation between packaging materials and GHG emissions, see Section 5.2. In Section 5.3 we describe the method used. First the general model structure is characterized, than we focus specifically on the packaging technologies included in the model, and finally the material management strategies that have been analyzed in the model calculations are characterized. In Section 5.4 and 5.5 we present and discuss the results of the model calculations and we end in Section 5.6 with conclusions.

5.2 Packaging and GHG Emissions

Many different materials are used for production of packaging. The material choices depend on the desired characteristics of the package such as barrier properties and strength, as well as marketing considerations. In Table 3 the materials most often used are listed and the related GHG emissions in the production and waste stage are estimated. Emissions for packaging production, cleaning, and transportation are not accounted for since they depend more on the products that are made from the basic materials than on the materials themselves.

Table 3 shows that, in 1994, the total GHG emission related to the material use for packaging in Western Europe was 144 Mtonnes. This is 3.3% of the total GHG emission in Western Europe. CO_2 emissions dominate, but non-CO_2 emissions are also relevant, especially methane emissions from disposal sites. In Table 3 this is included as 'other GHG emissions' due to paper and board consumption. The amount of recycled material is estimated, based on recycling statistics for individual packaging types and materials. Recycling is important because recycling of materials generally results in considerably lower GHG emissions than production of materials from natural resources. The remaining waste fraction is either incinerated or disposed. On average 80% of all municipal solid waste (MSW) in Western Europe is still disposed of; the remaining 20% is incinerated (about 15% is incinerated with energy recovery, this recovery is not accounted for in Table 3[50]) [17]. The emissions for plastics

[50] Table 3 presents a quick calculation of the relevance of materials in GHG emissions. It does not present a model outcome where practices like energy recovery from waste incinerators are included.

are based on actual emission accounting (carbon storage in disposal sites is not accounted as emission, in line with IPCC emission accounting guidelines).

Table 3: Material consumption for Western European packaging and associated GHG emissions in 1994 [6,13,18].

	Consumption Mtonne p.a.	Recycling rate	CO_2 emission (Mt CO_2 p.a.)	other GHG emission[51] (Mt CO_2 eq. p.a.)	total GHG emission (Mt CO_2 equiv.p.a.)
Paper and board	28	50%	14	24	38
Glass	17	50%	8	0	8
Plastics	12	0%	50	0	50
Metals	6	50%	25	8	32
Others [52]	13	25%	10	5	15
Total	75		107	37	144

Whereas paper and board are generally considered environmentally benign materials due to their origin from renewable biomass, the GHG balance is influenced by the methane emissions in the waste disposal stage. The high GHG emission for metal packaging is mainly related to aluminum packaging. Whereas recycling rates for beverage cans are high in some European countries[53], aluminum foils, laminates etc. are virtually not recycled because of high costs and high energy use for collection. This is important since the GHG emissions for primary aluminum are 10-20 times higher than for secondary aluminum [19].

For a proper comparison of the GHG impact of different packaging materials the packaging service must be considered. An example of a packaging service is 'packing 1000 liters of product'. The packaging service of a tonne of plastics is generally 5-10 times higher than the same packaging service delivered by a tonne of paper, board, or glass. On a service basis, plastics constitute the most important packaging material. As a consequence, the emissions per service unit for plastics are 5-10 times lower (see [20]).

5.3 The model structure

The MATTER-MARKAL model

To investigate material management strategies to reduce GHG emissions, an integrated energy and materials systems analysis is needed, as different reduction strategies influence each others effectiveness. For example, if the

[51] Includes CH_4 emissions from disposal sites for paper and board and for wood; PFC emissions for aluminum production

[52] Includes wood

[53] The average recycling rate of aluminum cans in western Europe is 35% but individual countries recycle up to 90% (Sweden).

reference electricity production plants become less CO_2 intensive, electricity production by waste incineration becomes a less attractive option for GHG emission reduction. Furthermore, a dynamic approach is needed because significant GHG emission reduction will take decades. Changing technology, changing consumption patterns, changing resource prices, and changing environmental policy goals are issues that must be considered within such a timeframe. Based on these two criteria, the MATTER-MARKAL model is designed to be both a dynamic model and an integrated model where both the energy and materials system are modeled.
The MATTER MARKAL model is a representation of (part of) the Western European economy. The economy is modeled by a network of processes and by physical and monetary flows between these processes. The processes represent all activities that are necessary to provide products and services. Many products and services can be generated through a number of alternative (sets of) processes. The model contains a database of more than one thousand processes, covering the total life cycle for both energy and materials (Figure 1).

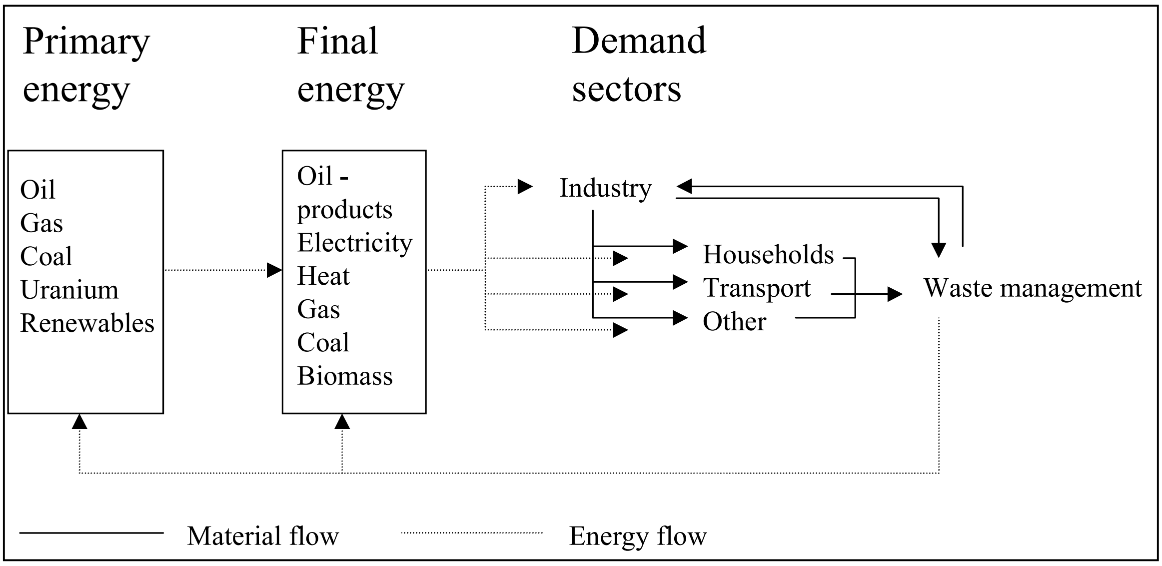

Figure 1: Generic MARKAL energy and materials system model structure [4]

The model calculates the least-cost system configuration. In the MATTER-MARKAL model GHG emissions are endogenized in the optimization through the introduction of emission penalties[54].
The time span to be modeled is divided into nine periods of equal length, generally covering a period of decades. The model is used to calculate the least-cost system configuration for the total time period, meeting exogenously defined product and service demands and emission reduction targets. This

[54] Introduction of GHG emission penalties results in higher costs for processes with large GHG emissions. Since the model calculates the lowest cost system, other processes with lower GHG emissions may replace these processes.

optimization is based on a so-called 'perfect foresight' approach, where all time periods are optimized simultaneously. Future constraints are taken into account in current investment decisions. The growth of economic activity is modeled by increasing product and service demand figures.

MARKAL has originally been developed as an energy systems analysis tool. The modeling approach has been extended to materials system analysis 'from cradle to grave' [21]. Figure 2 shows the life cycle structure for materials and products. All bulk material flows that are related to the Western European end-use of materials and products are included in the MATTER model. The model covers more than 25 energy carriers and 125 materials. More than 50 products represent the applications of these materials. Thirty categories of waste materials are modeled.

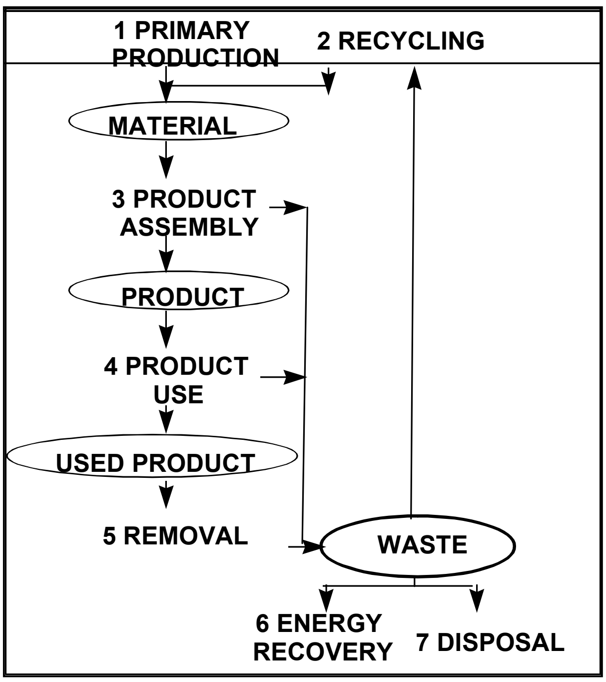

Figure 2: Materials system model structure [31]

The modeling results for the packaging sector are not only influenced by the model input for these packaging processes but also by many other parameters that are included in the model like energy prices, costs of energy saving technologies, possible use of biomass as source for energy and materials, etc. It is impossible to give insight in all model input in this paper. We therefore refer to [20, 22-29]. Furthermore, the full database and the model output files are available via Internet [30]. Also, the general model structure is discussed in [31]. A detailed discussion of modeling results for all sectors but packaging can be found in [4].

However, to create some insight in the general ideas about energy use, supply, and efficiency in the future, economic development and future ways of material management that are the backbone of the model we refer to Table 4. In this Table we have listed a number of parameters that are of large influence of the model output. Besides some general parameters like energy prices and GDP developments, for some technical GHG emission reduction options the potential and costs are stated in generic terms.

Table 4: Characteristics of the MATTER-MARKAL model for the year 2030

Parameter	Unit	
GDP growth	(%/yr)	2
Physical demand growth	(%/yr)	0.5
Fossil fuel prices growth	(%/yr)	0.7
Discount rate	(%/yr)	8
Average efficiency for electricity from fossil fuels	(% LHV)	60
Nuclear energy	(% Base case energy use)	6
Cost-effective energy efficiency improvement	(% 1990 efficiency)	25
CO_2 storage	(% Base case emissions)	12
Biomass potential	(% Base case energy use)	25
Other renewables	(% Base case energy use)	15
Energy use truck transport	(% 1990 energy use/ton.km)	60

5.3 The Model Structure for Packaging

To model current and future demand for packaging materials in the MATTER-MARKAL model three types of information are fed into the model. First, the current and future demand for packaging products is defined. Second, the current packaging technology required to fulfil the demand for packaging products is described. Third, future options for improved material use to fulfil the future demand for packaging products are indicated. We will now describe the model structure for packaging based on this categorization.

Current and future demand for packaging

To pack a specific product, several types of packaging can be used. Milk, for example, can be packed in liquid board packages or in glass bottles, and the milk bottles can be packed in cardboard boxes, plastic crates, or stretch film. To be able to model all these substitutions, a demand for packaging services is modeled instead of a demand for packages. Examples of a packaging service are 1000 liters of packed beverages or one tonne of packed food products.
Since not each specific packaging service can be modeled because of the wide variety, they are categorized in a few representative groups. The categorization is based on specific characteristics of the service and the effect on the packaging characteristics necessary to fulfil this service. In Table 5 the modeled service categories are given.

We discern 'packaging of carbonated beverages' and 'packaging of non-carbonated beverages' since not all packages suitable for non-carbonated beverages are also suitable for carbonated beverages, due to differences in required barrier properties. The category 'packaging of dairy products, other than milk' is modeled to take the consumption of PS and PP cups into account that are specifically used for this purpose, e.g. packaging of margarine and yogurt. We discern a category 'packaging of wet food' to model the high strength packages such as steel food cans and glass jars. Further, we discern two types of dry food packaging: 'packaging of non-susceptible dry food' and 'packaging of susceptible dry food'. These packaging types differ in the barrier characteristics needed to pack susceptible and non-susceptible food products. We distinguish between 'Packaging of non-food liquids' and beverage packaging because of different legislation concerning recycled material content. We differentiate between 'carrier bags' and 'industrial bags' because the strength characteristics of industrial bags are much higher than those of carrier bags. We also make a distinction between 'pallets and 'transport packaging' where the latter represents tertiary packaging like corrugated boxes and crates that are placed on pallets when transported. Finally we discern 'pallet wrapping'. This represents bot shrink films and stretch foils that are wrapped around loaded pallets to keep them dry and clean.

Since the economy in Western Europe is expected to increase in the period 1990 - 2050, the demand for packaging services is expected to increase as well. Table 5 summarizes the modeled growth factors for the different packaging service categories.
GDP increases in this study by a factor 3.5 in the period 1990 - 2050. Packaging services do not increase at the same rate due to a "dematerialization" of the economy. The consumption of food and beverages, a major packaging category, is generally stabilizing due to stabilizing population and stabilizing per capita food consumption. The remaining growth is to some extent caused by a shift from "simple" food ingredients (e.g., raw vegetables) to prepared ingredients (that require packaging), changing household size, and changing lifestyles. Differences for food and beverage categories are based on the demand growth rates during the last decade (EC, 1997). Higher growth rates than for food are assumed for non-food packaging. Growth rates for these categories have been coupled to transportation growth rates. Still, dematerialization results in a decoupling from GDP growth.

Table 5: Packaging service categories and demand trends in the MATTER model (index)[55]

Cat.no.	Packaging service category	Unit	1990	2020	2050
1	Packaging of carbonated beverages	(liters of product)	100	117	131
2	Packaging of non-carbonated beverages	(liters of product)	100	120	139
3	Packaging of dairy products, other than milk	(liters of product)	100	132	163
4	Packaging of wet food	(liters of product)	100	152	204
5	Packaging of non-susceptible dry food	(liters of product)	100	112	125
6	Packaging of susceptible dry food	(liters of product)	100	152	204
7	Packaging of non-food liquids	(liters of product)	100	151	203
8	Packaging of dry non-food	(liters of product)	100	111	123
9	Carrier bags	(bags)	100	115	130
10	Industrial bags	(tonnes of product)	100	157	213
11	Transport packaging	(liters of product)	100	142	185
12	Pallet wrapping	(trip units)	100	175	250
13	Pallets	(pieces)	100	125	150

Current and future packaging technology

In the MATTER MARKAL model both current packaging practices and improved packaging technologies are modeled. Current packaging practices are modeled by defining representative reference packages within all packaging service categories. Future packaging technologies are modeled by defining improved packages. In [14,16] all reference and material efficient packages that are modeled, from now on called improved packages, are described extensively. In this section we will give a short overview of the modeled packages. In Table 5 all current and improved packages that are modeled are listed. The table also indicates for which packaging services the packages can be used.

To pack carbonated beverages, beverage cans made from steel or aluminum, bottles made from PET and bottles made from glass are commonly used. The cans can be improved by reducing their weight. These developments are modeled by 'light cans'. The lid of steel cans are normally made out of aluminum. This is problematic for recycling processes as aluminum incinerates in the recycling process. The all steel can, with a lid made from steel, can be completely recycled and is therefore modeled as an improvement option.

Most PET bottles in Western Europe are used only once. We modeled a 1.5 liter single use (one way) PET bottle as a reference package. In several countries re-usable PET bottles are commonly used. Because these bottles have a trip number of about 25 trips and are only twice the weight of single use bottles, the material use per packaging service is a fraction of the original material use

[55] In Table 5 the growth of the demand for packaging services is indicated by means of indices. The actual demand for 1990 is estimated based on packaging consumption data and demand data for specific product groups. In [14,16] the modeled demand and all assumptions to calculate that demand are described. The abbreviation Cat. No. stands for Category Number.

[33]. The re-usable PET bottle can be made partly from recycled PET [34]. This development is modeled as an 'improved re-usable PET bottle'.

Glass is a heavy weight material compared to alternatives such as the PET bottle but it is still extensively used by the packaging industry. We have modeled both a large (1 liter) bottle and a small (0.3 liter) bottle that represents the beer bottle. Large bottles can be made lighter (-25%) and for the small glass bottle re-usable bottles are an option, as this is commonly used in some European countries [35]. For re-usable glass bottles we assume a trip number of 20 trips [36].

The liquid board package is commonly used for milk and juice packaging. We have modeled two alternatives for the liquid board package: the pouch and the PC bottle. The pouch is a flexible PE or PP package that only weighs 4 - 10 grams whereas a liquid board package weighs 28 grams [35, 37]. The PC bottle is introduced in 1996 to the Dutch market to replace the glass bottle. The PC bottle can be re-used about 30 times before recycling the PC for other purposes [38].

Both PS and PP cups are used for packaging of margarine and yogurt products. We have modeled possible substitutions between these packaging types as an improvement option. Further, the glass jar is modeled as an alternative package.

The glass jar is also suitable for packing of 'wet food' such as jelly and canned vegetables. In this category it competes with the steel food can. Both the steel can and the glass jar can be made lighter. For the steel food can it is possible to use a honeycomb structure to make the can lighter without compromising its strength [39].

For packaging of dry food products both cardboard boxes and flexible packaging can be used. Commonly used flexible packages are foils and bags made out of LDPE or PP. The thickness of the films is expected to decrease in future years because of the introduction of a new catalyst which improves polymerization control (metallocene films) [40]. The weight of cardboard boxes can be decreased by 20% by removing unnecessary material, increasing product quantity, removal of outer boxes, and using thinner cardboard [41-43].

Besides the cardboard box, plastic boxes are used for packing of foodstuffs. We have modeled a PVC box. The same model box is used as a representative for blister packaging for non-food purposes. The blister package can be improved by replacement of the PVC blister by an all cardboard blister. This type of substitution is a clear trend in the Do It Yourself (DIY) sector in The Netherlands [43,44].

Plastic films can also be used to pack susceptible foodstuffs. In that case they are often laminated or metalized in order to improve the barrier characteristics of the films. These very thin films can be made even lighter by using metallocene films.

Table 6: Current and improved packaging technologies and associated service categories (the service category numbers refer to the numbers in Table 4)[56]

Current packaging technology	Cat. no.	Future packaging technology	Cat. no.
steel beverage can	1	light aluminum can	1
aluminum beverage can	1	light steel can	1
		all steel can	1
one way PET bottle	1,2	PET bottle re-usable	1,2
		Improved PET bottle re-usable	1,2
large glass bottle	1,2	light glass bottle	1
small glass bottle	1,2	returnable small glass bottle	1
liquid board package	2	pouch	2,7
		PC bottle	2
PS cup	3		
PP cup	3		
glass jar	3,4	light glass jar	3,4
steel food can	4	honeycomb steel food can	4
cardboard box	5,8	light cardboard box	
cardboard box + bag	5	light cardboard box +bag	
PVC box	5,8	cardboard blister	8
LDPE-film	5,8	metallocene film	5,8
PP-film	5,8		
paper packaging	5,8		
PP-laminate film	6	metallocene - laminate film	6
PET-laminate film	6		
PP-metalised film	6	metallocene - metalised film	6
PET-metalised film	6		
HDPE bottle	7	recycled HDPE bottle	7
		liquid board package	7
PE carrier bag	9	recycled PE carrier bag	9
paper carrier bag	9	multiple use carrier bag	9
PE industrial bag	10	one way FIBC	10
paper industrial bag	10	returnable FIBC	10
corrugated box	11	improved corrugated box	11
cardboard crate	11	plastic crate	11
shrink foil	11	wooden crate	11
one way wooden pallet	12	PE pallet returnable	12
returnable wooden pallet	12	PE pallet recycled	12
PE pallet one way	12	PC pallet recycled	12
		Corrugated fiberboard pallet	12
		pressed wood pallet	12
shrink cover	13		
stretch film	13		

[56] The costs and energy requirements for these packaging concepts are determined by costs and energy use for material manufacturing, product assembly, transport, waste management, and recycling. See [14,16,20] for these figures.

For non-food liquids such as shampoos and detergents HDPE bottles are often used for packaging because these bottles are cheap and do not need specific barrier characteristics. The standard HDPE bottle can be improved by using recycled material. It is also possible to replace the bottle by a liquid board package [40].
Carrier bags are most often made out of PE and a small percentage is made from paper. Improvement options are using recycled PE and the introduction of a multiple use carrier bag.
Industrial bags are also most often made out of PE, but for cement and fertilizer paper bags are often used. As an improvement option the Flexible Intermediate Bulk Container (FIBC) is modeled. FIBCs are very large and very strong bags (capable of carrying 1000 kg) made out of PP straps [45]. Most FIBCs are used only once but multiple use bags are in use as well [45].
Transport boxes are most often made out of corrugated board. Less corrugated board can be used for the same packaging service by many of the same measures as described for cardboard boxes [35,40,43]. Improvements in the primary packages may also lead to smaller corrugated boxes. We have modeled these developments by defining a light corrugated box that weighs 20% less. In some cases the corrugated box can be replaced by shrink film to bundle multiple primary packages [35,41]. Other improvements are the use of multiple use (plastic) crates [47]. These crates compete in other sectors (fruit and vegetable sector) with wooden multiple use crates and cardboard single use crates [49].
Pallets are generally made out of wood. Two thirds of the wooden pallets are used once and the rest is used multiple times (about 40 trips) [49, 50]. Wooden pallets are in competition with plastic pallets (either PE, recycled PE or recycled PC) that are also multiple use pallets and with corrugated fibreboard and pressed wood pallets that have trip numbers of 1 and 5 trips, respectively [51].
To bundle boxes on a pallet or to protect them from weather influences both stretch films and shrink covers are used. Both these films can be made thinner and in the case of stretch film the amount of film used can be decreased by using more efficient wrapping machines [52]. These developments are modeled by defining lighter films.

Model runs

In the introduction several questions are raised that can be answered by an integrated analysis of improvements in the energy and materials system of an economy. In our analysis several model runs have been used to answer the questions. The model runs are related to different material management strategies and described in Table 7.

Table 7: Model runs for this study

Abbreviation	Name of model run	Final packaging demand	Efficiency improvement	Penalty /tonne CO_2 eq.
FE	Frozen efficiency run	included	none	-
BAU	Business as usual run	included	due to packaging directive	-
BCP	Base case run	included	all cost effective measures	-
100P	100 ECU penalty run	included	due to penalty	100 ECU
500P	500 ECU penalty run	included	due to penalty	500 ECU
FE-NP	Frozen efficiency run excl. packaging	excluded	none	-
BAU-NP	Business as usual run excl. packaging	excluded	due to packaging directive	-
BC-NP	Base case run excl. packaging	excluded	cost effective	-
100-NP	100 ECU penalty run excl. packaging	excluded	due to penalty	100 ECU
500-NP	500 ECU penalty run excl. packaging	excluded	due to penalty	500 ECU

In the model runs we have included three variables: The first variable is the final demand for packaging. The final demand for packaging services has been set to zero in the runs excluding packaging demand. As a consequence, the production and waste handling of packaging materials is omitted from the energy and materials system, including all upstream and downstream emissions. The emission difference in the model runs with and without packaging demand (FE vs. FE-NP, BCP vs. BCNP, etc.) is a measure for the emissions contributed by packaging. An emission penalty of 100 ECU/tonne can be seen as a realistic emission penalty when large GHG emission reductions are striven for. The 500 ECU/tonne penalty is not a realistic penalty but by means of this penalty the technical limits of emission reduction are discovered.

The second variable is the autonomous development of improved use of materials. The MATTER MARKAL model works in such a way that all cost-effective measures are included in the base case of any model run. Many of the improved packages are cost-effective and are therefore part of the base case (BCP) [14,16]. In order to quantify the potential GHG emission reduction of the improved packages, the model has been run with a fixed materials efficiency for packaging[57]. We have chosen the fixed materials efficiency for packaging in such a way that it simulates the goals stated in The European Packaging Directive (EPD). This implicates a recovery of plastic waste of 65% and an average recycling rate of 35% (which is an important improvement compared

[57] Materials efficiency is defined as all changes in relation to materials use

to the current situation). Since the European Packaging Directive is implemented in Western Europe, this model run simulates the 'Business As Usual' packaging developments in Western Europe. The difference in GHG emissions between the BCP and the BAU run is a measure for the extra GHG emission reduction that can be reached on top of the impact of the packaging directive. In order to compare the effect of the European Packaging Directive to the situation where no improvements in packaging technology have taken place, we compared the BAU run with the FE run. In the FE run all possible improvement options for packaging have been excluded from the model. It simulates a situation where the packaging demand in 2030 is fulfilled by 1990 packaging technology and demand structure.
The third variable is a GHG emission penalty. This penalty increases the costs of GHG emission, which will lead to shifts towards more efficient technologies. The 100 ECU/t CO_2 model run represents a penalty level that is considered feasible in the framework of current emission reduction policies in Europe. The 500 ECU/t CO_2 model run represents a very high penalty that is not feasible in the current policy discussion. Instead, it should be considered as a measure for the technical emission-reduction potential. The penalties increase from zero in the year 2000 to their maximum level in 2020 and stabilize afterwards.

5.4 Results

Figure 3 shows the GHG emissions from packaging for simulation of increasingly stringent policy goals in the year 2030. The emissions related to packaging are calculated by subtracting the emissions from model runs that include packaging demand by the emissions from model runs that exclude packaging demand. The GHG emission in the BAU case is 130 Mt CO_2-equivalents. This is approximately 15 Mt less than the emissions in Table 3, despite a doubling of packaging services. This decrease can be attributed to expected autonomous efficiency gains in materials production and changes in waste management, and the impact of the packaging ordinance. Emissions decrease from a level of 130 Mt CO_2 equivalents in the BAU case to 98 Mt in the base case, to 85 Mt in the 100 ECU/t penalty case and to 55 Mt in the 500 ECU/t penalty case. This is equivalent to an economic reduction potential of 25%, an economic reduction potential of 45% when CO_2 emissions are penalized by 100 ECU/t, and a technical reduction potential of 58%[58]. The difference between the BAU case and the Base case is completely accounted for by cost-effective measures that increase packaging efficiency. Emissions per tonne material decrease significantly when an emission penalty of 100 ECU/t is

[58] A technical potential is defined as the achievable savings resulting from the most effective combination of the efficiency improvement options available in the period under investigation. An economic potential is defined as the potential that can be achieved at a net positive economic effect (Worrell et al., 1997).

introduced, due to the introduction of renewable energy, increased energy efficiency in materials production, and end-of-pipe technology for CO_2 removal and underground storage. The additional emission reduction through materials substitution and product substitution is limited, because most of these options are cost-effective and therefore part of the base case. When an emission penalty of 100 ECU/t is introduced, major changes occur in the waste handling stage. Methane is recovered from disposal sites, recycling rates are increased, and energy recovery from waste incineration is increased. The difference in GHG emissions between the 100 ECU/t case and the 500 ECU/t case can be attributed to a larger input of renewable energy and large scale input of renewable feedstock sources in the petrochemical industry.
Since most material management options are part of the base case, we may answer question 2 raised in Section 1 by stating that material management options are low cost options compared to many other GHG reduction options.
The impact of current waste prevention policies on GHG emissions is indicated by the difference of the BAU scenario and the FE scenario (-10%). From this we can learn that current waste prevention programs have a significant positive effect on GHG emission reduction in the packaging life cycle.

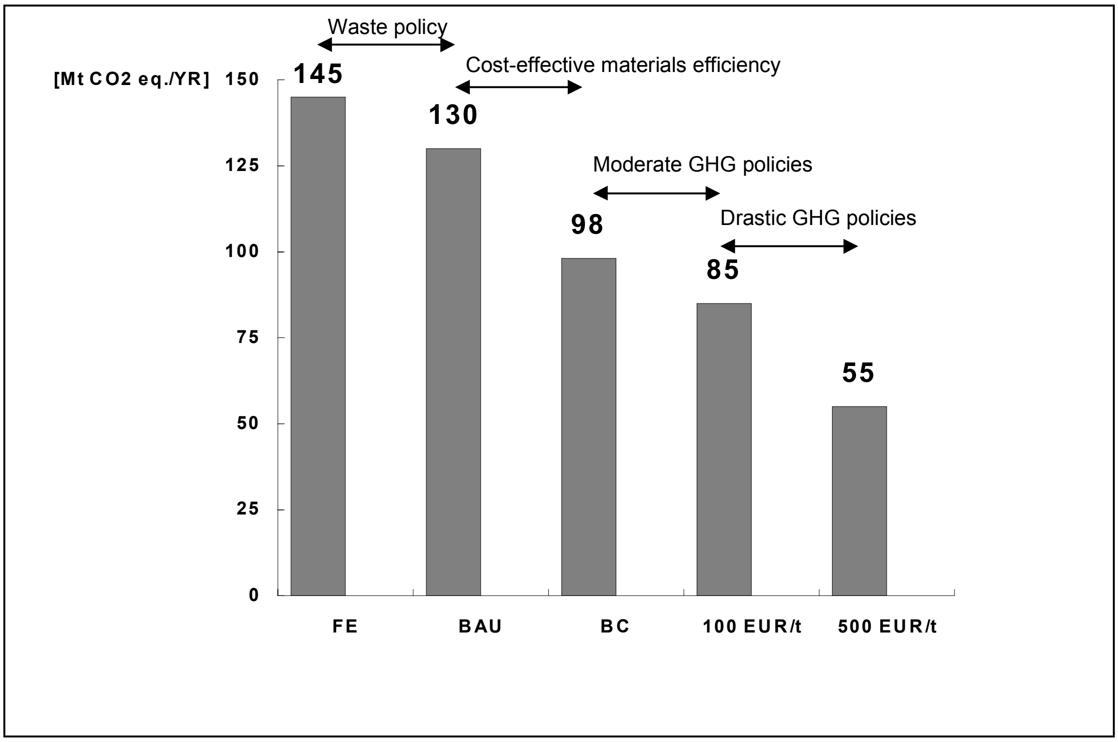

Figure 3: GHG emissions in the packaging life cycle for different model runs that simulate increasingly stringent GHG emission reduction policies, 2030.

Figure 4 shows the material use for packaging production for the different model runs that simulate increasingly stringent GHG emission reduction policies. The figure shows that the amount of materials is strongly reduced in the BCP compared to the BAU case (66 vs. 83 Mt). This shows that GHG emission reduction goals may lead to more significant waste reduction than the

European Packaging Directive.
The reduction in material use is the result of shifts towards product re-use, material recycling, and development of thinner materials. The largest reduction is visible in the plastics and glass production due to the fact that both materials are very suitable for product reuse. Plastics are partially replaced by wood. Therefore, the amount of wood is increasing. An emission penalty of 100 ECU/t results in a material use of 59 Mt/yr: a reduction of 11% compared to BCP. Reduction in glass consumption is the main cause of the reduction in material use. Glass is replaced by (refillable) plastic packages and steel packages. The amount of steel packages increases because the CO_2 intensity of steel production is strongly reduced due to CO_2 removal when a CO_2 emission reduction penalty of 100 ECU/t is introduced. The total amount of paper and board that is used increases because it serves as a substitute for several types of plastic packaging.
An increase in CO_2 emission penalty from 100 ECU/t to 500 ECU/t does not lead to a reduced use of materials. All available options for more efficient materials management are already implemented in the 100 ECU/t case. Although the material consumption stays the same, the emission of GHGs does decline according to Figure 3. As stated before, this reduction can be attributed to renewable feedstock resources and input of renewable energy (changes in materials production).

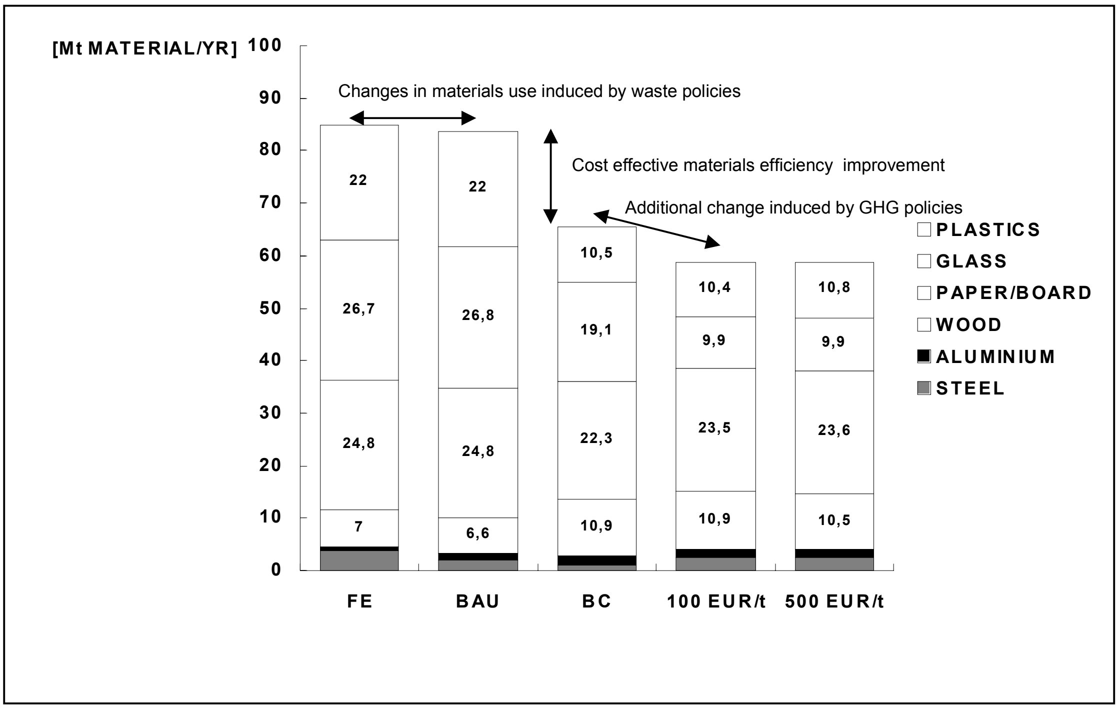

Figure 4: Shifts in packaging material use (expressed in Mtonne material use per year) for model runs that simulate increasingly stringent GHG reduction policies, 2030

Table 8 shows how material and waste prices in the MATTER-MARKAL model are influenced by a GHG emission penalties. The prices are significantly affected. Generally speaking, prices of materials and waste that lead to large GHG emissions are significantly increased when an emission penalty is introduced. However, cost effective GHG emission reduction options (with costs below the penalty level) may reduce the price increases. In case of polypropylene (PP), the price effect is much larger than can be expected based on the associated GHG emissions. The reason is the co-production of propylene and ethylene in the petrochemical industry. While several alternative production routes are available in the model for ethylene production, no alternative routes have been encountered for propylene. To fulfil the propylene demand large quantities of ethylene are produced. As a consequence, the model allocates the full burden of the co-production emissions to the propylene production, which results in large price effects. Also note the significant price effects for waste materials. Due to the GHG emission reduction potential of recycling waste materials the prices become less negative (packaging paper) or even positive (PET, steel and aluminum). On the other hand the price of plastic waste in municipal solid waste (MSW) decreases dramatically because of the comparatively low efficiency of energy recovery from MSW. The increased value of certain waste materials makes increased waste collection and expensive recycling technologies cost-effective.

Table 8: Changing prices due to GHG penalties, 2030 (shaded areas indicate a price increase in excess of 100 EUR/t) [53]

Material type	Basic product	Base case (EUR/t)	100 EUR/t (EUR/t)
Metals	Cold rolled steel coil	326	436
	Steel scrap	100	118
	Primary aluminum ingots	2182	3079
	Aluminum scrap	1524	2341
Natural organic materials	Packaging paper	382	365
	Waste paper	-47	-98
	Sawn timber	311	337
Synthetic organic materials	Polyethylene	409	349
	Polypropylene	670	1126
	PE/PP waste in MSW	-365	-595
	PET	894	1106
	Clean PET waste	186	372

The impact on packaging services is less pronounced than the impact on packaging materials (see Figure 5). The reason is that additional costs for packaging manufacturing and packaging handling consist mainly of labor and capital costs with comparatively low GHG emissions per financial unit, in comparison to the GHG intensity of materials production. This effect reduces the tendency for materials substitution.

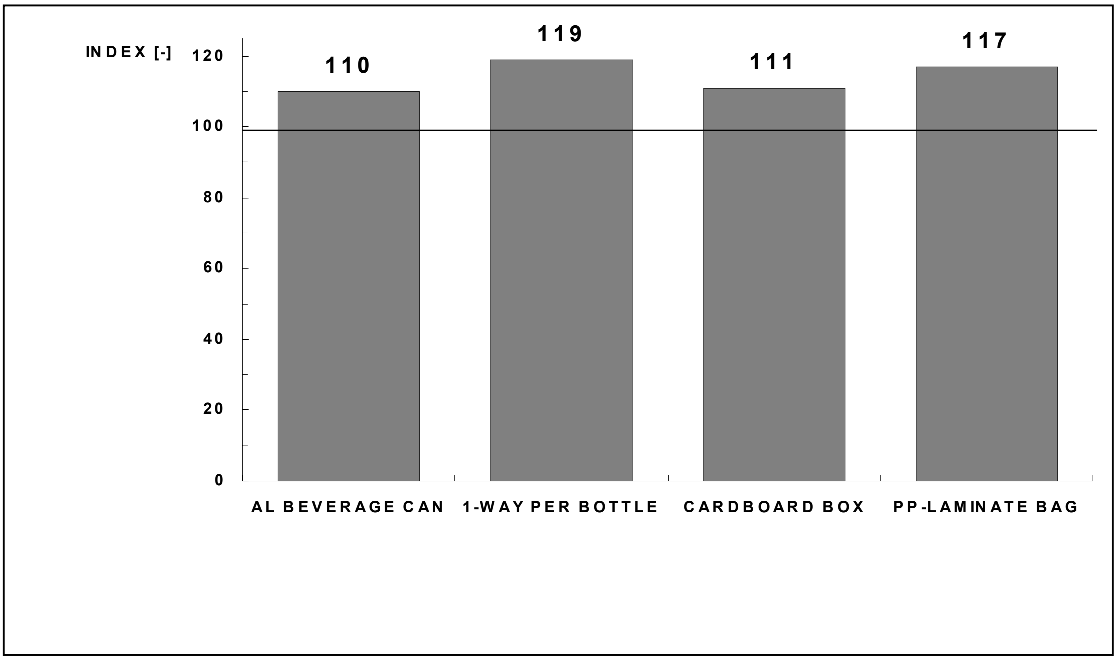

Figure 5: Changing packaging service costs, 100 ECU/t penalty scenario, 2030 (BC=100)

The discussion regarding environmental impacts of packaging is largely a discussion concerning plastics. However the emission accounting in the life cycle of plastics is complicated by the fact that carbon is stored in synthetic organic materials, which is only released if these materials are incinerated. Moreover biomass feedstocks can be applied in order to produce 'biochemicals'. As a consequence, the emissions in the life cycle of plastics will decrease dramatically. This is illustrated in [54], which shows that the emissions in the life cycle of Western European petrochemical products decrease by a factor 2 when an emission penalty of 200 EUR/t is applied in the model. Such reductions will decrease the relevance of materials substitution.

5.5 Discussion

The results show a reduction in GHG emissions of 32% in the base case relative to the FE scenario and a 25% reduction relative to the BAU scenario. These reductions can be attributed to material management options. The 100 ECU/t CO_2 scenario shows further reductions (41% compared to the FE scenario) but not all reductions are related to changes in the materials system. How do these GHG emission reduction potentials that are the results of efficient material management compare with the results in earlier studies where changes in the energy system and large scale changes in waste management practices are not taken into account? These studies show a reduction in GHG emissions of 40% for transport packaging and 51% for primary packaging [14, 16]. The total reductions related to changes in the material system in this study is smaller than 40% and therefore the potential reduction is smaller than was expected based on the other two studies. This is the result of longer timeframe of this study compared to the other two which leads to higher efficiencies in energy conversion, new material production technologies, and more efficient waste management practices. The fact that the interaction of emission reduction strategies are considered is an added value of an integrated model like the MATTER-MARKAL model.

The reliability of the results depends on the input data of the MATTER-MARKAL model and the methodology that is used in the model. We will discuss both aspects.

To discuss the influence of the input data we make a distinction between the packaging data and other model input data. The level of detail in the packaging input data is limited (even though this is the most detailed modeled sector in the model relative to the emission importance). This is due to the large geographical area and the diversity of the product group 'packaging' that is modeled. Average data for Western Europe are used as model input. Also, a limited number of standard (33) and improved packaging concepts (31) are modeled. The definition of the standard and improved packaging concepts have a significant influence on the results since these data determine which substitutions between packaging concepts lead to lower GHG emissions. The most sensitive packaging type is the corrugated box, which can be substituted by shrink foils and multiple use crates. When the standard corrugated box, for example, is modeled to be 10% lighter, the GHG emission reduction potential of substitution by shrink foils declines by a factor 2. We have decreased the influence of the material demand per packaging type on substitution options by modeling defining both standard and light packaging concepts. For an extensive discussion on the influences of the quality of the packaging data on the final results we refer to [14, 16]

Besides the input data for packaging also other input data influence the results. Since, for all scenarios we subtracted GHG emissions for a model run that excludes packaging demand from a run that includes packaging demand, data influences for other product groups than packaging are filtered out. Only processes that are in direct relation to the packaging life cycle are relevant for the model output. This means that a data input for the building sector, which is a difficult sector to model due to large regional differences, has no influence on the packaging results.

When the GHG emission due to energy consumption is decreased, the potential GHG emission reduction of material management options also decrease. In Table 4 some qualitative characteristics of the energy system are stated. Large shifts towards further decarbonization of the energy supply would increase the total GHG emission potential that can be reached in the packaging system but decrease the relative importance of material

management options.
It is always difficult to make a forecast about the future efficiency and costs of new technologies. Large uncertainties are introduced when using data about technologies that are still in an early stage of development. No adequate method has yet been developed to incorporate data quality in the MARKAL type computer models. The Monte Carlo approach, for example, is no viable option because of the years of calculation time that are required.
The timeframe of this study introduces another type of uncertainty. Improvement options are modeled when current literature reveals the relevance of these options for the future. However, in the time span that is studied in this paper many inventions may take place that are not yet known. These options may lead to a larger improvement potential. These may be incremental improvements in production processes or large technological and cultural shifts.
Besides data input also the model characteristics influence the reliability of the results.
The MARKAL model always minimizes the total costs of the modeled system. This results in situations where the model chooses the cheapest solution for its maximum potential while the competing technologies are just slightly more expensive. The sudden switch from one system configuration to another as soon as a certain parameter reaches a threshold value is called a 'flip-flop' effect. This effect is a sign that not enough detail is put into the model. Many runs with the MATTER-MARKAL model have been done and no flip-flop effects that were of large influences on the results have been detected. This suggests an acceptable level of detail in the model.
Finally, the model does not account for carbon leakage (relocation of materials producing industries to other regions) or for large changes in product demand[59]. Both effects may be substantial as shown in [4]. These effects may have a substantial impact on the materials intensive and lifestyle sensitive packaging sector. A new model version is currently being developed by ECN, which accounts for such effects.
Due to uncertainties that are described above, this type of model is not suited for very detailed analyses of specific technologies on GHG emission reduction. However, on the level of a product sector where many changes are possible the reliability of the results are expected to be reasonable. The final outcomes of the model should not be treated as true figures but more like a strong indication of the possible GHG emission reduction in a sector and the related shifts in material use.

5.6 Conclusions

By means of the MATTER MARKAL model we modeled the Western European energy and materials system in the period 1990 - 2050. In this paper we

[59] For packaging only small changes in demand are taken into account (see Table 4)

described several model runs that simulate less or more stringent GHG reduction policies related to packaging within a changing energy and materials systems model configuration.

Packaging materials constitute at this moment approximately 3.3% of the total GHG emission and 14% of the material related GHG emissions in Western Europe. Packaging services are growing rapidly, but there is ample room for improved management of materials, such as materials substitution and increased recycling and reuse.

Thirty-three packaging concepts are modeled and 31 improvement options. The improvement options can be classified as lighter and thinner packages, material substitution, material recycling and product recycling or reusable packaging. The largest material effects are visible for plastics and glass packaging since these materials are very suitable for product reuse, glass packaging is also very suitable for substitution by refillable plastic packages. The model results suggest that a 30% reduction in material use is possible in the Western European packaging sector.

The results show in 2030 a cost effective GHG reduction potential of 25% compared to the model run where the current goals of the European Packaging Directive are simulated and 32% compared to the Frozen Efficiency scenario. When a GHG emission reduction penalty of 100 ECU/t is introduced a GHG reduction of 45% is achieved compared to the BAU scenario. A technological improvement potential of 58% is calculated by introducing a GHG emission penalty of 500 ECU/t. Generally speaking, improved material management dominates the gains that can be achieved without or with low GHG emission penalties, whereas the reduction of emissions in materials production and the reduction of emissions in waste handling dominate when high GHG penalties are applied. Due to limitations in data availability and uncertainties that are introduced when modeling technologies that are in an early stage of development, the reduction percentages should not be treated as true figures but more like general levels of GHG emission reduction that is possible under more or less stringent GHG emission reduction goals.

The results suggest that more attention should be paid to material efficiency improvement in climate change policy due to the technical potential and the low life cycle costs of material efficiency improvement compared to other GHG emission reduction measures.

The results also show that policies directed to waste reduction lead to GHG emission reduction. The BAU scenario which simulated the goals of the European packaging Directive showed a 10% reduction to the Frozen Efficiency run. Furthermore, we have shown that effective GHG emission reduction policy in its turn leads to significant waste reduction. Results of this study show that GHG emission reduction goals may lead to more significant waste reduction than the European Packaging Directive.

Based on the above we find that integration of several (inter)national policy areas like GHG emission reduction policies, waste reduction policies, and product policies may be an effective and efficient way to reach both GHG

emission reduction and waste minimization.
The added value of the MARKAL approach is that the interactions of emission reduction strategies are considered. The improvements in energy efficiency reduce the emission reduction potential of materials production and waste handling. Moreover, the mix of "best" emission reduction options is influenced by these interactions. Such interactions must be accounted for in the development of long term emission reduction strategies. We recommend considering such interactions in the development of long term policies with a time horizon of several decades.

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Chapter 6

Modeling the Potential Impact of Material Efficient End-use Technologies on Communication Paper Use and Greenhouse Gas Emissions[60]

Abstract

The production and consumption of paper leads to emissions of greenhouse gases. Therefore, reducing the paper demand will lead to greenhouse gas emission reduction. Paper use for communication is responsible for GHG emissions of 121 Mt CO_2-eq. in Western Europe (1995). In this paper a baseline scenario is developed for Western Europe that forecasts a rise in communication paper consumption from 31 Mtons per year in 1995 to 53 Mtons in 2015. We show that several measures are available to reduce the demand for publication papers, e.g., thinner paper, efficient printing technologies, duplexing, and printing on demand. We estimate that it is technically possible to reduce paper demand in 2015 with 37% compared to the baseline scenario. This would correspond to a greenhouse gas emission reduction of 70 Mt CO_2 eq.. We calculate that the intensity of use of publication papers may drop from 5.2 kg /$1000 GDP in 1995 to 3.4 kg/ $1000 GDP in 2015. The measures with the largest emission reduction potential are lowering the basis weight of paper as well as Printing on Demand (POD). Assumptions on the market potential of POD are uncertain and have a large influence on the results. Further research should focus on determining the influence of increasing access to (digital) information on paper demand. In the analysis only material improvements are taken into account; no improvements in energy efficiency other waste management practices are taken into account.

Keywords: reduction of paper demand; material efficiency, greenhouse gas emission reduction, communication papers

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6.1 Introduction

Global warming is considered as one of the major environmental problems of the 21st century. To prevent global warming becoming a serious threat to our society, the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change strives towards a stabilization of greenhouse gases (GHGs) in the atmosphere [1]. To reach stabilization at acceptable levels, a reduction in greenhouse gas emissions is necessary [2]. A more efficient use of fossil energy use is considered to be one of the main opportunities to achieve a reduction [3].

The industrial sector is a large consumer of fossil fuels. This sector, where the production of materials and products takes place, consumed about 40% of the total world primary energy use in 1995[61] [4]. To reduce industrial energy demand most studies have focused on improving the energy efficiency of industrial processes.

However, more efficient management of materials can also reduce industrial energy demand since this may lead to either a smaller demand for materials or a shift in material use towards less energy intensive materials. Examples of efficient material management are material efficient product design, material substitution or use of materials with increased properties, using less materials for the same product, re-use of products and recycling of materials.

Several studies have also shown that improved material management can be an effective and often cost-efficient way to reduce GHG emissions. In Worrell et al. (1995) an approach for analyzing the potential for material efficiency improvement is presented [5]. Modeling results by Gielen (1999) show that increased material efficiency has a large GHG emission reduction potential. The results also show that a combination of material and energy efficiency measures is often cheaper than energy efficiency measures alone [6]. Patel (1999) shows that 24% of the CO_2 emissions related to plastics in Germany can be reduced by a selection of material management measures [7]. Hekkert et al. (2000) show that more efficient management of packaging materials may lead to a 51% CO_2 emission reduction in the primary packaging cycle [8]. Improved material management is especially useful for materials that are consumed in large quantities and require large amounts of energy in the production stage. One of the most energy intensive and most used materials is paper [9]. Globally the pulp and paper industry is the fifth largest industrial energy user, accounting for 10% of all industrial energy consumption [10]

The production and waste management of paper products and the related effects on the emission of GHGs has been the subject of many studies. Many

[61] Excluding refineries

studies focus on improvement of the energy efficiency of the paper making process on the short and long term, e.g., [11-13]. Furthermore, the relation between GHG emission and material efficiency is intensively studied for paper recycling. Often Life Cycle Assessments (LCA) are used to quantify the environmental impacts of paper recycling compared to a reference paper cycle. GHG emission are part of the LCA's, e.g. [14-18]. In Finnveden and Ekvall (1998) the findings of some of these studies are evaluated and compared [19].
All the studies focus on the paper production process and waste management system to reduce environmental impacts. The rest of the paper cycle is often not studied in terms of energy and material efficiency. For energy efficiency studies this is logical since a vast majority of the total energy consumption is used in the paper production stage, while landfills are an important source of GHG emissions. When studying material efficiency improvement however, the part of the paper cycle between material production and waste management may contain many options to improve the material efficiency of the paper cycle and thereby reducing GHG emissions [10].

In this study we want to explore the opportunities of changing the traditional focus of reducing energy and material use *per ton of paper product* to reducing energy and material use *to perform a specific service*[62]. The importance of creating insights in the possibilities for more efficient paper consumption is highlighted by an OECD workshop on rethinking paper consumption [20]. In a study of the International Institute for Environment and Development called *'Towards a sustainable paper cycle'*, optimizing paper use per service is addressed as an important issue but no technical opportunities are assessed [10]. A well known study of the Environmental Defense Fund called '*The paper taskforce*', presents some opportunities to reduce paper use per service, but does not quantify the potentials of these measures [21]. The goal of this article is to investigate possible opportunities for more efficient use of paper and to quantify the effects of these measures on GHG emissions related to paper consumption.
In international statistics five main paper grades are defined where packaging (40%), Printing and Writing paper (34%) (P&W paper), and Newsprint (14%) are the largest in volume [22]. Possibilities for using less paper packaging and the consequences for GHG emissions are explored in Hekkert et al. (2000) [8]. Therefore, in this study we focus on the categories 'Newsprint' and 'P&W paper', also called 'communication papers'.
Many studies, e.g., [14-19], focused on paper recycling as a material efficiency option. The results show that the influence of paper recycling on GHG emissions strongly vary per paper type and geographical region [23]. In this article we focus on the potentials of different end-use technologies and do not take recycling into account in order to keep the results comprehensible. Furthermore we focus on measures that are currently technically available or

[62] Examples of a service of paper are to carry information and to pack a good.

will be available soon. The time horizon of this study is therefore set at 2015. The geographical focus of this study is Western Europe.

In this paper we address the following research question: *What opportunities, apart from paper recycling, are available to fulfill the current services of communication paper more efficiently and what is the influence on GHG emissions in Western Europe for the period 1995 – 2015?*

In the next section we will present the method that we used to answer our research question. In section 3 we will describe the historical consumption trends and a scenario until the year 2015. Section 4 describes the technical options for more efficient use of paper for communication. In section 5 we assess the potential of GHG emission reduction by using a dynamic paper consumption model. We end with a discussion of the results and conclusions.

6.2 Method

The research method used in this study consists of several steps. First we make a forecast of the communication paper consumption in the period 1995 – 2015. Second, we investigate the technical opportunities for more efficient use of these papers. Third, we model the potential impact of the technical measures on the GHG emissions related to paper consumption. All paper flows are expressed in metric tons.

Reference scenario

First, We analyze the historical developments of paper consumption in Western Europe in the period 1960-1995. Then, we establish a reference scenario to reflect the autonomous development of paper demand for communication in Western Europe for the period 1995-2015. The reference scenario will be used as a baseline to assess the potential impact of implementing measures to improve efficient use of paper for communication purposes. A study by Cutler (1995) is used as a basis for the reference scenario [24].
The reference scenario contains information on the future demand for several categories of communication papers in the period 1995 - 2015. Differentiation of categories of communication paper types is essential, as reduction measures are specific for certain categories.
In the reference scenario explicit assumptions are made about drivers that influence future paper demand. These drivers may overlap with the measures investigated in this article. For all improvement measures the potential overlap with the drivers in the reference scenario is assessed. We assume that besides these drivers, no other factors are taken into account that may lead to either dematerialization or increased paper use.

Investigation of measures for more efficient paper consumption

We concentrate on the following two types of measures: (1) producing paper products that use less paper and (2) using less or different paper products for the same service. For all measures the possible reduction in paper consumption is determined. The timeframe that it is needed to implement the measures to their full potential is set for all measures at 15 years. An S-curve is used to simulate the implementation trajectory.

Calculation of possible GHG emission reduction

To calculate the reduction in GHG emissions that are the result of the investigated reduction measures, the GHG emissions related to the categories of communication papers are determined on a life cycle basis (see Figure 3). For every category of communication paper future demand (and the GHG emissions) is modeled by combining the autonomous developments and the reduction measures. For this purpose a dynamic model is constructed using STELLA [25]. In Figure 1, an overview of the model is presented for one paper category, one reduction measure, and one model year.

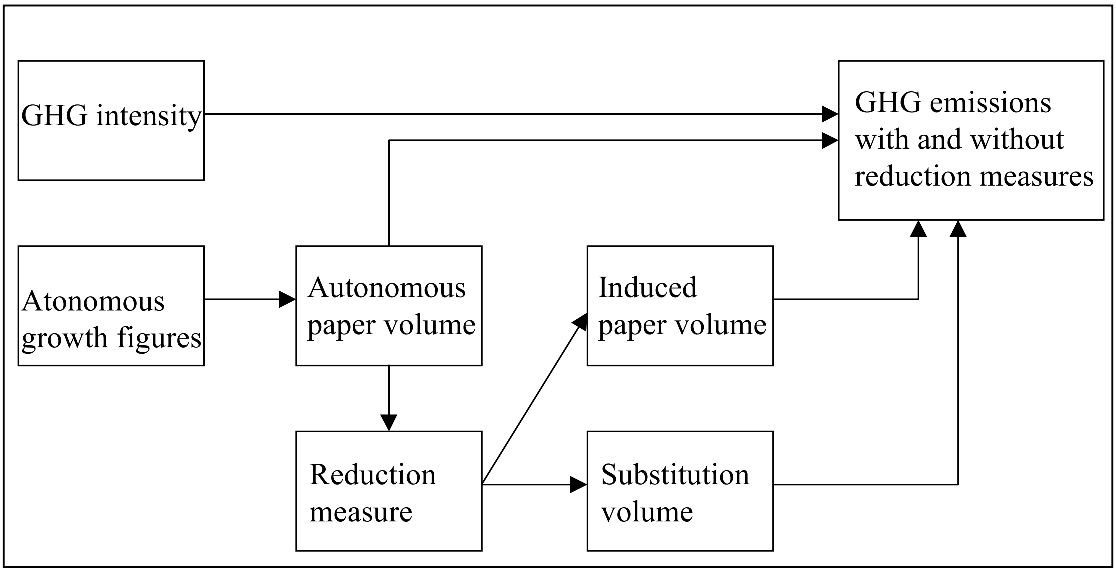

Figure 1: Simplified overview of the Stella model used to calculate potential GHG emission reduction for publication papers due to material efficient technologies.

Individual growth factors for different paper products determine the autonomous paper volume in 2015. For each paper product these drivers are determined by Cutler (1995) and used for the baseline scenario in this article [24]. The forecast by Cutler (1995) ends in 2006. In this article the growth rates for the paper types in the period 1995 – 2006 are extrapolated to the period 1995 – 2015 since for the most paper types no convincing arguments are available to change the growth rates after 2006. For some paper types, the effect of other growth rates will be discussed in Section 6. Reduction measures determine the change in paper volume. In some cases a substitution effect needs to be taken into account. GHG intensities, defined as the greenhouse gas emission associated with the production and consumption of one tonne of paper, of the paper types are used to determine the reduction in GHG emissions caused by the reduction measures.

System boundaries

The analysis focuses on Western Europe as geographical region. New technologies are only taken into account when technically a large implementation level is expected to be possible in 2015. Only material efficient technologies are studied. Neither technology that increases the energy efficiency of the pulp and paper production processes, nor new waste management technologies are taken into account. This implies that the results will overestimate the potential of material efficient technologies in this respect since historic developments of energy efficiency in industry shows an autonomous increase in the efficiency.

6.3 Historic and future trends of paper consumption in Western Europe

To be able to make a baseline prognosis of future paper consumption for communication purposes we first study historical paper consumption patterns. In Figure 2 the consumption of Newsprint and P&W paper in Western Europe is depicted for the period 1960 – 1995.
Newsprint is generally used for the production of newspapers and P&W paper suitable for printing, writing or other graphic purposes. P&W paper is generally used to produce the following product categories: books, magazines, catalogues, directories, inserts/flyers, commercial printing, business papers, and cut size papers.
Figure 2 shows that the paper demand more than tripled in the period 1960 – 1995. It also shows that Newsprint is not growing as fast as P&W paper. Furthermore, the figure shows that the growth varies over time. In Table 1 the growth figures are given for three time periods 1960 – 1975, 1975-1990, and 1990 – 1995.

Table 1 shows that in the period 1975 – 1990 paper consumption growth accelerates compared to the period 1960 - 1975 and that the growth in paper consumption seems to decline in the last period. These differences in growth rates make it difficult to assess future paper growth rates, using single trend analysis techniques only. Therefore an analysis on paper product level is necessary. Such an analysis is done by Cutler (1995) [24]. We will use this analysis to construct our baseline scenario.

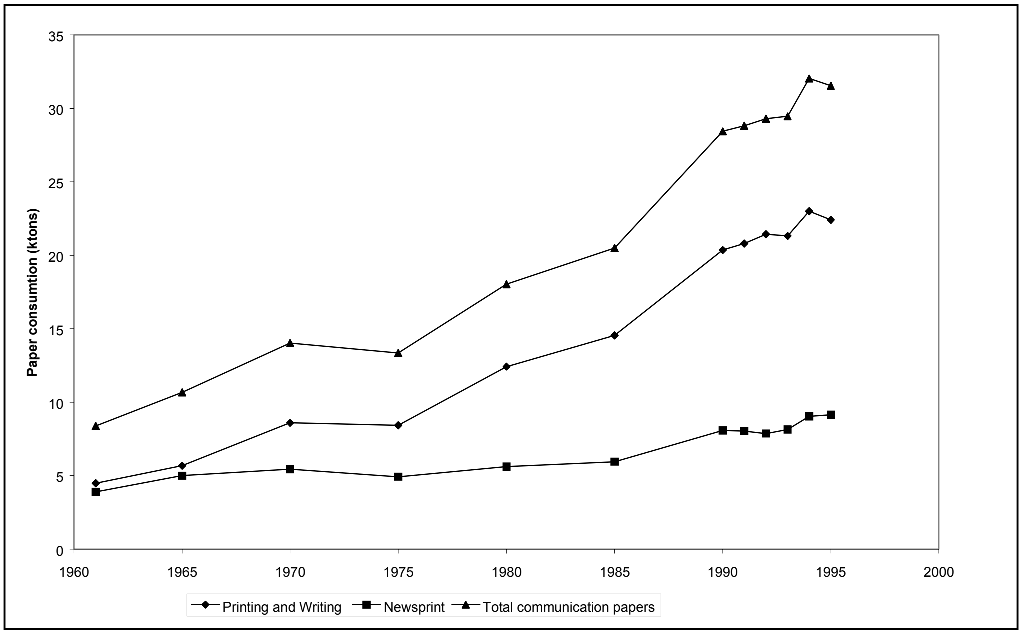

Figure 2: Consumption of Newsprint and P&W paper in Western Europe in the period 1960-1995 [22,26].

Table 1: Paper consumption growth per year for three time periods and total period (in %).

	1960 - 1975	1975 – 1990	1990 - 1995
Newsprint	1.5	3.5	1
P&W	5	5.5	2

The basic assumption in the analysis of Cutler (1995) is that total paper growth is directly correlated with GDP, or 1% GDP growth will result in 1% paper growth. This is in line with historic data in the period 1990 - 1995 [24]. For the period 1995 – 2007, Cutler (1995) assumes an average GDP growth in Western Europe of 2.5%. In our analysis we extrapolate this growth rate up to the year 2015. From Table 1 it follows that a growth rate of 2.5% is rather low compared to the average growth in the period 1975 – 1990, and is more in line with the growth rate in the period 1990 – 1995. In Figure 3 this forecast is depicted in relation to the historic consumption figures.

Even though total paper consumption growth is in line with GDP growth, the growth rates of the individual paper types may differ strongly. Based on a large number of specific drivers for the individual paper products, Cutler (1995) determines the growth rates for these products. Table 3 summarizes the drivers and the effects on the paper products.

6.4 Options for more efficient use of communication papers

We differentiate between options that reduce the amount of materials necessary for manufacturing paper products and options that reduce the amount of paper products to fulfill a service.

Options that reduce the amount of paper for paper products.

Three options are available that reduce the amount of paper necessary for manufacturing paper products: (1) increasing the resource efficiency in the paper production process (2) increasing the efficiency of the graphical production process, by decreasing production losses, and (3) decreasing paper weight. Neither of these options is part of the baseline scenario.

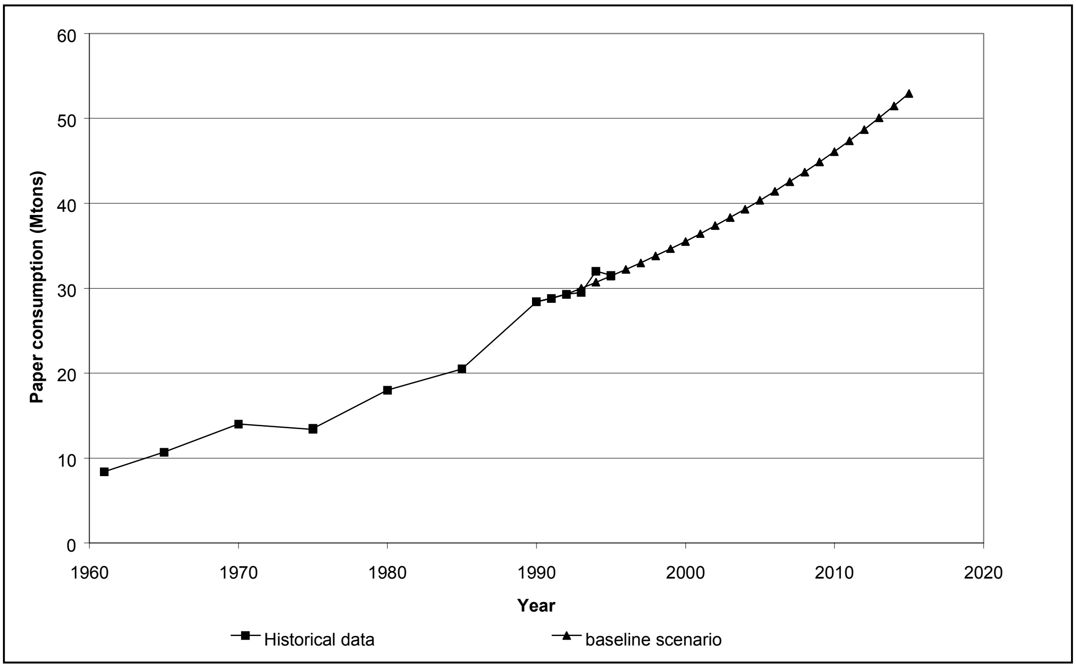

Figure 3: baseline scenario of communication paper consumption based on Cutler (1995).

Even though the paper production process is a highly mechanized and efficient process, not all paper produced is suitable for sale. Damaged paper rolls, paper break during the production process and quality variations limit the *production efficiency*. Increasing the efficiency of the production process is seen by the Dutch paper manufacturers as one of the major area's where (indirect) energy savings can be achieved [27]. A 2% efficiency improvement is possible for the Dutch paper industry[27]. As no data are available for other Western European countries we extrapolate this efficiency improvement to all Western European countries.

In the graphical industry also an increase in paper efficiency is possible. For every new printing job, paper input is needed to adjust the printing presses. New press technology can decrease these adjustment periods, which will result in paper savings. According to the Dutch graphical industry the graphical production process can be 2% more efficient when new techniques are

incorporated [27]. This number will also be used for western Europe as there are no reasons to assume a different number.
Another option that decreases the amount of paper necessary to produce paper products *is reduction of paperweight*. The minimum paperweight that is necessary for newspaper production is about 42 grams/m2 based on minimal transparency and stiffness requirements [28],[27]. At present, some newspaper producers use these paperweights [29], [27]. On the other hand 35% of all newspapers are printed on paperweights of more than 48.8 grams/m2 [28]. The average weight of Newsprint in Western Europe is estimated at 45 grams/m2 [30]. Therefore, a reduction of 7% in paperweight seems technically possible.
For P&W paper a far wider range in paperweight is used. The standard weight of cut size in Europe is 80 grams/m2 and the dominating paperweight in the magazine sector is about 52 grams/m2 [29]. The weight of cut size papers can easily be reduced to 70 grams/m2 and still be suitable for duplex copying and printing [30]. We expect that for all P&W paper, except magazines and books, the same reduction percentage (15%) is possible. Magazines and books already have shown a development towards thinner paper. Here, we expect a reduction of 10% to be possible without significantly compromising the appearance of magazines (and books).

Options that reduce the amount of paper products to fulfil a service

We have investigated several options that may lead to reduced consumption of paper to fulfill the same service. These options can be categorized as (1) good housekeeping, (2) improved copying and printing technologies, and (3) matching production and demand.

Good housekeeping

In 1994, a program was launched by WWF in the Netherlands to reduce the amount of paper use in offices. Companies that joined the program committed themselves to a reduction in paper use of 10% within a year. The program proved to be very successful. Currently 143 companies have joined the program, reaching an average paper reduction of 10.3% [Internet, 2000 #511]. No investments were made by the companies to reach the 10% reduction goal [31]. The reduction is reached solely by good housekeeping [27]. Based on this program we assume that 10% reduction of office paper use is possible (business papers and cut size papers). As we see later, about 75% of cut size papers is used in offices, the other part is used in professional printing and copying shops[63,64]. Hence, we apply this to 75% of cut-size paper demand.

[63] Based on the assumption that copying machines with a speed higher than 69 copies per minute are used for professional printing and copying jobs (not in offices). Table 3 indicates that this represents about 25% of the copying market.

Table 3: Drivers and growth rates for paper types in the period 1995 – 2006 [24]

Paper product type	Drivers	Effect	Annual growth rate in period 1995-2006
Newsprint	Declining readership levels Loss of advertising Competition of other media	Negative Negative Negative	1.6%
Magazines	Increase in number of titles Competition of other media	Positive Negative	2.5%
Commercial printing	Large increase in advertisement Competition of other media	Positive Negative	3.9%
Business papers	Growth of service industries Strong shift towards cut size paper Shift towards electronic data transfer	Positive Negative Negative	-0.7%
Cut size papers	Maturing copying market Growing printer market Growth in information access No competition of electronic services until 2007	Negative Positive Positive Neutral	5.1%
Books	Slow but gradual shifts towards electronic formats	Negative	0.3%
Catalogues	Stable market	Neutral	2.1%
Inserts/Flyers	Growth in advertisement Long period before electronic media will become a threat	Positive Neutral	4.7%
Directories	Long term threat of CD-ROM and on-line systems	Neutral	2.5%

Improved copying and printing technologies

Due to improvements in copying and printing technology increases are possible in the amount of paper that is copied or printed in a duplex mode.

[64] We neglected cut size paper use in households since low volume printers are used in both small offices and homes. Table 3 shows that this low volume segment is good for 11% of cut size paper consumption in Western-Europe.

Table 3 shows the current duplex rate for different copier types and the share of these copier types in the total demand for paper for copying purposes.
The table shows that the duplexing rate strongly increases with copying speed[65]. The machines in the volume segments 5 and 6 are normally used for professional purposes like commercial copy shops. There are several reasons for the relatively low duplexing rates in black and white copying and printing: many machines do not have an automatic duplexing mode or people do not use the existing duplexing mode. The latter can be due to decreasing machine speed during copying in the duplexing mode, experiencing more paper jams, and unawareness of the possibility [30] [32]. Technological innovations in the copier market will lead to more machines that contain a duplex mode and these innovations are likely to solve the problems mentioned above. An important innovation is that manufacturers deliver their copying machines with the duplex mode as the default mode. We expect that a strong increase in the duplexing rate should be possible based on the technological developments that are currently going on the copying market. We assume that in 2015 the duplexing rate of the high segments in 1995 should be possible. This implies an increase of the average duplexing rate of about 30% in 1995 to 60% in 2015. This estimate is in line with estimates by [33]. This increase in duplexing rate would lead to a reduction of 19% on cut size paper demand for copying.
Currently, printing in the office differs from copying in terms of technology used. The duplexing rates for printing are much lower than for copying, 5.5% in 1995 [34]. Current developments in the copying and printing market suggest that copying and printing will take place on the same machines. For printing we therefore assume the same future duplexing rates as for copying. This results in a 28% reduction in cut size paper for printing purposes. Since copying paper and printing paper have market shares of 56% and 34% respectively in the cut size market [30], the total cut size paper reduction due to improved copying and printing technologies is calculated at 22%.
Another technological improvement in the printing market is the shift towards digital printing. We will focus on this development in the next section.

Matching production and demand

Communication papers are used to carry information and deliver it to a consumer. In many cases, consumers are confronted with much more information than that they are interested in. Therefore, if only the information is delivered what interests the consumer (version control), much paper could be saved. Three ways of version control can be distinguished: Personalization, Customization, and Versioning [35].
Personalization is one-to-one marketing tailored to a specific individual. Customization is creating documents as a template with different messages based on stated consumer preferences. In this case several individuals may receive the same information that appears to be personalized but is in fact

[65] Duplexing rate is defined as the number of sheets of paper that are used two-sided divided by the total number of sheets of paper used.

based on a database of predetermined customer preferences. Versioning is based on data mining techniques - often using broad demographic, psychographic, or purchase history data - that produces a generic document that appears personalized but is identical to that produced for others with the same profile.
Personalization might be possible for *newspapers*. Newspapers currently contain the same information for all subscribers while the interest of these people may differ. One way to personalize newspaper is to offer a choice in the sections subscribers want to receive. Assuming that at least one section of the average five sections is not of interest to a reader, the demand for Newsprint can be reduced by 20% [30]. In this case the function of the newspaper, i.e., delivering information that is of interest to a reader would stay the same but the amount of paper to do so would be reduced. To make this measure work changes are necessary in the way newspapers are delivered. The influence of this aspect will be discussed in section 6.

Table 3: Duplexing rate for copying in Europe [34]

Copier segment	Copier speed (cpm)[1]	Paper consumption of total (%)	Duplexing rate 1996 (%)
1AA	<10	1.0	0.0
1A	10-13	6.0	2.1
1B	14-19	3.9	3.2
2	20-30	16.8	6.8
3	31-45	16.6	14.8
4	46-69	29.2	23.5
5	70-90	11.6	41.5
6	>91	13.6	57.9
Color	All	0.8	0
Over-all		100[66]	28.6

[1] cpm: copies per minute

For *advertisements* and *commercial printing* all three types of version control are possible. Advertisements are an often-mentioned example of inefficient function fulfillment. Paper is wasted since it is used to deliver information about products that are not of interest to the receivers of the advertisement. Commercial printing is also an example of inefficient paper use. Since the fixed costs of offset printing are large and these costs decline when the edition increases, often more copies are printed than necessary. According to Rombout (1998) about 40% of all commercial printing in The Netherlands is not used at all, since it is outdated before distribution [36].

[66] The total consumption of European copier paper was 1.2 million tons in 1996. This is about half the size of total Cut Size.

New technology, called Printing On Demand (POD), is available to make version control possible and reduce the number of unused prints. POD can be defined as '…processing information in digital form with the primary objective of producing printed documents in optimal quantities within the shortest possible timeframe, with content selectively targeted (customized) for the recipient' [37]. POD involves digital printing presses that are able to print documents directly from digital documents. Therefore, no costs are necessary to produce printing plates and prepare the press for a print job. For large editions offset printing is still cheaper, but for editions smaller than about 5000 units, POD becomes interesting from an economic point of view [38,39]. This resembles 45% of the commercial printing market [38].
For commercial printing we assume that the number of outdated copies can be reduced to 5%. Taking into account a maximum market share of 45% for POD leads to a reduction in paper demand of 15%.
POD technologies and coupling of printing processes with data mining activities (to make versioning possible) can increase the effectiveness of advertisements by a factor five [38]. Hence, 80% less advertisement paper is necessary for fulfilling the same service (increasing sales to the same level through advertising). In the discussion we will focus on the influence of lower reduction percentages on the final results
Advertisements can also be reduced by consumer action. In the Netherlands mailbox stickers were introduced, to prevent unwanted commercial information from being delivered. By means of a sticker on the mailbox, households can indicate whether they are interested in receiving commercial advertisements and/or local newspapers. Ten percent of the Dutch households currently use these stickers which leads to a similar reduction on inserts and flyers [40].
Besides commercial printing also large quantities of *books* are unnecessarily printed. According to Vleggenaar (1997) 35 to 50% of all published books are not sold in the bookstores and are returned to the publisher [41]. The reason for this surplus of printed books is the low costs per page of offset printing when large numbers are printed. POD offers good opportunities to reduce the excess amount of printed books. First, a small number of books are printed by means of POD and offered to a few representative book stores to test the market demand for these books. Based on these test results a more profound estimate can be made on the total demand for these books. When the books are sold out, POD offers the opportunity to distribute a small number of books to satisfy the remaining demand [42]. Based on Ref. [42] we assume that the total demand of paper for books can be reduced by 25% due to more effective market orientation based on POD. We will use the same assumption for catalogues since for this paper product POD offers the same possibilities to make improved estimates about the quantities needed.
Distribute and Print, or DAP, means distributing the information in a digital, low cost form to distributors or potential consumers, so that these recipients can make a selection out of this information for printing. The potential for DAP on the short term varies strongly, depending on the definition that is used. When

using and printing information from the internet is seen as DAP, the potential on the short term is large. For example, this vision is shared by Hewlett Packard that focuses on the low end of the printer market, which is well suited for DAP, as they expect the largest growth figures for this part of the print market [43]. However, in this article we use the term DAP for those situations where traditional ways of distributing information are replaced by digital distribution. To study the potential GHG emission reduction that can be achieved by DAP we focus on one example that is likely to gain a significant market share in the near future: digital newspapers.

Already many large newspapers distribute a digital version of their paper through the Internet. The considerable information content of most newspapers, combined with high fixed costs and the subsidizing of content by advertising, makes them particularly vulnerable to electronic substitution [44]. Even though the Internet might be a good substitution for newspapers, it is hard to predict what the future share of electronic newspapers might be. Parameters that effect the substitution of traditional media by electronic media are the enhanced functionality of electronic media, the economics of both media, the reading habits of the readers, and the emotional attachment of the readers to paper media [44]. The Boston Consulting Group expects that a 7% decline in Newsprint consumption can be expected in the period 1996-2003 due to electronic newspapers [44]. In the baseline scenario only very limited competition of electronic newspapers is expected, about 1%–2% decline of newsprint in the period up to 2006.

The goal of this paper is not to predict the future demand of Newsprint but to create insight in GHG emission reduction due to the introduction of technological changes. We will therefore make calculations with a range of possible impacts of electronic media. We will use a degree of substitution of 20% in the first calculations but we will discuss the influence of the impacts of newspaper substitution for the range 10% - 50%.

An important aspect of the environmental aspects of electronic Newsprint is the energy needed to power a computer for newspaper reading. According to Götsching (1999) all environmental benefits of using less Newsprint diminish due to the energy demand of computers and the increased use of cut size paper (for printing electronic newspapers) [46]. The results are strongly determined by the chosen functional unit for the analysis. Götsching defines the functional unit as the time needed to read a reference article of 477 words. We wish to emphasize that the advantage of DAP is the possibility to select text sections that are of interest to a reader. Based on Ref. [30] we assume that only 10% of the information present in newspapers is read digitally and that 20% of this information is printed (on cut size papers). This results in an extra consumption of 0.2 kg cut size papers for every kg Newsprint reduction. In the discussion we will discuss a range of other assumptions.

In Table 4 the influences of the measures on paper demand are summarized.

Table 4: Effect of reduction measures on paper demand for different product categories

Measures	Book	B.P[2].	Cat.[2]	CP[2]	Cut.s.[2]	Direct.[2]	Insert	Magaz.[2]	Misc.[2]	NP[2,3]
	%	%	%	%	%	%	%	%	%	%
Efficient paper production	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
Efficient paper printing	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
Decreasing paper weight	-10	-15	-15	-15	-15		-15	-10	-15	-7
Good housekeeping		-10			-10					
Duplex copying and printing					-22					
Personalized newspapers										-20
Printing on Demand	-25		-25	-15			-80			
Distribute and print					+4[1]					-18

[1] +4% of Newsprint consumption

[2] B.P.=Business papers, Cat=Cataloques, CP=commercial printing, Cut.s.=Cut size, Direct.=directories, Magaz.=Magazines, Misc.=Miscellaneous, NP=Newsprint

[3] 20% reduction minus 2% that is already part of the baseline scenario

6.5 Assessment of GHG emission reduction potential

GHG emissions related to the paper life cycle

First, we assess the GHG emissions that are emitted due to production and consumption of paper products. In Figure 3 a schematic overview is presented of the paper life cycle and associated emissions of CO_2 and CH_4. For forest management we assume that all wood used for paper production is renewable and therefore CO_2 neutral. The energy use for forest management is small compared to the energy use in the rest of the life cycle (315 MJprim/tonne wood) [61]. For pulp production we differentiate between mechanical pulping, chemical pulping and de-inked waste paper pulping. The energy use for these processes is stated in Table 4. In this table we differentiate between renewable energy use, fossil energy use and electricity (power from grid) [47]. No emissions are allocated to the renewable energy use. For the CO_2 emissions due to fossil energy use we use IEA data on primary energy use in the paper industry for individual Western European countries in 1995 [48]. A weighted average for Western Europe was calculated based on the production data of the pulp types for the individual countries [22]. For the CO_2 emissions due to electricity use from the grid we take into account the differences in power production in the different Western European countries since in 1995 these emissions varied between 0.08 kg CO_2 /kWh (Sweden) and 0,57 kg CO_2 /kWh (Germany) [22,49].

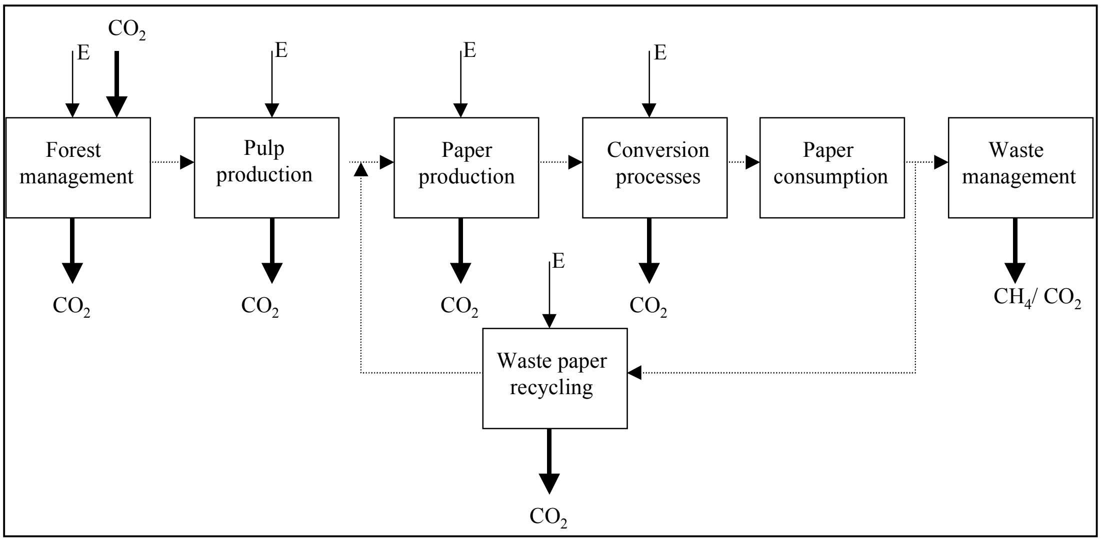

Figure 3: Paper life cycle including sources and sinks of CO_2 and CH_4 emissions and energy use

For paper manufacturing we differentiated between newsprint and other graphical paper production. Graphical paper production requires more energy than newsprint production [12].

Table 4: Energy use and related CO_2 emissions for three pulping processes and paper manufacturing in 1995 in Western Europe [17,47-50][67]

	Fossil energy (GJ_{prim}/ton)	**Power from grid (GJ_{el}/ton)**	**Renewable fuel (GJ_{prim}/ton)**	**CO_2 emission (kg CO_2/ton)**
Chemical pulping	2.0	1.3	18.4	227
Deinked waste paper pulping		2.2	1.2	300
Mechanical pulping	3.4	6.5	0.8	798
Newsprint manufacturing	2.8	1.4		214
Other graphical paper manufacturing	7.8	2		715

To calculate the energy consumption for paper *products*, in Table 5 we have broken down the pulp use for the different paper products [24]. In Table 6 the total CO_2 emissions for paper production are stated as calculated per paper product.

Waste management is an important source of GHG emissions due to the emissions of CH_4 at landfill sites. To calculate the GHG emissions from waste management we use the following assumptions. 38% of waste paper from communication papers is recovered while 62% is treated in the final waste management system[51]. In Western-Europe, 75% of the final waste paper is

[67] The large difference in carbon intensity between newsprint and other graphical papers is due to differences in carbon intensity of fossil fuel and electricity use between different European countries.

landfilled and 25% is incinerated [52]. Forty percent of paper consists of carbon [53]. Anaerobic digestion in landfills leads to an emission of 0.5 kg CH_4 per kg biodegradable carbon [53]. CH_4 has a global warming potential of 21 CO_2 equivalents [54]. Lignin takes very long to degrade and is therefore not regarded as biodegradable carbon. Thirty percent of mechanical pulp consists of lignin [54]. Since the share of mechanical pulp differs per paper product, so does the CH_4 emission. Not all CH_4 produced is released to the atmosphere since 25% is burnt [55]. For paper that is incinerated we assume that 13% of the waste is incinerated with energy recovery, either heat (54%), power (12%), or combined heat and power (34%) [52,56]. For plants that just produce electricity, we assume that 1 GJ waste (lower heating value) substitutes about 0.55 GJ of primary energy required to produce the same amount of electricity in power stations [7]. 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% [56]. Table 6 presents the emissions from waste management per paper product. The data above are 1995 data that are used for the complete model period.

The energy use of other processes that are necessary to produce paper products are small compared to the energy use for paper production. Printing of newspapers requires 0.3 GJ_{el} /ton [56]. Copying of cut size papers requires a little bit more, 0.4 GJ_{el} /ton [30]. Printing of magazines requires 1.1 GJ_{el} and 1.3 GJ_{prim} [57]. For transport we assume an energy consumption of 0.238 liter diesel per km for a 20 tons truck [58]. We furthermore assume an average transportation distance of 300 km [59]. This leads to an energy use of 0.2 GJ_{prim} /ton paper. For waste paper recovery we assume an average transportation distance of 100 km.

The emissions related to electronic reading are based on Göttsching (1999) who calculated an energy use of 18 kWh to read the information present on one kg newsprint [46]. This is based on an average power demand of 154 W for a computer system [59]. Since we earlier assumed that 10% of the newspaper is read, we also calculate with 1/10th of this energy use.

Assessment of potential reduction in GHG emissions

In this section we combine the GHG emission data related to the life cycle of the paper products and the reduction measures as described in section 2. Figure 4 shows the influence of the reduction measures on the demand for communication papers for the period 1995 - 2015. The figure shows that technically a reduction in paper demand seems possible of 37% in 2010 compared to the baseline scenario. The reduction of 37% in paper demand equals a reduction of 35% in GHG emissions; this implies an absolute reduction of about 70 Mtonne CO_2-eq. Figure 4 also shows that in the efficient paper use scenario, the total demand for publication papers hardly increases compared to the situation in 1995.

Table 5: break down of pulp use for paper products in Western Europe in 1995 [51] [24].

	Mechanical pulp (share in %)	**Chemical pulp (share in %)**	**Deinked pulp (share in %)**
Books	39	57	4
Business papers	4	92	4
Catalogues	79	17	4
Commercial printing	15	81	4
Cut size	0	96	4
Directories	90	7	4
Inserts, Flyers	86	11	4
Magazines	76	20	4
Miscellaneous	25	71	4
Newspapers	86		14

Table 6: Calculated GHG emissions for paper production, waste management and other processes like printing and transport in Western Europe (1995).

	GHG emissions from production ton CO_2-eq./ton	**GHG emissions from waste management ton CO_2-eq./ton**	**GHG emissions from other processes ton CO_2-eq./ton**	**Total GHG Emissions per ton ton CO_2-eq. /ton**	**Total GHG emissions per paper product Mton CO_2-eq.**
Books	1.5	2.2	0.04	3.8	6.2
Business papers	1.5	2.3	0.06	3.9	9.7
Catalogues	0.9	2.9	0.21	4.0	6.7
Commercial printing	0.9	3.0	0.21	4.1	21.5
Cut size	0.9	3.0	0.06	4.0	10.7
Directories	0.9	2.8	0.04	3.8	2.8
Inserts, Flyers	1.1	2.7	0.21	3.9	3.5
Magazines	1.4	2.3	0.21	3.9	19.8
Miscellaneous	1.6	2.3	0.04	3.9	8.5
Newspapers	1.0	2.2	0.04	3.2	26.7

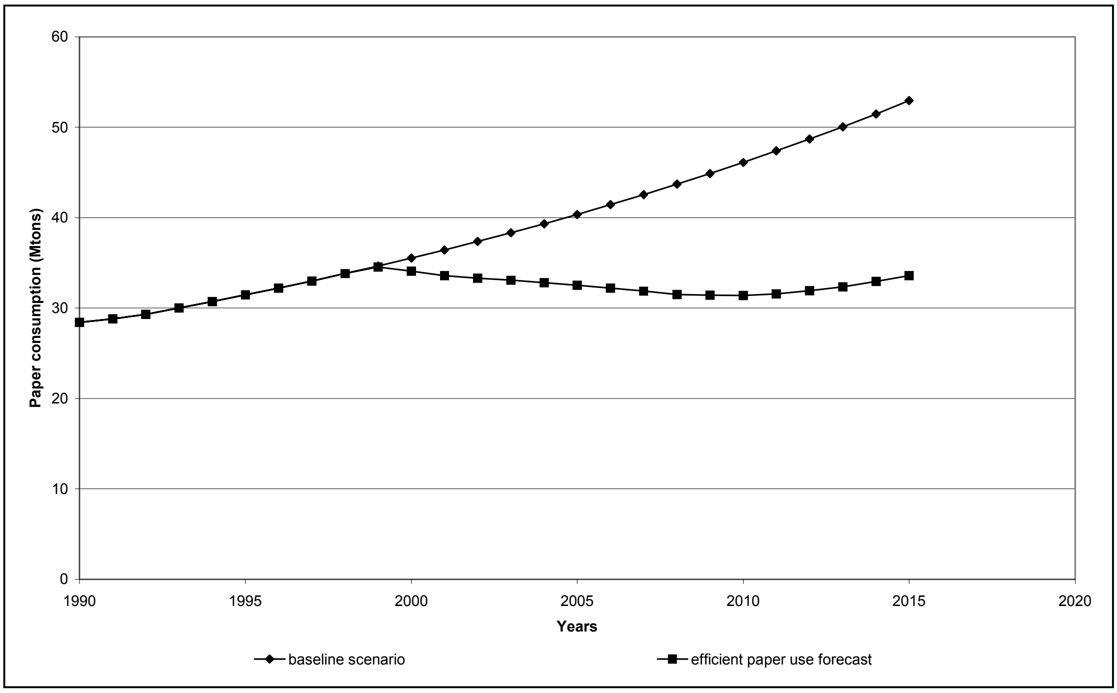

Figure 4: Forecast of demand for communication papers in Western Europe (1990 – 2015)

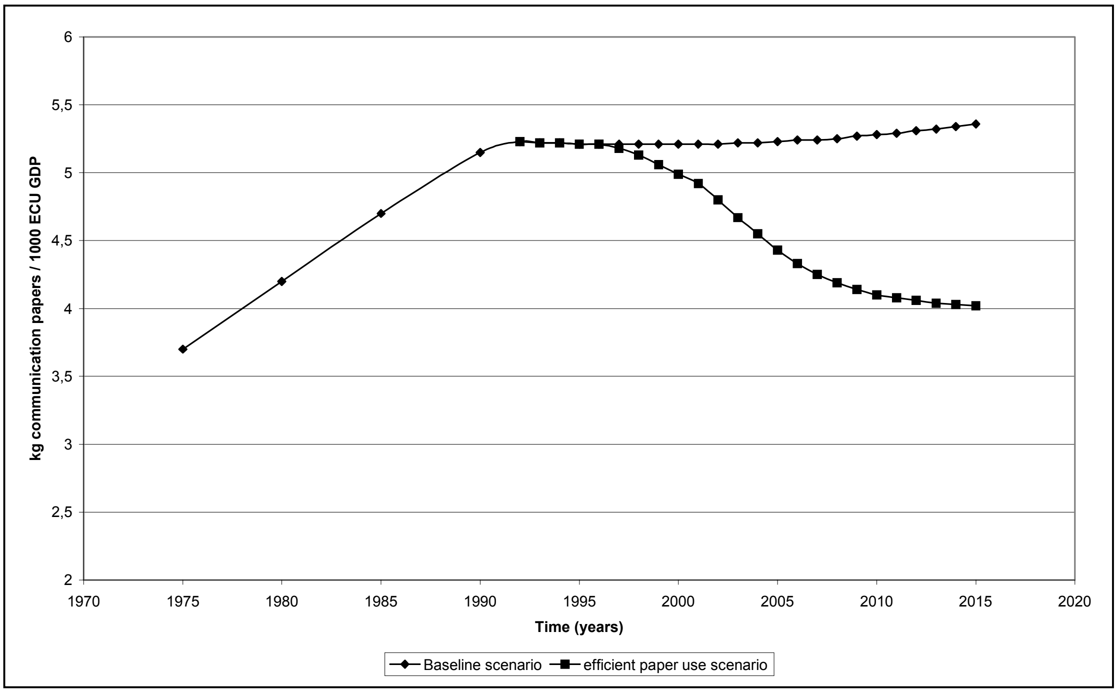

Figure 5: Paper intensity (kg / 1000 ECU GDP) for communication papers in the period 1975 - 2015 for both the baseline scenario and the improved paper use scenario. 1 ECU (1990) is 1.31 USD.

The intensity of paper use, expressed in kg paper use per 100$ GDP is depicted in Figure 5. The figure shows a reduction in the intensity of use of 5.2

kg / $1000 GDP in the baseline scenario to 3.4 kg / $1000 GDP in the efficient paper use scenario.

Table 7 gives a breakdown of the reduction in greenhouse gas emissions per reduction measure. The measures that have the largest effect are lowering the paperweight and Printing on Demand.

Table 7: Reduction of greenhouse gas emissions per material efficiency measure

Type of measure	Reduction of greenhouse gas emissions
Lowering paperweight	12%
Personalized newspapers	4%
Efficient production/printing	4%
Distribute and print	2%
Good housekeeping	2%
Extra duplexing	3%
POD	10%

Table 8 shows how paper demand is influenced by the improvement options for the different paper types in 2015 compared to the situation in 1995 and the baseline scenario for 2015.

Table 8: Paper use in 1995 and 2015 (for 2 forecasts) broken down per paper type

Paper type	**1995**	**Baseline scenario (Mtons)**	**Efficient paper use scenario (Mtons)**	**Reduction percentage (Efficient paper use scenario versus baseline scenario)**
Newsprint	8.3	11.5	5.9	49%
Commercial Printing	5.2	11.6	7.1	39%
Magazines	5.0	8.5	7.3	14%
Cut Size Papers	2.7	7.5	4.7	37%
Catalogues	1.7	2.6	1.6	39%
Business Papers	2.5	2.1	1.5	29%
Inserts/flyers	0.9	2.3	0.1	98%
Books	1.6	1.7	1.1	39%
Directories	0.7	1.2	1.2	4%
Rest	2.2	3.9	3.2	19%

The largest reductions compared to the baseline scenario take place for inserts/flyers, newsprint, commercial printing and books. All these reductions are largely driven by POD. For cut size papers we have calculated the smallest reduction since DAP leads to increased cut size use, which largely offsets other material efficiency options. Table 8 furthermore shows that 5 out of 10 paper markets show an absolute decrease compared to the situation in 1995.

6.6 Discussion

Baseline Assumptions

For the baseline scenario we used forecasts from Cutler (1995) until the year 2007. We extrapolated this forecast to the year 2015. For most paper products and investigated measures this extrapolation has no effect since Cutler (1995) did not foresee changes for these paper products in the period after 2007. Only for Inserts and Directories long term threats from electronic media are mentioned. For these categories a decline may be expected after 2007, which implies an overestimation of the calculated reduction potential. Due to the small market shares of these categories we expect the influence to be minimal.
We only studied measures that lead to more efficient paper use. Efficiency improvements in energy use and new waste management technologies are not taken into account. This leads to an over estimation of the absolute greenhouse gas emission reduction that is possible by implementing the technical measures investigated in this article. Especially a reduction in methane emissions from landfills may strongly decrease the calculated greenhouse gas emission reduction potential in absolute terms. When all methane would be burnt, the absolute emission reduction of the material efficiency measures would be reduced by 50%.
In the baseline scenario an economic growth of 2.5% per year is used. This is close to an extrapolation of trends in paper consumption in the period 1990 – 1995 (this can be clearly seen in Figure 5 where the growth per unit GDP is depicted). When the paper consumption trends of the last 30 years would be extrapolated, much higher paper consumption figures would be expected in 2015 in the baseline scenario; 71 Mtons per year in 2015 instead of 53 Mtons per year. In this scenario, material efficiency improvement would lead to higher emission reductions in absolute terms.

Measures Assumptions

Estimating the potential impact of emerging technologies is always difficult. In the previous chapters we have made a number of assumptions. In this chapter we will assess the consequences of these choices. We especially focus on those measures of which the potential is hard to estimate.
For Printing on Demand we have assumed that for inserts and flyers an 80% efficiency gain can be expected by better data mining techniques. When we assume a 40% efficiency gain the total greenhouse gas emission reduction potential decreases 2.5%. For commercial printing we assumed a reduction of 50% for outdated prints. When this effect is reduced to 20%, the greenhouse gas emission reduction potential decreases by 4%. Thus, less optimistic estimates about the influence of POD on paper demand result in a decrease of the total greenhouse gas emission reduction from 35% to 29%.
The greenhouse gas emission reduction due to Distribute and Print is limited since in our calculations it only influences newsprint demand. Many other

applications seem to be possible. This may increase the potential of this measure. In the original calculations we assumed that 20% of the newspapers are replaced by DAP. When we assume that 50% of the newspapers are replaced an additional greenhouse gas emission reduction of 5% is calculated, leading tot a total emission reduction of 42%.

The potential of Distribute and Print is influenced by many variables since substitution effects take place. The most important variable is the reading time (since this influences the energy use related to computers and monitors). To determine the influence reading time on the effect of distribute and Print, in Figure 6 the reading time from screen is set out on the horizontal axis as a percentage of the theoretical reading time. This is the time necessary to real all information in a kg newsprint. We assume that not all information is of interest to all readers and that every reader makes her own selection. Figure 6 shows that the positive effect of DAP is strongly related to the text selection made by the reader. We calculate that when less than about 33% of the original text is read on screen, DAP has a positive effect on greenhouse gas emission reduction. The figure also shows the effect of more efficient screens. When computers and screens use half the energy of current machines, 60% of text can be read on screen and still DAP has a positive effect. This increase in energy efficiency is very likely. Koomey (1995) expects that future machines are a factor 3 more efficient than current stock [60][68]. The reduction in greenhouse gas emissions in Figure 6 is based on the same assumptions for substitution potential of DAP as in paragraph 4.
The amount of paper used to print the electronically received information is also important on the potential of DAP. We assumed 0.2 kg cut size per kg newsprint. When no paper is printed the total greenhouse gas emission reduction increases by 0.8%. On the other hand when 0.4 kg cut size is printed than the emissions reduction decreases by 0.8%.
The measures addressed in this article are technical improvement options. The potential of these measures should also be regarded as a technical one. For some measures significant changes in current behavior and infrastructure are necessary. Personalized newspapers, for example, will require new logistics in the newspaper printing process and in the current delivering methods. Research that focuses on the specific barriers associated with these technical measures is needed to assess the implementation potential of efficient material technologies.

6.7 Conclusions

In this paper we have constructed a baseline scenario for communication paper use in Western Europe for the period 1995 – 2015. In this scenario the

[68] Note that for other processes, like paper production, no improvements in energy efficiency are taken into account. The exception for computer equipment is based on the potential increases in energy efficiency that are expected.

paper demand grows from 31 Mtonne in 1995 to 53 Mtonne in 2015. This scenario is consistent with developments in the paper market in 1990 - 1995. Extrapolation of paper use in the period 1965 – 1995 would result in a paper demand of 71 Mtons per year in 2015.

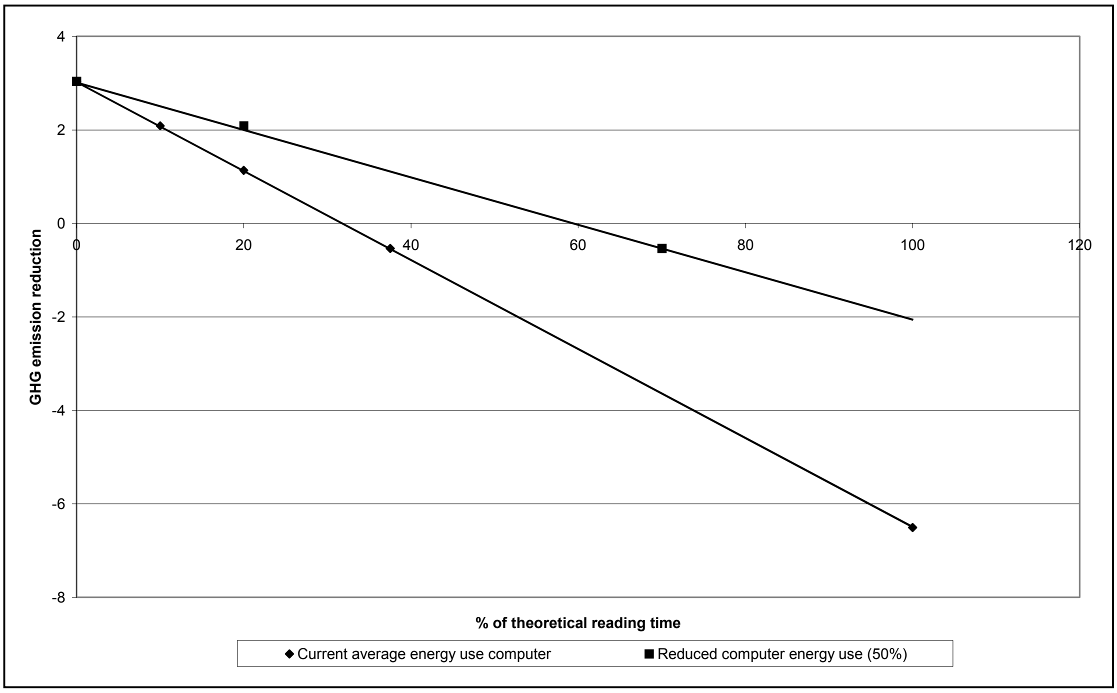

Figure 6: The influence of the factor "screen reading time / theoretical reading time for reading newspapers" on greenhouse gas emission reduction related to DAP for normal and low computer energy demand (factor 2 increase in energy efficiency).

In this article we shown that several measures are available to reduce the demand for communication paper grades, i.e. Newsprint and Printing & Writing paper. We estimate that it is technically possible to reduce paper demand in 2015 with 37% compared to the baseline paper demand in 2015. This results in a greenhouse gas emission reduction of 35% or 70 Mt CO_2-eq.. Compared to 1995, paper demand is still expected to rise with 7%. We calculate that the intensity of use of publication papers can technically be reduced from 5.2 kg /$1000 GDP to 3.4 kg/ $1000 GDP in the period 1995 - 2015.

The measures with the largest emission reduction potential are (1) lowering the basis weight of paper and (2) Printing on Demand (POD). Assumptions on the market potential of POD are uncertain and have a large influence on the results. Distribute and Print has a significant impact in the time period studied but is likely to have a larger potential in the years beyond 2015. The time spent on reading from screen has a significant impact on the positive effect of DAP on greenhouse gas emission reduction.

In this study we did not take paper recycling as a material efficiency measure into account. Furthermore, the influence of energy efficiency improvement in

the pulp and paper industry, nor more efficient waste management practices are taken into account. These latter developments reduce the influence of material efficient technologies on the absolute reduction of greenhouse gases.
The potentials in this article are of a technical nature. More research is necessary to assess the implementation potential of material efficient technologies on paper demand.

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Chapter 7

Wood in the residential construction sector; Opportunities and constraints[69]

Abstract

We study the opportunities to increase the use of wood in the Dutch residential construction sector and assess the effects on material related CO_2 emission. Four house types are modeled with increasing quantities of wood used in constructions. CO_2 emission reductions of almost 50% are technically possible. We assess the innovation characteristics of these wood applications to create insights in the complexity of the necessary change process. Then we relate the innovation characteristics of the wood options to the context in which the technologies take place. The options vary strongly in the required technical and network changes. Based on this we expect that a 12% CO_2 emission reduction related to material use for residential buildings is possible on the short term by an increased share of wood use. We also study the possibilities for increased wood recycling practices. A large technical potential exists. To achieve this potential a significant policy effort is needed since significant changes in both technical and network dimensions are necessary. To stimulate innovation in the use of wood in residential construction, important focus points of policy making should be the culture in the Dutch construction sector, the way new building projects are commissioned by the government, the subjects of research within the building sector, and stabilization of building networks.

Key words: wood use, construction sector, innovation characteristics, material management, policy, CO_2 emission reduction

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7.1 Introduction

Wood is an important building material; it is a lightweight material easy to process and repair, and it is widely available to the construction industry. In addition, wood is potentially a CO_2 neutral material if produced in a sustainable way; it takes up as much CO_2 during growth as it releases during decay or combustion. Since the production of wood also requires relatively little energy for forestry and wood processing, it can be defined as a 'low energy building material' [1]. Several studies have focused on the energy and CO_2 effects of using wood in the construction sector to replace other materials like concrete and steel. They show that CO_2 emissions related to material use in the construction sector can be reduced by 30% - 85% [2-4]. For an overview of a number of options to rearrange material use in the construction sector to accomplish CO_2 emission reduction; see Gielen [5]. When wood is used for long-life products it could even function as a temporary CO_2 sink[70].

The low CO_2 emission characteristics of wood, makes it a well suited material to use in CO_2 abatement strategies. However, in many countries forest clearing accelerates as population expands and pressures to exploit natural resources increase [7]. The decline of tropical forests but also the degradation of forests in temperate zones due to current management practices and acidification put the protection of forests high on the political agenda. Therefore, as a compromise between the positive CO_2 characteristics of wood on one hand and deforestation on the other, one can argue for an increase of wood application in long-life products like buildings and a decrease of wood use for short-life products like paper. In order to keep the wood consumption within the regeneration capacity of forests another strategy would be a more efficient use of long-life wood products by means of recycling and product reuse [8].

The Netherlands Government follows these strategies in environmental policy formulation. This has resulted in a voluntary agreement between the Dutch construction sector and the government about an increase of wood in the construction sector with 20% in 2000 compared to 1990 [9,10]. Even though a 20% increase in the use of wood may be a desirable development, the impact on CO_2 emissions is likely to be small, as the use of wood in the Dutch construction sector is small. However, the intended policy is significant because implementation will result in the reversal of current trends in materials use in Dutch construction, if implemented successfully.

In this context, in this article we will study the opportunities to increase the use of wood in the Dutch construction sector. Also we will investigate the potential effects on CO_2 emissions related to material use in the Dutch construction sector. In addition we will assess the potential improvement of wood recycling in the Dutch construction sector in a qualitative manner.

[70] In the current IPCC guidelines for National Greenhouse Gas Inventories CO_2 emission, the default assumption for changes from woody biomass stocks is that all carbon in biomass is oxidized in the removal year [6]. However, in the informal IPCC workshop at the Conference of the Parties 5 in Bonn new ways to deal with these temporary sinks were discussed.

Research has indicated that there can be many barriers to the implementation of new technologies. These barriers are often non-technical but institutional, economic, and social [11-13]. Construction is often regarded as a mature, slow to change sector [14]. Implementation of new wood technologies in construction is therefore expected to encounter these types of barriers as well. By studying the innovation characteristics of the technical options more insight can be obtained in the barriers that might obstruct successful implementation. In this article we therefore also want to create insight in the innovation characteristics of technologies for increased and efficient wood use and discuss how these characteristics might affect implementation.
For two reasons attention to implementation is important to climate and environmental policy makers. First, it gives the opportunity to rank and select improvement options according to their implementation opportunities and likelyhood of success. Second, the assessment provides the key to answer the question: which economic and social groups need to be addressed to implement the changes?
The article starts with an introduction to various concepts of innovation in order to relate these concepts in later sections to wood technologies. In section 3 we identify options for increased use of wood in the construction sector, determine the CO_2 emission reduction potential associated with these options, and link the options to the innovation concepts. In section 4 we will present measures to improve the efficiency of wood consumption and also link these to the innovation concepts. We end this article with conclusions.

7.2 Concepts of innovation

The socio-economic environment, in which changes need to be made to optimize the use of wood, is of crucial importance for the success of implementation. The implementation environment of the wood applications that we study in this article, is predominantly the building sector. In this sector technical change occurs rather slowly and there appear to be many social and economic factors that influence the implementation of new material technologies [15]. Empirical studies of innovation and diffusion processes have shown that in many sectors innovations take two to three decades to diffuse to a significant extent [16]. In the building sector changes occur even more slowly; the period for changes to diffuse in construction may range from several decades up to a century [17].
The implementation of technical changes depends on both the characteristics of the changes themselves and the characteristics of the socio-economic environment. It is often said that technical changes (or innovations) take place in co-evolution with changes in the implementation environment (also called 'context') [18] [19]. Therefore, to achieve innovation, changes in the context are often necessary [20]. Examples of important context variables that influence innovation in the construction sector are the strength of the knowledge base, the nature of strategic alliances, the attitude towards costs / quality ratios, the role of the government, and the role of the material manufacturers [21]. In this

article, first, the innovation characteristics of the technical changes are determined and second, the context variables of the Dutch construction sector are assessed. The latter is based on [21].
To determine the characteristics of the wood innovations we discern two dimensions: the technological complexity of the innovation and the necessary change in socio-economic networks.
The first dimension is defined as to which extend skills and expertise of organizations need to adjust to apply the new technology. An example of such a change is the switch of a manufacturer of steel parts to producing plastic parts. It either requires hiring new personnel with prior experience or education, or it requires considerable learning of the current workforce.
The second dimension concerns the change in the structure of the socio-economic production network around an innovation. For example, a shift from combustion powered vehicles to electric vehicles requires changes in fuel supply and repair facilities in addition to the new engine components.
To indicate the level of change on these dimensions we use several concepts from the literature on innovation in terms of changes involved: *incremental, radical, modular, architectural, and system innovations* [22,23]. Incremental and radical innovations represent the level of technical complexity of new innovations while modular, architectural and systems innovations represent changes in networks. The two dimensions of change are related; an innovation combines both technical and network dimensions. Table 1 summarizes the classification of innovation characteristics along the technical and network dimension of change.

Table 1: Classification of innovations according to the dimensions of technical complexity and network change.

		Network change	
Technical complexity	Modular	Architectural	System
Incremental	Small technical change No network change	Small technical change Small network change	Small technical change Large network change
Radical	Large technical change No network change	Large technical change Small network change	Large technical change Large network change

Incremental innovations are technical changes that can be regarded as a refinement of previous technology [25]. Continuous improvement of the technology on relevant technical aspects is central. Incremental innovations are based upon experience and knowledge in the existing production and use system. In other words, the technological basis does not change. Typical incremental changes are those where technical improvements lead to greater production capacity. *Radical innovations*, on the contrary, introduce changes that dramatically divert from the existing technical situation [26]. Previous linkages and interactions may become irrelevant. Radical innovations may be recognized by a new set of engineering and scientific principles and may create new businesses and transform existing ones by delivering dramatically better product performance or lower production costs. One well-known historical example is the introduction of the float glass process by Pilkington. The experience and production facilities of the other glass producers became outdated immediately [27].

Modular, architectural and systems innovations differ in terms of change in network. This distinction is an important addition to the existing classification in incremental and radical innovations since it explains why even minor innovations sometimes do have a large effect on the ability of established firms to follow the innovation pattern [22]. A *modular innovation* does not result in change in networks. It only changes the elements that constitute a product, whereas the linkage pattern between actors remain unchanged. Technically, such changes still might be radical. Many phone producers, for example, could not follow the transition from analogue to digital telephones [22].

An *architectural innovation* has a small network effect. It demands change of the set of associated interacting actors; the pattern of linkages between actors is changed without necessarily effectuating change within the modules. Architectural innovations limit the usefulness of knowledge exploited by established firms. A shift in the knowledge structures may result in major difficulties in adopting architectural innovations by established firms.

A *system innovation* implies a large network change. It integrates multiple independent innovations by different actors that must work together to perform new functions or improve the facility performance as a whole; it involves many changes at the same time. The linkages are explicitly among the innovations and entail changes in the links between actors. Many actors are involved in a system innovation. In construction an example can be the way in which modularity in building requires architects, builders and others to work together.

7.3 Increase of wood use in the construction sector

Technical opportunities

Before we can apply the innovation concepts to wood in construction we need to create insights in the opportunities for the use of wood in the construction sector. The Dutch construction sector can be split in construction of residential buildings, renovation practices, construction of non-residential buildings and civil engineering. To indicate the possibilities and potentials of increased wood use in the construction sector, in this article we focus on the construction of new houses since this is the only sector on which reliable data regarding material use are readily available.

Contrary to the situation in some other regions, like Scandinavia and North America, wood is not a major construction material in the Netherlands. Concrete and bricks are used in larger quantities than wood products. Especially the application of wood for structural purposes is low. For example, in 1997 only 5% of the houses built in The Netherlands were timber frame buildings [28,29]. To estimate the technical opportunities for increased use of wood in the Dutch construction sector we use standardized models of Dutch houses. Three standard houses have been defined to investigate energy use, material requirements and building costs of new houses [30-32]; a serial house, a single family house and a multi-family house. In our study we will focus on the serial house as reference building (house type A), since this is the most common type of house in The Netherlands, having a market share of 66% [29].[71] In our calculations we will use figures on material use of this reference building by Vringer and Blok [33]. To calculate the potential for increased use of wood we define three other houses that use increasing volumes of wood. The three newly defined house types are identical to house type A in terms of architecture and volume. The only difference is the choice of material for the various building components. For house types B to D wood is increasingly replacing traditional materials. In Table 2, the material use for different building parts are stated for the four house types. House type B represents the situation where more building parts are made out of wood than usually is done in The Netherlands. House types C and D represent timber frame houses, which differ strongly from the traditional Dutch houses in building practice. Table 3 states the total material use for the four house types. It shows that substitution of the traditional building materials by wood leads to large reductions in the weight of houses; house type D is 62% lighter than house type A. In other words, using wood as a construction material would lead to dematerialization in the Dutch construction sector (expressed as weight of material used). In Table 4 the material related CO_2 emissions are stated for the four house types. To calculate the effect of changing material input in construction on the CO_2 emissions related to material use we used the Gross Energy Requirements (GER) of the building materials as given in Worrell et al. [34], broken down per fuel type. We used IEA CO_2 emission factors to convert the energy input to CO_2 emissions [35]. Table 2 shows that, by changing material use, a reduction in CO_2 emissions is possible of almost 50%. Even though this is a large reduction, it is fairly low compared to the results of Buchanan and Honey (1994) who calculated a possible reduction of 86% [2]. The explanation for this may lie in the fact that Dutch houses are constructed with relatively small amounts of steel.

[71] A more detailed model that also takes multi family houses and single family houses into account is not likely to lead to drastically different results since for multi family houses less wood can be used and for single family houses the opposite holds.

Table 2: Material use per building component for 4 house types

Materials (in kg)	Cement				Sand				Gravel			
House type	A	B	C	D	A	B	C	D	A	B	C	D
Groundwork					4050	4050	4050	4050				
Sewerage												
Terrace	69	69	69	69	147	147	147	147	297	297	297	297
Fences												
Piles[1]	2087	285	285	285	4436	605	605	605	8412	1223	1223	1223
Foundation[2]	1486	1486	1115	1115	3154	3154	2366	2366	6374	6374	4781	4781
Exterior cavity wall[3]	213	142	142		855	570	570					
Walls of shed[4]	126				508							
Insulation												
Inner cavity wall[5]	178	178			716	716						
Non bearing inner walls[6]												
Bearing inner walls[7]												
First floor	1285	1285	1285	1285	2726	2726	2726	2726	5508	5508	5508	5508
Floor of shed	336	336	336	336	713	713	713	713	1440	1440	1440	1440
Second and third floor[8]	4425	4425			8624	8624			18932	18932		
Roof construction shed												
Roof construction house	366	366	366	366	777	777	777	777	1567	1567	1567	1567
Drainpipes												
Gutters												
Front and back doors												
Shed door												
Inner doors												
Window frames												
Stairs												
Plasterwork	73	73	73	73	290	290	290	290				
Tiled wall												
Tiled floor												
Kitchen												
Skirting board												
Windowsill												

Materials (in kg)	Wood based panels				Wood				Iron			
House type	A	B	C	D	A	B	C	D	A	B	C	D
Groundwork												
Sewerage												
Terrace												
Fences					78	78	78	78				
Piles[1]					1049	6922	6922	6922	485	70	70	70
Foundation[2]									339	339	254	254
Exterior cavity wall[3]				676		172	172	423				
Walls of shed[4]		261	261	261		239	239	239				
Insulation												
Inner cavity wall[5]			287	287			150	150				
Non bearing inner walls[6]		745	745	745		197	197	197				
Bearing inner walls[7]			676	676			423	423				
First floor									207	207	207	207
Floor of shed									54	54	54	54
Second and third floor[8]			975	975			683	683	709	709		
Roof construction shed	106	106	106	106	26	26	26	26				
Roof construction house	229	229	229	229	203	203	203	203				
Drainpipes												
Gutters												
Front and back doors					154	154	154	154				
Shed door					39	39	39	39				
Inner doors	38	38	38	38	70	70	70	70	100	100	100	100
Window frames					217	217	217	217				
Stairs					237	237	237	237				
Plasterwork												
Tiled wall												
Tiled floor												
Kitchen	75	75	75	75					34	34	34	34
Skirting board					15	15	15	15				
Windowsill	12	12	12	12								

Materials (in kg)	Brick				Sand lime Stone				Gypsum Bricks/panels				Module quantity
House type	A	B	C	D	A	B	C	D	A	B	C	D	
Groundwork													30 m2
Sewerage													
Terrace													6 m2
Fences													3 m2
Piles[1]													8 piles
Foundation[2]													75 m2
Exterior cavity wall[3]	5112	3408	3408										42 m2
Walls of shed[4]	3038												25 m2
Insulation													26 m2
Inner cavity wall[5]					10582	10582							35 m2
Non bearing inner walls[6]									3839	756	756	756	57 m2
Bearing inner walls[7]					18837	18837					1372	1372	46 m2
First floor													46 m2
Floor of shed													8 m2
Second and third floor[8]											990	990	75 m2
Roof construction shed													8 m2
Roof construction house													65 m2
Drainpipes													73 m2
Gutters													65 m2
Front and back doors													2 doors
Shed door													1 doors
Inner doors													8 doors
Window frames													13 m2
Stairs													1 stairs
Plasterwork													22 m2
Tiled wall	208	208	208	208									21 m2
Tiled floor	100	100	100	100									5 m2
Kitchen													1 kitchen
Skirting board													68 m
Windowsill													13 m2

1In house type A two types of piles are used: 6.75 concrete piles for the serial house and 2 wooden piles for the shed. For house type B, C and D all piles are made from wood. The piles have a length of 20 m and contain 1.5 m3 wood per pile. The top of the wooden piles is made from concrete: length 2 m, diameter 0.31 m. This results in 0.15 m3 per pile. For 1 m3 concrete 280 kg cement, 594 kg sand and 1200 kg gravel is needed [33].
2 Timber frame buildings are lighter than buildings made from concrete and bricks. We therefore lowered the weight of the foundation that is necessary for the construction of timber frame buildings. We assumed that 25% less concrete is necessary in case of timber frame buildings.
3 In house type A the exterior cavity wall built from bricks. House type B is for 33% covered with wood (14 m2). We assumed that joists are used of 6 cm by 2 cm. This leads to 0.0212 m3 joists per m2 wall. Boards are used as covering with a thickness of 2 cm.
4 The total area of the walls of the shed amount to 22.5 m2. Again 0.0212 m3 joists are used per m2 wall area. 2 cm OSB is used for stabilisation covered with boards.
5 The inner cavity walls constitute 22.1 m3. Joists of 0.38 cm by 12.1 cm are used every 0.5 meter. Joists of 10.2 meter in length are used on the top and bottom of the walls. OSB (2 cm thick) is used as wood based panel.
6 The non-bearing inner walls are built for the house types B, C, and D of a wooden frame covered with OSB. Gypsum board is used on both sides as cladding. The total constitutes 57.3 m2. Gypsum board has a thickness of 1.2 cm and weighs 1100 kg/m3. The same joists are used as for the inner cavity walls.
7 The bearing inner walls consist of two individual walls separated by a split. For both walls a wooden frame is used that is covered on both sides with OSB. On the inside of the two walls OSB is used in turns for noise abatement. On the outside of the two walls gypsum board is used.
8 The wooden construction 2nd and 3rd floor is identical. The total area is 75 m2. Every 0.5 meter a wooden beam (23.5 cm by 3.8 cm by 5.1 meter) is used.

Table 3: Total material use for four house types (in tons (1000 kg) per house)

	house A standard	house B ←	house C alternatives	House D →
Cement	10.6	4.2	3.7	3.7
Sand	27.0	13.7	12.2	12.2
Gravel	42.5	16.4	14.8	14.8
wood based panels	0.5	2.4	3.4	3.4
wood	2.1	9.2	9.8	10.2
Iron	1.9	0.8	0.7	0.7
Brick	8.5	3.7	3.7	0.3
Sand lime stone	29.4	29.4	0.0	0.0
Gypsum bricks	3.8	1.7	3.1	3.1
Total	126.4	81.7	51.5	48.4

Table 4: Total material related CO_2 emissions for four house types (in tons CO_2 per house).

	house A standard	house B ←	house C alternatives	house D →
Cement	8.8	3.5	3.0	3.0
Sand	0.2	0.1	0.1	0.1
Gravel	0.3	0.1	0.1	0.1
Wood based panels	0.3	1.5	2.2	2.2
Wood	0.3	1.3	1.3	1.4
Iron	3.5	1.4	1.3	1.3
Brick	1.4	0.6	0.6	0.1
Sand lime stone	1.3	1.3	0.0	0.0
Gypsum bricks	0.2	0.1	0.1	0.1
Total	16.1	9.9	8.7	8.2

In the period 1995 - 1999 approximately 427,000 new houses were built in The Netherlands. When these houses would have been built with a maximum input of wood, 3.4 Mtons less CO_2 would have been emitted for production of building materials; which is on average about 0.68 Mtons per year. This corresponds to 0.4% of the annual Dutch energy related CO_2 emissions in 1995 [36]. This CO_2 emission reduction is only a fraction of the total CO_2 emission reduction that is possible when more wood is used in all construction activities in The Netherlands. Especially material changes in construction of non-residential buildings have a large potential due to the relative short lifetime of these buildings and therefore the large material input for this sector [37]. Also the current trends in The Netherlands towards substituting sand lime stone by concrete leads to an increased CO_2 emission reduction potential when wood is used instead[72].

Innovation characteristics of technical opportunities in house type B

In this section we relate the technical options that constitute the house type B to it's innovation characteristics. The results are summarized in Figure 2 (section 5). We discuss the innovation characteristics of the increase in the use of wood in the residential construction sector by examining four examples: floors, piles, walls and window frames. Although wooden window frames are also included into the reference house, type A, this options is examined as well, since the use of wood for this product in houses is declining [38].

Floors

The wooden floor, which used to be common in Dutch house building at the beginning of last century, has almost completely disappeared in traditional

[72] More CO_2 is emitted during the production of concrete than for the production of sand limestone.

residential building [37]. Instead the market share of prefab concrete floors has become high in the Netherlands (80-85%) [39].
Increasing the use of wooden floors in the traditional segment would imply a reversal of the past trend. This in itself is hard, because of competition from the now well-established supply structure for concrete floors[73]. Trend reversal is also difficult, due to the high additional costs for wooden flooring compared to concrete floors. Due to the optimization of concrete flooring and the decrease in the development and use of wooden flooring, the additional costs of wooden story floors are considerable (+18% compared to current concrete floors) [40]. However, improved wooden floors are expected to benefit from a scale effect once its application increases again. Prefabrication will reduce production costs. Also, an increase in the number of suppliers may result in a price reduction.
The return of the wooden story floor requires change by actors involved in one part of the building concept: the suppliers of wooden floors. This makes wooden floors a modular innovation. To be a competitive alternative for concrete floors, the product needs to be improved technically to fulfil contemporary requirements, such as standards of (acoustic) insulation. Production of such wooden floors currently takes place only at a small scale. Since the product is not supplied prefabricated, wooden flooring is labor-intensive. Moreover, together with the application of wooden floors, the technical knowledge of wood technology for flooring has gradually disappeared. Therefore, substitution of concrete floors by wooden floors has the characteristics of a radical innovation.

Piles

Because large parts of the (western) provinces in The Netherlands consist of soft soils, the use of pilework is necessary to obtain a stable foundation. This has been the situation over centuries and cities like Amsterdam are largely built on wooden piles. However, at present mostly concrete piles are used, although wooden piles still have a constant but small market share [41].
The piles driving takes place before the actual building process starts and the type of piles have no consequences for the rest of the building process. So the substitution or improvement of piles only takes place at the level of one compartment. The innovation needed is therefore considered to be modular. Since the wooden piles industry still exists and does not have to make technical changes in the production process to make the piles competitive with concrete piles, we characterize an increase in the use of wooden piles as an incremental innovation.

[73] There are only a few companies specialized in wooden floors left in the Netherlands. In contrast to the wooden floor industry, the 35 prefab concrete floor suppliers are well organized; almost 90% of the producing companies are member of the industry association for concrete flooring, a daughter of the Dutch precast concrete industry association.

Walls

Wood is a suitable material for interior non-bearing walls. In Dutch buildings an increased use of wood in walls would either imply the substitution of sand lime, clay bricks, concrete, or gypsum.

In The Netherlands, wooden walls are more often used than wooden floors. However, just like wooden floors, product improvement is required, in order to enhance the use of wood in walls. Technical weaknesses such as fire resistance, noise isolation and appearance of the surfaces should be addressed by the industry [39]. Since knowledge about wooden walls is still available in the sector, increasing the technical performance of wooden walls is considered to be an incremental innovation. Unless the decision is made to complete the building in in situ cast concrete[74], the choice of materials does not affect other parts of the building. Therefore, an increase in the use of wooden walls is also considered to be a modular innovation.

Window frames

Window frames are made of wood, metal (aluminum and steel), or plastics. In new residential buildings the wooden window frame is market leader with over 80% market share [38] [42]. At the end of the 1980ies this was the case for all buildings[75] and not just for new residential buildings. In 1995, the market share of wooden window frames for all buildings had dropped to 53% [43]. The reason for the decline was the decline in the imports of tropical sawn wood between 1988 and 1995 in the Netherlands; in 1988 about 90% of the wood used for window frames was tropical hardwood [38] . In renovation, an increasing market in the Netherlands, and in non-residential buildings plastics and aluminum are used predominantly. The suppliers of metal and plastic window frames act in the building process as subcontractors. These industries offer a complete product: the industry not only supplies but also installs the product. Table 5 shows the distribution of the materials over the total window frame market [43].

Table 5: Estimates of the market share of different materials in window frames [43].

Material	Window frames (%)
Topical wood	24
Non-tropical wood	29
PVC	35
Aluminium	11
Other	1

[74] In-situ casting of concrete is a so-called wet building method. The characteristics of wood do not allow for a combination of this wet building method together with a dry wood building method.

[75] Including renovation practices and utility buildings.

In the Netherlands, there are around 300 suppliers of wooden window frames, 150 suppliers of aluminum, and 150 of plastics window frames [39]. One producer of plastic profiles dominates the plastic window frame market, whereas wooden and aluminum frame manufacturers buy their materials from different producers.
The position of wood in the window frame industry is well established. Still, innovations are needed to enhance or secure the position of wooden window frames, which is under pressure especially now the discussion on tropical hard wood is an issue in the Netherlands and competition with other materials increases. A shift towards the use of environmentally friendly wood and service oriented supply and installation systems seems to be necessary.
The choice of window frame materials is made early in the building process. In contrast to other building parts, it is predominantly the client of the house who decides which materials should be used for window frames [44]. Important criteria for the selection are the life cycle costs. This is not surprisingly as outer window frames cause the highest repair costs for a new house [45]. Since the infrastructure of wooden frame window frames is mature and the technical improvements are a refinement of previous technology, innovation of window frames is a typical example of a modular and incremental innovation. It requires only minor technical change, limited to actors associated with this building part.

Innovation characteristics of house type C and D: timber frame building

In this section we determine the innovation characteristics of house types C and D, timber frame buildings. This type of building is a non-traditional building system in the Netherlands; it is currently applied to a limited extend only. A transition towards timber frame building implies great changes in the existing brick-concrete dominated building market. A switch to timber frame building can be considered to be the introduction of a new system of building for the Dutch building sector.
Knowledge of timber frame building is limited to a fairly small group of actors. In contrast to traditional building methods, the building system for timber frames allows for a high degree of prefabrication [46]. Designers and contractors can only switch over to this form of building after being thoroughly informed about timber frame building, because of the total different character of the building process and the specific sensitivities of the method. The sector has no experience with designing timber frame houses, methods of process planning, construction calculations, and the required craftsmanship. These factors make this technology a radical innovation.
The timber frame building technique as applied in the Netherlands at present

comes from Scandinavia and Canada. In the 1980s this technique diffused to the Netherlands [47]. Still, some of the larger timber frame building companies that operate on the Dutch building market are Nordic or Canadian. As a result both the actual and the cultural distance of these companies to the Dutch building partners is large compared to the local supply of concrete or bricks. Next to these cultural differences, a reorientation for existing building companies towards timber frame houses would require considerable investment in new expertise, logistics, skills and partners. It is not just a change in the product concept that affects the actors in the building process, but it is the introduction of an entire new product concept with different materials suppliers, that requires new knowledge and experiences built up in practice and supported by the educational system. In other words, the substitution of the traditional concrete/bricks building by timber frame building is not only a radical innovation but also a system innovation involving many actors and technical changes at the same time.

7.4 Increased wood recycling

Increasing wood recycling offers the possibility to enhance the resource efficiency of wood. These options, however, are generic and cannot easily be linked to one of the house types given before. Both the technical potential and the innovation characteristics for the options to increase wood recycling are discussed in this section. The results are presented in Figure 2.

Technical potential

Before discussing the possibilities for increased wood recycling in The Netherlands we first discuss several definitions regarding material recycling. We may discern three types of recycling: product reuse, material recycling and energy recovery [34]. Product reuse is defined as reusing the product. In case of material recycling, product material is reused as secondary material. In case of energy recovery, the material is incinerated and energy is recovered.
In case of wood, there are many types of material recycling possible, e.g. reusing an old beam for production of floor panels or reusing old window frames for chipboard production. The different ways of material recycling vary strongly in the way the structural capacity of wood is retained for future applications. Therefore, it seems useful to differentiate between high quality material recycling and low quality material recycling. In high quality material recycling the structural capacity of the wood is largely maintained while this is not the case for low quality material recycling.
Fraanje (1998) describes a method to use the full potential of resources in their lifetime. This method is called resource cascading and extends the practical lifetime of resources by using it for as many sequential applications as possible by minimizing the quality loss of the resources in each cycle, see Figure 1[37].

When the current Dutch recycling practices are compared to the resource cascading option, it shows that some steps in the cascade chain exist, e.g., high quality recycling of large beams, recycling wood in chipboard, and energy recycling, but that there is no integrated policy to use the full potential of wood resources [48]. More high and low quality material recycling can take place.
To indicate the potential for increased wood recycling it is possible to use the parameter 'total wood life time' [37]. Current practices in The Netherlands result in an average 'total wood life time' of construction wood of 75 - 150 years[76]. The high end of this range only occurs for a small percentage of total wood use [48]. It is estimated that the total lifetime of wood in the construction sector can be increased to more than 400 years [35].

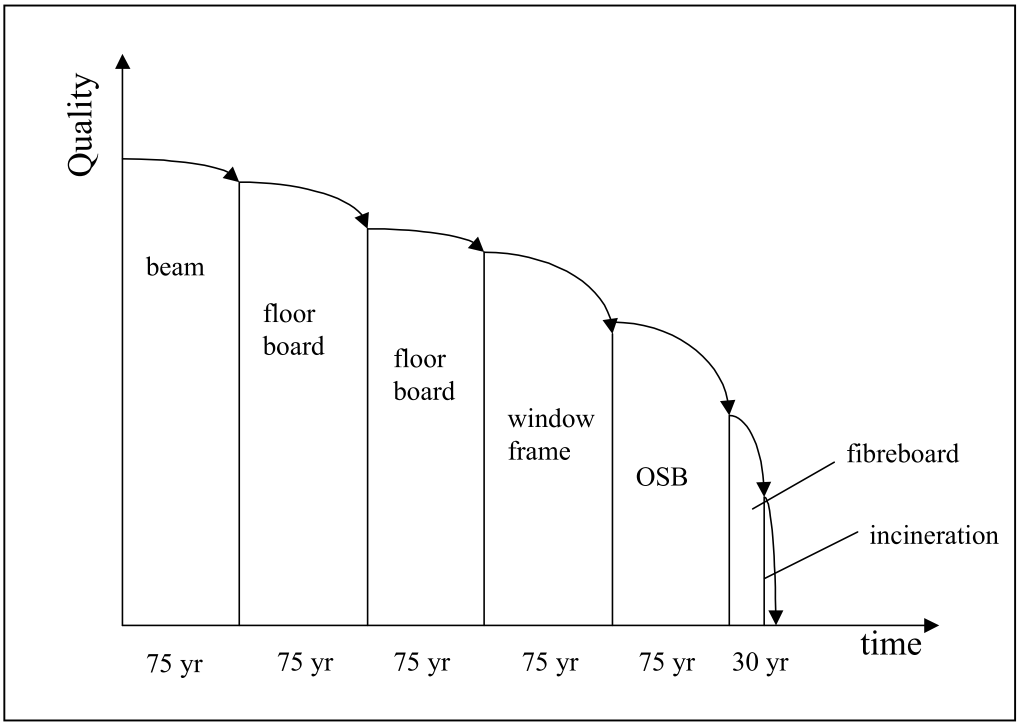

Figure 1: Potential wood product cascade for pinewood (based on [37]).

Innovation characteristics of high quality wood recycling

Wood waste is mainly incinerated or chipped for recycling. The actual reuse of wooden building parts for new buildings occurs sparsely. As far as it does exist, demolition contractors dominate the second-hand timber market. In addition, some small (ideological) wood reuse firms exist in the Netherlands. Reused wood has some beneficial characteristics, especially in construction: the “old look”, which is attractive to some customers, especially in floors, and the lack of creep.

[76] This is based on the assumption that a structural application of wood in the construction sector has an average life time of 75 years [37].

Reuse of wood requires no technical change in the application of wood in the Dutch building practice. However, to increase reuse of high quality wood technical change is needed in other parts of the wood chain; careful and selective demolishing of buildings is needed. To be able to do so, in the design and building phase adjustments are required to make this process easier. Also, the waste separation companies, currently serving the low quality recycling market, need to become involved in the network as suppliers. They need to include an extra step in their waste separation process to select the large, reusable pieces and provide extra storage capacity. Also, the wood needs to be treated before it can be reused (e.g. removal of dirt and nails, and standardization of dimensions).
All actors that need to be involved to implement high quality recycling at a higher rate are already involved in existing building networks. However, to make this option work, new links are needed between the companies involved (waste management industry, demolishers, builders, and architects). Building such a network makes high quality recycling an architectural innovation. Changing technical practices in building, demolishing, and waste management are reasons to categorize this innovation as radical.

Innovation characteristics of low quality wood recycling

Due to increasing disposal costs and a recent ban on landfill for combustible waste, the recycling of wood waste has already been set up in the Netherlands. The main actors in wood recycling are the demolishers, waste separation plants, waste incineration installations (thermal recycling) and the chipboard industry. Even though wood recycling takes place, the full potential of recycling is not yet utilized. For instance, wood waste is now separated in two fractions at the waste separation plant, whereas in some German federal states 4 types of wood products are separated already on the building site.
The infrastructure for low quality wood recycling exists. However, it needs to be optimized in order to enhance the recycling rates. This asks for a joint effort of different actors related to the building industry: the demolishers, the waste separation companies and the chipboard industry. These actors are not directly linked to the product concept of a building but operate in the building system in the broadest sense. As such, the optimization of recycling is a system innovation. Since it needs optimization of existing practices this option is incremental in character.

7.5 The options in relation to the context.

In Figure 2, the technical measures to increase wood in the construction sector are ordered according to their innovation characteristics along two dimensions. First, the technical radicality of a measure and second, the impact of the measure on the existing configuration of actors in the socio-economic context.
Most options for increasing the use of wood are modular, whereas the options to improve the resource efficiency by increased recycling requires small up to

considerable change of relations between actors. Although all measures that are part of house type B are characterized as modular, the technical radicality differs. This shows that modular innovations are not necessarily easy to implement. Although recycling is often used as a single strategy for increasing resource efficiency, Figure 2 summarizes that high and low quality recycling clearly differ in the demand for technical and network change.

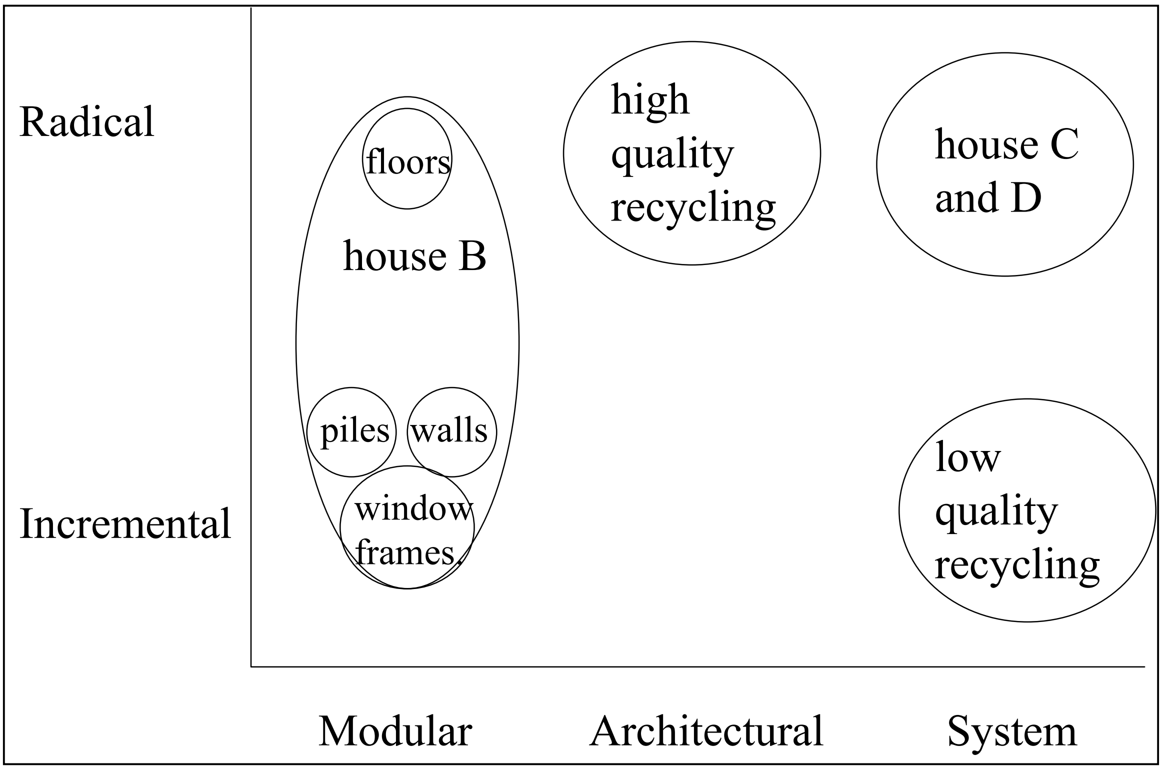

Figure 2: Innovation characterization of wood technologies based on their implications for change from current practices and the changes in existing relational structures.

The innovation typology is the first step to derive the policy measures that could be helpful to stimulate these wood technologies. The second step that needs to be taken is an analysis of the context in which these innovations take place. In Jacobs et al. (1992) a detailed analysis is made for the socio-economic environment (context) in the Dutch construction sector and how this environment influences the implementation of inventions[77] [21]. We have selected 10 context variables that are likely to influence the implementation of material innovations and added one variable based on the descriptions in Section 3.

1. The Dutch building sector can be characterized by a very open market, leading to strong competition. This competition only takes place at the level of costs and hardly at the level of delivering innovative products and better quality.

[77] The analysis by Jacobs (1992) is based on the so-called diamant of Porter as introduced in Porter's The Competitive Advantage of Nations (1990) [49]

2. The building networks are not stable. They vary strongly with every new commission. These unstable networks prevent that learning processes in networks take place, which inhibits innovations taking place.
3. The Dutch building sector is strongly nationally and regionally oriented. This makes it difficult for foreign construction companies to penetrate the Dutch market.
4. Product innovations take place at the level of material producers and hardly in the construction sector itself. The influence of the material producers in the building process is large. They even deliver workmanship to the actual building process. The most important material producers manufacture non-wood materials.
5. Research that takes place in the building sector is strongly focused on improving the efficiency at the building site; this leads to building time reduction. New materials or products should be designed in such a way that the efficiency is no reduced.
6. Research at universities and commercial research organizations is largely focused on existing specialisms.
7. Standardization of building materials and methods is important. This implies that new products should fit within the current building standards.
8. In general the commissions are contracted out based on building costs and not on life cycle costs and other quality parameters. Also commissions are contracted out based on specific requirements regarding building method and materials used.
9. Many sector organizations exist and their coordination is fragmented. This leads to relative small attention for environmental initiatives.
10. There is a poor communication between architect and contracter in the design stage.
11. The public perception regarding building methods is important.

To create insight in the barriers related to the wood technologies and the potential measures to overcome these barriers, it is important to know how the identified wood innovations interact with the context variables. We will describe this in the following.

The characteristics of the modular and incremental innovation in Figure 2 (piles, walls, and window frames) hardly interact with the context variables of the construction sector. Basically, the technologies can be fit into the standard production process without too much trouble. However, the fact that material producers have a large influence on the building process and that they are not focused on the material wood, prevents these technologies from being taken. One might say, that the general culture or attitude of the construction sector towards wood hinders these innovations. For wooden window frames, the importance of efficiency and standardization at the building site may lead to reducing market shares. Product innovation at this point is necessary.

For wooden floors several context variables hinder a successful implementation. The cost-competitiveness of the sector, its striving towards efficiency at the building site and standardization of building materials and methods, and the fact that the knowledge base is strongly focused on traditional materials makes implementation difficult. Also, the unstable building networks prevent knowledge building regarding the use of wooden floors.

Timber frame construction has characteristics that fit well within the context variables: It is a highly standardized building method and it can be prefabricated which makes the activities at the building site very efficient. However, other context variables will hinder successful implementation: the strong national orientation of the sector (much knowledge about this construction method is present at foreign companies), the influence of non-wood material producers, the fact that wood technology is not an important research subject at the universities and commercial research organizations, and the fact that many contracts are commissioned based on specific (non-wood) requirements. Also the public acceptation of houses with wooden outer walls will hinder successful implementation of house type D.

High quality recycling is hindered by a poor interaction between architect and contractor and the fact that life-cycle thinking is not part of the building culture. Also the poor interaction between sector organizations is likely to hinder implementation.

Low quality recycling also suffers from the poor interaction between sector organizations. Quickly changing building networks are likely to hinder successful implementation as well. At the technical level no interference is expected between the innovation characteristics and the context variables.

7.6 Policy implications

In order to stimulate the implementation of wood technologies policy efforts are necessary. Based on the specific characteristics of the Dutch building sector, four focus points can be discerned at which policy can be directed.

The first focus point is the way contracts for the construction of new houses are commissioned by the Dutch government. This is related to context variables 1, 2, and 8. When the government would act like a launching customer, minimum requirements could be set for quality of construction instead of cost-price, the share of (old) wood use, and the characteristics of the building network. Also regulations and subsidies for increased use of wood can be used to stimulate wood use.

The second focus point is the culture of the Dutch building sector and the customers. This is related to context variables 4, 5, 6, and 11). Building with wood is in many cases not part of this culture and neither is a strong focus on wood recycling. A change in this culture can be achieved by increasing information services about wood use in construction, initiate model projects

and action programs, and addressing the subject in the training programs of the craftsmen. Already, a wood stimulating program to increase the share of wood with 20% is set up in The Netherlands. Also, much attention is paid stimulate sustainable building practices, including material use, by means of model projects. These current government actions are a good development in changing the culture.
Attention for research is the third focus point (context variables 4 and 5). By means of research programs with a focus on wood technology, the knowledge base in the building sector can be improved. Research directed at discarding, separation, and use of old wood may lead to improved recycling rates.
The final focus point is the stabilization and upgrading of the construction networks (related to context variables 2, 3, 4, 9, and 10). Unstable networks prevent innovations from taking place since built up of collective knowledge does not take place. Upgrading of networks implies that knowledge intensive actors are part of the network. Cluster policy is a tool to stabilize and upgrade these networks. Cluster policy aims to facilitate the efficient functioning of clusters. These clusters are characterized as networks of production of strongly interdependent firms linked to each other in a value adding production chain. Clusters also encompass strategic alliances with universities, research institutes, knowledge-intensive business services, and bridging institutions. Successful clusters are characterized by being knowledge intensive, being able to deliver more complex products due to scale advantages, and the existence of complementary knowledge [20]. Since companies within the clusters invest in each other's knowledge base to reach joint advantages, the relations between these companies become more stable. In OECD (1999) ways to build a successful cluster policy are described [20].

7.7 Conclusions

In this article we have shown that substitution of wood for other materials in current building practices in The Netherlands can reduce materials related CO_2 emissions significantly. When only some building parts are replaced by wood, technically, a material related CO_2 emission of 38% can be realized per house built. When timber frame houses are considered, a reduction of almost 50% in CO_2 emissions is technically feasible. When the houses that were built in the period 1995 – 1999, would have been built with maximum input of wood, 0.68 Mtons less CO_2 would have been emitted yearly by the production of building materials. This corresponds to 0.4% of the total Dutch energy related CO_2 emissions in 1995. This CO_2 emission reduction will rise to higher percentages when more wood is used in all construction activities in The Netherlands including renovation and construction of non-residential buildings.
We have classified different options to increase wood use. Wooden piles, walls, and window frames can be characterized as incremental and modular innovations. Since implementation of these options is not complicated from a technical and network point of few, implementation should be possible in the

short term. We calculated that implementation of these options may lead to a reduction of material related CO_2 emissions of 12%.
Wooden floors are more complex to implement from a technical point of view and successful implementation of timber frame buildings requires large policy efforts to overcome severe technical and network related barriers. For a successful implementation of these options, policy is needed that addresses the culture in the Dutch construction sector, the way new building projects are commissioned, the research activities in the construction sector, and the stabilization and upgrading of networks.
There exists a large technical potential to increase wood recycling in the Dutch construction sector. The average lifetime of wood as a construction material can be increased from 75 years to 400 years, using a recycling strategy that is build on optimized cascading principles. We discerned both high and low quality wood recycling; the innovation characteristics of these two options clearly differ. Low quality recycling already exists to some extend in the Dutch construction sector while there is little experience in high quality recycling of wood. Both low and high quality recycling can benefit from cluster policies and policies focused on cultural change.

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Chapter 8

Summary and Conclusions

8.1 Introduction

Climate change due to greenhouse gas emissions caused by human actions is probably one of the major global environmental problems that we face today. In order to reduce the risk of climate change and the potential effects thereof, the emission of greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) should be reduced.

Much greenhouse gases are emitted due to the combustion of fossil fuels. At present, these fuels fulfil about 60% of our global energy needs. Therefore, a more efficient use of fossil energy is generally viewed as an important option to reduce the emissions of greenhouse gases.

A large part of global fossil energy use (about 40%) is consumed in the industrial sector to manufacture materials and products. Not surprisingly, several studies show that options that lead to more efficient use of materials often lead to reduced greenhouse gas emissions. Yet, in current greenhouse gas emission reduction policies, not much attention is paid to more efficient material management as an option to reduce greenhouse gas emissions.

In the introductory chapter, several studies are briefly discussed that focus on the material use of economies over time. The general conclusion of these studies is that for materials the consumption per unit GDP has decreased over the last decades, but that the total consumption of these materials is still growing due to economic growth.

In this thesis the focus is on improved material management options that lead to greenhouse gas emission reduction. It aims to contribute to the following question: Which greenhouse gas emission reduction can be achieved potentially, by improved management of materials?

The scope is limited in the number of product groups that are studied, the number of greenhouse gases studied and the geographical area. The question that is addressed in this thesis is therefore:

Which greenhouse gas emission reduction, especially CO_2, can be achieved potentially in Western Europe or The Netherlands, by improved management of materials in the product groups 'packaging', 'residential buildings', and 'publication paper'?

8.2 Summary of individual case studies (Chapters 2 –7)

To answer this question, a technology-oriented approach is used. Technologies and measures are analyzed that are available or are expected to come available in the near future (10-20 years). For each measure that might lead to an improved use of materials, the potential reduction in greenhouse gases is determined. For a significant part of the investigated measures, the costs of the measures are calculated. To assess the technical or techno-economic potential of improved material management, the cumulative effect of the measures is determined and corrected for inter-measure influences. Even though technical and techno-economic potentials provide valuable information, they do not give any information about actual market potential of these measures. The reason for this is that all kind of barriers may prevent measures from being implemented, e.g., knowledge deficits, the need for large organizational efforts or changes, uncertainties about market acceptation of changed products, as well as inexperience with new technologies. In several chapters in this thesis, first steps are taken to incorporate information about expected implementation difficulties in the technical and techno-economic assessments.

In this thesis, it is not possible to assess the potential of efficient material management measures for *all* materials. Therefore, the focus is on three product groups that are important from a material use and greenhouse gas emission point of view: packaging, communication papers, and residential buildings. Packaging is an important product groups since 40% of the municipal solid waste in Western Europe consists of packaging. Furthermore, the production of packaging materials leads to an annual emission of about 105 Mtonne CO_2, or 3% of Western Europe's anthropogenic greenhouse gas emissions. Residential buildings is an important product group since it represents the construction sector. This sector consumes about half of the total amount of materials in Western Europe. The product group publication papers is important since it is the largest consumer of paper and the production of these papers requires about 40 Mtonnes of CO_2.

In all three product-groups, renewable materials like paper and wood play an important role.

- Paper and wood are used in large quantities for packaging purposes. In the Western European packaging flows analyzed in this thesis, 20 Mtonnes paper and wood are used for packaging purposes on a total packaging consumption of about 50 Mtonnes in Western Europe (see Chapters 3, 4 and 5).
- The product group 'communication papers' is an important use category of paper, while large technical challenges may lay ahead in this market segment that may affect paper use (see Chapter 6).
- For the residential building sector, wood is seen as a material with large potentials to reduce energy use and GHG emissions associated with materials manufacturing (see Chapter 7).

The first step in analyzing the potential improved in material management is to create insights in the size of material flows through our economy. For many materials (inter)national statistics are available on production, consumption and foreign trade. These data should be used with care since they present information about the *apparent* consumption of materials. This is the production of materials by a country plus imports minus exports. The imports and exports of goods and services that contain the materials are not incorporated in these statistics. Consequently, the apparent consumption data are not always equal to the 'real' consumption of materials in a country, also called: *final* consumption.

In Chapter 2, a contribution is made to the development of a methodology to create insights in the final consumption of materials, focused on The Netherlands. The method is based on data available from the so-called supply and use tables; these tables are made available by Statistics Netherlands and describe the economy of a country in terms of annual supply and use of goods and services by industries and consumers. The method provides detailed information on flows that are normally not visible in statistics: indirect flows like packaging materials and product parts. These indirect flows are normally not visible since they are part of other products and not discerned in regular statistics.

The original method, developed by Joosten et al. (1999), was tested and improved. The improved method resulted in an improvement of the estimates of physical flow quantities based on monetary data and in an improvement of the indirect flow estimates.

The analysis focused on two material flows, i.e. paper and wood. For the paper flows in the Netherlands, insights in the amount of paper that leaves and enters the Dutch economy in the shape of packaging leads to a correction of the paper recovery data as currently used in international statistics. In Chapter 2, a final consumption of 237 kg paper per capita is calculated for the Netherlands while international statistics present an apparent consumption of 204 kg per capita for the same year (1990). Where international statistics calculate a recovery rate of 51% for the Netherlands (i.e. the amount of waste paper recovered as share of the total paper consumption) based on apparent consumption data, our analysis shows that the recovery rate is more likely to be 45% based on final consumption data. The improved method proves to be very useful in analyzing the final consumption of paper and wood in The Netherlands.

Chapter 3 focuses on the potential reduction in CO_2 emissions and cost-efficiency of material efficiency improvement in the product group 'packaging'. More specifically, Chapter 3 focuses on primary packaging. This is all packaging that is in direct contact with the packed product. Consequently, it excludes transport packaging that is used to protect the products and primary packaging during transport. The CO_2 emissions related to primary packaging account for about 3% of Western Europe's CO_2 emissions. In our analysis measures for improved use of primary packaging material are identified and

evaluated. The potential and cost of each measure is determined. 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% (= 40 Mtonne CO_2) by implementing new packaging technology that is expected to become available between 1995 and 2010. In our analysis, options like 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 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 in Western Europe may be very complex, because of needed changes in the current infrastructural organization.
Chapter 4 focuses on transport packaging in Western Europe. Like in Chapter 3, measures for improved use of packaging material are identified and evaluated. For transport packaging in Western Europe 12 Mtonne corrugated board is used, 5 Mtonne wood and 3.5 Mtonne plastics. The production and consumption of these materials leads to an annual CO_2 emission of 29 Mtonne. A supply curve for CO_2-emission reduction is presented based on data about the use of transport packaging in 1995. We show that technically it seems possible to reduce the CO_2 emissions related to the production and use of transport packaging in 1995 by 40% (= 12 Mtonne) when new packaging technology is implemented that is expected to become available between 1995 and 2010. In this analysis, improvement of energy efficiency in material production processes and changes in packaging demand are not taken into account, as well. Most evaluated measures can be implemented cost-effectively, when taking life-cycle costs into account. This would result in a CO_2 emission reduction of 34% for transportation packaging. Evaluation of the measures shows that 12% reduction can be achieved by using lighter packages. Material substitution can lead to a reduction of 12% as well. The most promising improvements, from a CO_2 emission reduction point of view, are large changes in the packaging system like substitution of single use packaging by re-usable packaging. This may lead to 16% reduction in CO_2 emissions. However, also in this case, large scale introduction of this option may be hindered by the complexity of implementation.
In Chapter 5 the analyses in the previous 2 chapters are expanded in terms of the number of greenhouse gases that are taken into account and the possible changes in non-material efficiency measures that may lead to reduced greenhouse gas emissions, e.g., energy efficiency improvement, renewable

energy, and CO_2 removal from flue gases. For this purpose, the dynamic MATTER MARKAL model is used in which the Western European energy and materials system is modeled. The results show that greenhouse gases related to packaging can technically be reduced by up to 58% in the period 1995-2030. Cost effective efficiency improvement of materials use contributes to a 32% greenhouse gas emission reduction. An additional 13% reduction becomes cost-effective when a greenhouse gas emission penalty of 100 ECU per tonne CO_2 would be introduced. This reduction figure is influenced by assumptions made about future price developments of different technologies. Generally speaking, improved material management dominates the gains that can be achieved without or with low greenhouse gas emission penalties, whereas the reductions of emissions in materials production and waste handling dominate when high greenhouse gas penalties are applied.

The next product group studied in this thesis is 'communication papers'. This product group resembles all paper used for communication purposes like newsprint and printing & writing paper. Paper use for communication (31 Mtonnes) is responsible for greenhouse gas emissions of 121 Mtonne CO_2-eq. in Western Europe (1995), or 4% of the total Western-European anthropogenic CO_2 emissions. In Chapter 6 a baseline scenario is developed for Western Europe that forecasts a rise in communication paper consumption from 31 Mtonnes per year in 1995 to 53 Mtonnes in 2015. Several measures are analyzed to reduce the demand for communication papers, e.g., thinner paper, efficient printing technologies, duplexing, and printing on demand. In Chapter 6 it is estimated that it is technically possible to reduce paper demand in 2015 with 37% compared to the paper demand in 2015 according the baseline scenario. This corresponds to a greenhouse gas emission reduction of 70 Mt CO_2 eq.. The measures with the largest emission reduction potential are lowering the basis weight of paper as well as Printing on Demand (POD), i.e. the printing of smaller editions of documents or publications or "on demand"). Besides improvements in material management, no other improvements in technology are taken into account. Improvements in energy efficiency, for example, would reduce the potential of the improved material management options.

In Chapter 7 the opportunities to increase the use of wood in the Dutch residential construction sector are studied and the effects on material related CO_2 emissions are assessed. Four house types are modeled with increasing quantities of wood used in the construction. The house type with the largest increase in wood use shows that a CO_2 emission reduction of almost 50% in material manufacturing is technically possible compared to current building styles. This equals 0.68 Mtonne CO_2, or 0.4% of the annual Dutch energy related CO_2 emissions. The innovation characteristics of these four house types are assessed to create insights in the complexity of the necessary process of change. Two concepts are used to describe the extent in which the new options differ from the current situation in technical terms: incremental and radical innovations. Three concepts are used to describe the necessary changes in network when these options are implemented: modular, architectural and system innovations. With network we mean the interaction between different actors in the building process. By combining the technical and network characteristics of the increased wood options qualitative insights are created in the degree of difficulty to overcome existing barriers. Some options like wooden window frames and wooden story floors will experience small technical and network changes compared to the current situation while an option like timber frame buildings will need large technical changes and network changes to become successful. It requires radical technical innovations and system innovations. It is expected that the full market potential of this option is more difficult to reach than of the other options. Based on this, we expect that a 12% CO_2 emission reduction can be achieved by increased use of wood in the construction of residential buildings in The Netherlands. We also study the possibilities for increased wood recycling practices. A large technical potential exists. To achieve this potential a significant policy effort is needed since significant changes in both technical and network dimensions are necessary. To stimulate innovation in the use of wood in residential construction, important focus points of policy making should be the culture in the Dutch construction sector, the way new building projects are commissioned by the government, the subjects of research within the building sector, and stabilization of building networks.

8.3 General conclusions

Since not all material flows and greenhouse gases are studied in this thesis, it is not possible to estimate the total greenhouse gas emission reduction by more efficient use of materials.

However, this thesis shows that the CO_2 emissions related to the production and consumption of primary packaging can be reduced by 51% by mare efficient management of materials. For transport packaging a reduction of 40% is calculated. For all packaging materials together, a reduction in greenhouse gas emissions of 58% is calculated by taking all greenhouse gases and changes in the energy system into account. For the product group communication papers a reduction in greenhouse gas emissions of 35% seems possible by changes in the material system when taking both CO_2 and CH_4 into account. Also in the construction sector, significant reductions in material related CO_2 emissions seem possible. A technical reduction in CO_2 emissions related to the production of construction materials of 60% seems technically possible in The Netherlands when more wood is used as building material. Due to implementation difficulties, a potential of 12% seems more realistic on the short term.

Based on these results, no quantified generic conclusions about the greenhouse gas reduction potential of more efficient material management can be made.

However, the results indicate that in all cases studied, material efficiency improvement has large technical potentials to reduce greenhouse gas emissions related to material use, generally 30%–50%. Adding all material related reduction options in this thesis together would lead to a total reduction of 130 Mtonnes CO_2-eq. In Western Europe, equal to 3% of the total anthropogenic Western European greenhouse gas emissions in 1990.
However, it should be kept in mind that different system boundaries are used in the case studies, Western Europe in Chapters 3, 4, 5, and 6 and The Netherlands in Chapter 7. To calculate the reduction potential the absolute reduction figures in Chapter 6 heve been adapted: no paper growth for the period 1995-2015 was taken into account[78]. The total emission reduction would be larger when for all product groups all greenhouse gas emissions would have been taken into account and Western Europe would have been used as geographical region in all chapters.

Furthermore, the results indicate that the costs of these measures are generally low and that a significant potential can even be cost-effective due to savings in material costs. This suggests that more attention should be paid to material efficiency improvement in climate change policy.

8.4 Further Research

To be able to study the role of materials in society, material flow analysis is an important tool. The development of dynamic material flow models that present data on end-use levels could be very useful in this respect. Trends are visible that statistical offices collect less physical data about material flows. This is a negative development since it will strongly limit the insights that can be obtained about the flows of materials through economies. Analyses and evaluations of potentially economically and effective GHG mitigation strategies, as well as for other policy goals, may be severely limited due to the increasing lack of data.
Even though the technical potentials of efficient material management seem large, a significant part of it is difficult to implement. In this thesis, except for increasing wood use in the Dutch construction sector, no detailed analysis has been made to investigate the barriers involved and the (policy-) measures that may be applied to overcome them. However, first analysis indicates that the network character of many improved material management options often increase the difficulty of implementing these options. Consequently, this implementation only occurs when in several parts of the material production and consumption chain measures are taken in an integrated way. This requires the involvement of different actors that are active in different parts of the material chain, which is difficult as these actors often have different interests

[78] In Chapter 6 an absolute reduction for the year 2015 was calculated (70 Mtonne CO_2-eq.). For the calcualtion of the potential of all material related options in this thesis we used the same relative reduction as in Chapter 6 (35%), but the paper demand figures for 1995 .

with regard to the material or product involved. Further research should therefore focus on creating more insight in these specific barriers related to improved management of materials and in the ways to overcome them.
Another theme for further research is the changing role of materials in our society. In this thesis it is often implicitly assumed that the services delivered by materials will not change over time. However, many trends are visible in our society that may influence the future role of materials in our society. Developments in the information and communication technology (ICT) sector, for example, may have large effects on future material use. These developments may lead to a substitution of material intensive services by material extensive services that are supported by ICT. It may also lead to increased consumption of products that are sold via the Internet which, in turn, may result in increased energy demand for transportation. Changing consumption patterns may also have profound effects on material use in society and the types of materials used, as well as the material intensity of society. Also, new technologies like micro-chips incorporated in products, might help to present information about the quality of the materials and products when they enter the waste stage. This innovation may lead to more efficient material and product re-use programs.
The influence of new innovations in the production and use of materials should be assessed to determine the chances and threats of these innovations related to the efficiency of material use and related environmental impacts. In this thesis several of these technological changes are investigated. Further analysis is needed to assess the broader impact of these and other technologies on society, and hence on material use and environmental impact.

Samenvatting en conclusies

Inleiding

Het versterkte broeikaseffect is zeer waarschijnlijk een van de belangrijkste milieuproblemen van dit moment. Een vermindering van de uitstoot van broeikasgassen als koolstofdioxide (CO_2) en methaan (CH_4) is nodig om het risico op klimaatverandering en de potentiële effecten hiervan op mens en milieu te verminderen.

Veel van de broeikasgasemissies worden veroorzaakt door het verbranden van fossiele brandstoffen. Deze brandstoffen vervullen momenteel ongeveer 60% van onze mondiale energiebehoefte. Vermindering van het gebruik van fossiele brandstoffen wordt dan ook vaak gezien als een belangrijke manier om de uitstoot van broeikasgassen te reduceren.

Een aanzienlijk deel (40%) van de fossiele brandstoffen die wij mondiaal gebruiken wordt toegepast in de industriële sector. Hier worden materialen en producten geproduceerd. Het is dan ook niet verwonderlijk dat verschillende studies laten zien dat beter omgaan met deze materialen tot een significante vermindering van broeikasgasemissies kan leiden. Echter, in het huidige beleid, gericht op de vermindering van broeikasgasemissies, spelen materialen en het beter omgaan met materialen nog nauwelijks een rol.

In de inleiding van dit proefschrift worden verschillende studies bediscusieerd die ingaan op het historische materiaalgebruik van economieën. Uit de resulaten van deze studies kan worden geconcludeerd dat de intensiteit waarmee westerse economieën materialen gebruiken is verminderd in de laatste decennia maar dat de totale consumptie van materialen in deze economieën nog steeds toeneemt. In dit verband is de intensiteit van materiaalgebruik gedefinieerd als de hoeveelheid materiaal dat wordt gebruikt in een land om een eenheid bruto nationaal product te produceren. Met andere woorden: we gebruiken materialen steeds efficiënter, maar door de economische groei neemt onze materiaalconsumptie nog steeds toe.

In dit proefschrift wordt ingegaan op verschillende mogelijkheden om beter en efficiënter met materialen om te gaan, zodat dit leidt tot een vermindering van broeikasgasemissies. In dit proefschrift wordt gepoogd een bijdrage te leveren aan het beantwoorden van de volgende vraag:

In welke mate kunnen broeikasgasemissies worden verminderd door beter met materialen om te gaan?

De focus van dit proefschrift is beperkt tot een aantal productgroepen, een gelimiteerd aantal broeikasgassen en bepaalde geografische regio's. De centrale vraagstelling is daarom als volgt:

In welke mate kunnen broeikasgasemissies, en speciaal CO_2, in West Europa of Nederland worden verminderd door beter om te gaan met materialen in de productgroepen verpakkingen, drukwerk en nieuwbouwhuizen?

Samenvatting van de individuele hoofdstukken

Om de vraag zoals gesteld in de inleiding te beantwoorden is een technologie-georiënteerde aanpak gebruikt. Dit houdt in dat mogelijke technologieën zijn geanalyseerd die nu of in de nabije toekomst kunnen worden ingezet om te komen tot een verminderde uitstoot van broeikasgasemissies via verbeterd materiaalgebruik. Voor elke technologische optie of maatregel die kan worden ingezet om beter met materialen om te gaan wordt ingeschat hoeveel broeikasgasemissies hiermee kunnen worden voorkomen. Voor een aanzienlijk deel van deze opties zijn ook de kosten berekend. Om de totale broeikasgasemissie van alle opties samen te bepalen zijn de individuele prestaties van de opties opgeteld en gecorrigeerd voor dubbeltellingen.
Informatie over de technologische opties en een berekening van de kosten die hiermee samenhangen geven inzicht in de zogenaamde technische en technisch-economische potentiëlen van verbeterd omgaan met materialen. Dit zijn de broeikasgasemissiereducties die kunnen worden verwacht indien alle technologische opties, respectievelijk alle economisch aantrekkelijke opties worden uitgevoerd. Dit is op zich waardevolle informatie, maar de potentiëlen zeggen niet veel over de werkelijke broeikasgasemissiereductie die je van deze technologische opties mag verwachten: het zogemaande marktpotentieel. De reden dat het marktpotentieel niet gelijk is aan het technisch economisch potentieel is dat vele barrières de implementatie van technologieën in de weg staan. Hierbij valt te denken aan een gebrek aan kennis over de beschikbaarheid van technologieën, het nodig zijn van grootschalige organisatorische veranderingen, onzekerheden over de marktacceptatie van nieuwe producten en processen en onervarenheid met het gebruik van nieuwe technologieën. In verschillende hoofdstukken van dit proefschrift worden eerste aanzetjes gedaan om informatie over de barrières te integreren in de technisch (economische) potentieelberekeningen.
Het was uiteraard niet mogelijk om in dit proefschrift voor alle materialen die wij in onze economie gebruiken de mogelijke verbeteringen in materiaalgebruik te analyseren. Om deze reden is de focus van dit proefschrift gelimiteerd tot een drietal productgroepen die interessant zijn vanuit het perspectief van materiaalgebruik en gerelateerde broeikasgasemissies. De productgroepen zijn: verpakkingen, drukwerk en huizen. Verpakkingen is een belangrijke productgroep omdat 40% van het afval dat vrijkomt bij huishoudens uit verpakkingsmateriaal bestaat. Verder leidt de productie en het gebruik van verpakkingen tot een jaarlijkse broeikasgasemissie van 105 miljoen ton (Mton) CO_2-equivalenten. Dit laatste komt overeen met 3% van de menselijke broeikasgasemissie in West Europa. De productgroep drukwerk is belangrijk omdat het de grootste gebruiker van papier is en omdat bij de productie van deze hoeveelheid papier 40 Mton aan broeikasgassen vrijkomt. Huizen is ook een belangrijke productgroep aangezien het de totale bouwsector representeert. De bouwsector consumeert ongeveer de helft van de

totale hoeveelheid materialen in West-Europa.
De drie productgroepen hebben met elkaar gemeen dat hernieuwbare materialen zoals hout en papier een belangrijke rol spelen.

- Hout en papier worden in grote hoeveelheden gebruikt voor verpakkingsdoeleinden. In de Europese verpakkingsmarkt, zoals geanalyseerd in dit proefschrift, wordt gebruik gemaakt van 20 Mton hout en papier op een totaal materiaalgebruik van 50 Mton (zie hoofdstukken 3,4 en 5).
- In productgroep drukwerk is papier het meest belangrijke materiaal (zie hoofdstuk 6).
- In verscheidene publicaties over de productgroep huizen wordt hout gezien als een materiaal met grote mogelijkheden om de broeikasgas emissies die samenhangen met de productie van bouwmaterialen te verminderen. Dit komt omdat hout een energie-extensief materiaal is om te produceren en toe te passen (zie hoofdstuk 7).

Om de potentiële reductie in broeikasgasemissies door verbeterd materiaalgebruik te kunnen bepalen, is het nodig om inzicht te hebben in de grootte van de materiaalstromen die onderwerp zijn van onderzoek. Voor veel materialen zijn (inter)nationale statistieken aanwezig met data over productie, consumptie en buitenlandse handel. Deze data dienen met enige voorzichtigheid te worden gebruikt aangezien zij zogenaamde 'apparent consumption' data presenteren. Deze term houdt in dat de consumptie van materialen in een land wordt berekend door de nationale productie en import van deze materialen op te tellen en hier de exportstroom van af te trekken. Voor het bepalen van de import- en exportstroom van de materialen wordt geen rekening gehouden met de import en export van producten die deze materialen bevatten. Ter illustratie: bij het bepalen van de import- en exportstromen van staal wordt geen rekening gehouden met de import en export van staalhoudende producten zoals auto's en wasmachines. Het is dan ook niet verwonderlijk dat de 'apparent consumption' data niet altijd overeenkomen met de werkelijke consumptiedata (finale consumptie).
In hoofdstuk 2 wordt een bijdrage geleverd aan de ontwikkeling van een bestaande methode (STREAMS methode) om beter inzicht te krijgen in de finale consumptie van materialen in de Nederlandse economie. Dit is gedaan door de STREAMS methode te testen en op een aantal punten aan te passen. De methode maakt gebruik van de zogenaamde aanbod- en gebruikstabellen die jaarlijks door het CBS worden gepubliceerd. Deze tabellen geven een overzicht van de economie in termen van het jaarlijkse aanbod en gebruik van producten en diensten door de Nederlandse industrie en consumenten. Het gebruik van de methode leidt tot een gedetailleerd inzicht in materiaalstromen die niet direct zichtbaar zijn in de aanbod- en gebruikstabellen: namelijk de materiaalstromen die onderdeel zijn van de producten die in Nederlands worden geproduceerd, geïmporteerd en geëxporteerd. We noemen deze stromen 'indirecte materiaalstromen'. Naast de materialen die in producten aanwezig zijn, worden ook de materialen die worden gebruikt als

verpakkingsmateriaal zichtbaar door deze methode te gebruiken. Het aanpassen van de bestaande methode heeft geleid tot verbeterde inschattingen van de grootte van fysieke stromen op basis van monetaire data. Ook de inschatting van de indirecte stromen is verbeterd.
De methode is uitgevoerd op twee materialen, namelijk papier en hout. De analyse van de papierstromen die werkelijk in Nederland worden geconsumeerd heeft geleid tot een andere inschatting van de hergebruikdata zoals die nu in de internationale statistieken worden gehanteerd. In hoofdstuk 2 rekenen wij uit dat de finale consumptie van papier in Nederland 237 kg papier per inwoner bedraagt terwijl de internationale statistieken uitgaan van 204 kg per inwoner in hetzelfde jaar (1990). De internationale statistieken berekenen hieruit een 'recovery rate' (dit is de hoeveelheid papier dat wordt gerecycleerd als aandeel van de totale papierconsumptie) van 51%. Onze berekeningen laten zien dat het waarschijnlijker is dat de recovery rate in 1990 ongeveer 45% bedroeg. Het testen van de methode heeft uitgewezen dat zij goed te gebruiken is voor het analyseren van de finale consumptie van de papier- en houtstromen in Nederland.
Hoofdstuk 3 gaat in op de mogelijke (kosteneffectieve) reductie in broeikasgasemissies die is te bereiken door beter gebruik te maken van verpakkingsmateriaal. In dit hoofdstuk is de focus verengd tot primaire verpakkingen. Dit is al het verpakkingsmateriaal dat direct in aanraking komt met de verpakte producten. Het onderscheidt zich van transportverpakkingen die worden gebruikt om het product plus het primaire verpakkingsmateriaal te beschermen gedurende transport. Ongeveer 3% van de west Europese CO_2-emissies wordt veroorzaakt door de productie en het gebruik van primair verpakkingsmateriaal. In onze analyse worden verschillende mogelijkheden voor het beter omgaan met verpakkingsmateriaal geïdentificeerd en geëvalueerd. Dit laatste houdt in dat de kosten en het potentieel van elke optie worden bepaald. Vervolgens is een aanbod curve voor CO_2-emissiereductie door verbeterd materiaalgebruik opgesteld. De aanbodcurve geeft aan hoeveel CO_2 kan worden bespaard bij een bepaald kostenniveau per ton vermeden CO_2 . Wij laten zien dat het technisch mogelijk lijkt om 51% van de aan primair verpakkingsmateriaal gerelateerde CO_2 emissies te reduceren door het implementeren van nieuwe en verbeterde verpakkingstechnologieën, waarvan te verwachten is dat ze tussen nu en 2010 kunnen worden ingezet. Dit komt overeen met een CO_2-emissiereductie van 40 Mton. Het moet worden opgemerkt dat verbeteringen in energie-efficiency en afvalverwerking en mogelijke veranderingen in de verpakkingsvraag niet zijn meegenomen in onze analyse. Uit onze berekeningen blijkt dat alle geïdentificeerde opties kosteneffectief zijn wanneer wordt uitgegaan van levenscycluskosten. De evaluatie van de verbeteropties laat zien dat ongeveer 9% van de CO_2-emissies is te reduceren door gebruik te maken van lichtere verpakkingen. Materiaalsubstitutie kan 10% reduceren. De optie met het grootste CO_2-

emissiereductiepotentieel is het vervangen van eenmalige verpakkingen door meerwegverpakkingen. Dit kan leiden tot een vermindering van 32% in verpakkingsmateriaal gerelateerde CO_2-emissies. Echter, grootschalige introductie van deze optie is waarschijnlijk erg lastig door de grote veranderingen die nodig zijn in de bestaande verpakkingsinfrastructuur.

In hoofdstuk 4 wordt ingegaan op transportverpakkingen. Net zoals in hoofdstuk 3 zijn verbeteropties geïdentificeerd en geëvalueerd. Voor transportverpakkingen wordt in Europa 12 Mton aan karton gebruikt, 5 Mton aan hout en 3.5 Mton aan kunststoffen. De productie en het gebruik van deze materialen leidt tot een CO_2-emissie van 29 Mton. Op basis van het gebruik van transportverpakkingen in 1995 in West Europa is een aanbodcurve opgesteld met betrekking tot CO_2-emissiereductie. We laten zien dat het technisch mogelijk lijkt om de aan transportverpakkingen gerelateerde CO_2 emissies te reduceren met 40% (12Mton) door het implementeren van nieuwe verpakkingstechnologieën die tussen nu en 2010 beschikbaar zijn. Ook in deze analyse zijn verbeteringen in energie-efficiency en verandering van de verpakkingsvraag niet in de berekeningen meegenomen. Het merendeel van de beschikbare opties blijkt kosteneffectief te zijn indien wordt uitgegaan van levenscycluskosten. Het kosteneffectieve CO_2-emissiereductiepotentieel bedraagt 34%. Hiervan blijkt een reductie van 12% mogelijk te zijn door het introduceren van lichtere verpakkingen. Ook materiaalsubstitutie kan leiden tot een reductie van 12%. De meest veelbelovende optie, vanuit CO_2-emissiereductieoptiek, is het implementeren van nieuwe verpakkingssystemen zoals het gebruik van meerweg- in plaats van eenmalige verpakkingen. Deze veranderingen kunnen technisch gezien leiden tot een reductie van 16% van de aan transportverpakkingen gerelateerde CO_2-emissies. Echter, ook in dit geval mag verwacht worden dat grootschalige implementatie van deze opties lastig zal zijn.

In hoofdstuk 5 worden de analyses van de vorige twee hoofdstukken samengevoegd en uitgebreid. Dit laatste met betrekking tot het aantal broeikasgassen dat wordt meegenomen in de berekeningen en het scala aan technologieën die niet ingrijpen in het materiaal gebruik maar wel invloed hebben op broeikasgasemissies. Voorbeelden van dergelijke technologieën zijn energiebesparingtechnologieën, efficiëntere afvalverwerking, duurzame energie en het ontkolen van rookgassen. Om dit te kunnen doen is gebruik gemaakt van het dynamische MATTER-MARKAL model waarin het West Europese energie- en materiaalsysteem is gemodelleerd. De resultaten laten zien dat de broeikasgasemissie gerelateerd aan verpakkingen kan worden gereduceerd met 58% in de periode 1995-2030. Ongeveer 32% van de broeikasgasemissie kan kosteneffectief worden vermeden. Een additionele reductie van 13% wordt kosteneffectief indien een boete van 100 euro per ton CO_2-equivalent wordt gehanteerd. De resultaten van de modelberekeningen worden sterk bepaald door de inschattingen van de prijsontwikkeling van toekomstige technologieën. In generieke zin kan worden gesteld dat verbeterd gebruik van materialen een grote rol speelt indien geen of lage emissieboetes

worden gehanteerd en dat emissiereducties in materiaalproductieprocessen en nieuwe afvalverwerkingsmethoden interessant zijn bij hogere boetes.
De volgende productgroep die is bestudeerd in dit proefschrift is drukwerk. Onder drukwerk vallen de papiercategorieën krantenpapier en overig grafisch papier. De productie van papier voor de fabricage van drukwerk (31 Mton) leidt tot een broeikasgasemissie van 121 Mton CO_2-equivalenten in West Europa. Dit komt overeen met 4% van de West Europese antropogene CO_2-emissies. In hoofdstuk 6 is een autonome ontwikkelingsscenario ontwikkeld dat stelt dat de papiervraag in West Europa toeneemt van 31 Mton per jaar in 1995 tot 53 Mton in 2015. Vervolgens zijn verschillende opties geïnventariseerd en geanalyseerd om de vraag naar drukwerk te verminderen. Voorbeelden van deze opties zijn dunner papier, efficiënte print- en kopieertechnologie en printing on demand. In hoofdstuk 6 wordt ingeschat dat het technische mogelijk moet zijn om de papiervraag in 2015 te verminderen met 37% ten opzichte van het autonome ontwikkelingsniveau in 2015. Dit komt overeen met een reductie van 70 Mton CO_2-equivalenten. De opties met het grootste broeikasgasemissiereductiepotentieel zijn het verminderen van het papiergewicht en printing on demand. Dit laatste staat voor het flexibel en digitaal reproduceren van drukwerk waardoor minder materiaalverliezen optreden dan bij het drukken van te grote oplagen. In deze analyse zijn geen andere opties geanalyseerd dan de verbeteringen in materiaalgebruik. Verbeteringen in energie-efficiency bijvoorbeeld zou het potentieel van materiaalefficiënte technologieën verminderen.
In hoofdstuk 7 is onderzocht welke mogelijkheden er zijn om het gebruik van hout in de Nederlandse huizenmarkt toe te laten nemen en wat de invloed hiervan is op de materiaalgerelateerde CO_2-emissies. Om dit te bepalen zijn vier modelhuizen gedefinieerd waarbij het gebruik van hout per huistype is toegenomen. We hebben berekend dat bij de constructie van het modelhuis met het grootste aandeel hout ongeveer de helft aan materiaalgerelateerde CO_2-emissies vrijkomt ten opzichte van de referentiewoning. Dit komt overeen met 0.68 Mton CO_2, of 0.4% van de jaarlijkse Nederlandse energiegerelateerde CO_2-emissie. Vervolgens zijn de innovatie-karakteristieken van de modelhuizen bepaald om inzicht te krijgen in de complexiteit van de veranderingsprocessen die samenhangen met de introductie van deze huistypen op de Nederlandse markt. We gebruiken twee concepten om de mate van technische verandering aan te geven: incrementele en radicale innovaties. Drie andere concepten worden gebruikt om de veranderingen in netwerk te beschrijven: modulaire, architecturale en systeeminnovaties. Met netwerk bedoelen we de interactie tussen de verschillende actoren die betrokken zijn in het bouwproces. Door de technische- en netwerkkarakteristieken van de 'meer-hout-opties' te combineren wordt een kwalitatief inzicht verkregen in de moeilijkheid om deze technische veranderingen geïmplementeerd te krijgen. Voor sommige opties zoals houten

kozijnen en houten verdiepingsvloeren zijn weinig technische- en netwerkbelemmeringen te verwachten terwijl voor een optie als de houtskeletbouwwoning grote technische- en netwerkveranderingen nodig zijn voor een succesvolle implementatie. Het is dan ook te verwachten dat het volledige technische potentieel van deze optie veel moeilijker is te realiseren dan van de minder ingrijpende opties. Op basis van deze redenering schatten we in dat een CO_2-emissiereductie van 12% kan worden verwacht door meer gebruik te maken van hout als bouwmateriaal. In hoofdstuk 7 zijn ook de mogelijkheden voor verbeterde recyclering van hout bestudeerd. Er lijkt een groot verbeteringspotentieel te zijn. Om dit te bereiken zijn significante veranderingen nodig van zowel technische- als netwerkaard. In hoofdstuk 7 worden verschillende beleidsaanbevelingen worden gedaan om de houtinnovaties in de Nederlandse bouwsector te bevorderen. Het lijkt aanbevelingswaardig om in het beleidproces aandacht te besteden aan de cultuur binnen de Nederlandse bouwnijverheid, de wijze waarop de overheid de bouw van woningen aanbesteed, de onderzoeksgebieden binnen de Nederlandse bouwsector en tenslotte het stabiliseren van netwerken.

Generieke conclusies

Aangezien niet alle materialen en alle broeikasgassen in dit proefschrift zijn bestudeerd, is het niet mogelijk om de totale broeikasgasemissiereductie te bepalen die bereikt kan worden door beter met materialen om te gaan.
Dit proefschrift heeft wel laten zien dat de CO_2 emissies gerelateerd aan de productie en gebruik van primaire verpakkingen verminderd kunnen worden met 51%. Voor transport verpakkingen is een reductie uitgerekend van 40%. Indien voor de gehele verpakkingen sector alle broeikasgassen worden meegenomen en rekening wordt gehouden met mogelijke veranderingen in het energiesysteem lijkt een reductie van 58% mogelijk te zijn. Voor de productgroep drukwerk is een mogelijke broeikasgasemissie reductie uitgerekend van 35% door veranderingen in het materialen systeem. Hierbij zijn alleen de (belangrijkste) broeikasgassen CO_2 en CH_4 in de berekeningen meegenomen. Ook in de bouwsector lijken grote emissie reducties mogelijk te zijn door ander materiaalgebruik. Een technische reductie van 60% van de CO_2 emissies die onstaan bij de productie van bouwmaterialen lijkt mogelijk te zijn in Nederland door meer gebruik te maken van het materiaal hout. Gezien de implementatiebarrieres die met deze maatregel samenhangen lijkt een reductie van 12% op de korte termijn meer op zijn plaats.

Deze resultaten kunnen in de huidige vorm nog niet leiden tot een generieke conclusie omtrend de totale reductie van broeikasgasemissies door verbeterd materiaalgebruik. Wel laten deze resulaten zien dat verbeterd omgaan met materialen in alle bestudeerde gevallen een groot technisch broeikasgas-emissiereductiepotentieel heeft. (ongeveer 30-50% van de bestudeerde broeikasgasemissies). Wanneer alle ''materiaal'' opties die in dit proefschrift zijn geïdentificeerd om beter met materialen om te gaan zouden worden geïmplementeerd dan zou een broeikasgasemissie van ongeveer 130 Mton kunnen worden vermeden, wat overeenkomt met een besparing van 3% van de totale West Europese antropogene broeikasgasemissies in 1990. Hierbij is de absolute broeikasgsemissie zoals berekend in hoofdstuk 6 aangepast zodat de toename in papiergebruik (en dus ook een toename in absoluut reductie potentieel) in de periode 1995-2015 buiten beschouwing blijft. Hierdoor wordt het potentieel in hoofdstuk 6 verminderd van 70 Mton naar 40 Mton CO_2-equivalenten. De totale emissie reductie zou groter zijn indien voor alle productgroepen alle broeikasgassen zouden zijn meegenomen en indien in alle hoofdstukken West-Europa als geografische regio zou zijn gehanteerd.

De resultaten laten verder zien dat de kosten voor dergelijke opties in het algemeen laag zijn en dat een aanzienlijk deel van de opties zelfs kosteneffectief is. Op basis hiervan kan worden gesteld dat beleid gericht op broeikasgasemissiereductie meer aandacht zou moeten besteden aan verbeterd omgaan met materialen.

Vervolgonderzoek

Materiaalstroomanalyse is een belangrijk instrument om de rol van materialen op de milieudruk die wordt veroorzaakt door economische activiteiten te kunnen bepalen. De ontwikkeling van dynamische materiaalstroommodellen met data op eindgebruiksniveau zouden op dit vlak zeer nuttig kunnen zijn. Er zijn duidelijke ontwikkelingen waarneembaar dat statistische organisaties zoals het Nederlandse Centraal Bureau voor de Statistiek (CBS) steeds minder fysieke data verzamelen over materiaalstromen. Dit is een kwalijke teneur omdat het zeer waarschijnlijk de mogelijke inzichten over de rol van materialen in onze economie sterk negatief zal beïnvloeden. Analyses en evaluaties van de rol van materialen op broeikasgasemissiereductie en andere milieueffecten zullen sterk worden belemmerd door een toenemend gebrek aan betrouwbare data.

Dit proefschrift laat zien dat er waarschijnlijk een groot potentieel is voor broeikasgasemissiereductie door een verbeterd gebruik van materialen. Echter, in dit proefschrift (exclusief hoofdstuk 7 over het gebruik van hout in de bouw) is niet gedetailleerd ingegaan op de mogelijke barrières die zijn te verwachten indien materiaalefficiënte technologieën geïmplementeerd zouden worden en hoe deze barrières te voorkomen of te slechten zouden zijn. Preliminaire analyses in dit proefschrift laten wel zien dat vooral de netwerkaspecten van het beter omgaan met materialen een belangrijke rol spelen in de moeilijkheid om dergelijke opties te implementeren. Een logisch gevolg is dan ook dat succesvolle implementatie alleen mogelijk is indien op verschillende plaatsen in de materiaalproductie- en -consumptieketen treffende en coherente maatregelen worden genomen. Hiervoor is de medewerking van verschillende actoren in verschillende delen van de materiaalketen nodig. Dit is vaak lastig

omdat deze actoren verschillende interesses en ideeën hebben met betrekking tot de materialen en gerelateerde producten. Nuttig vervolgonderzoek betreft dan ook het creëren van inzicht in de specifieke barrières gerelateerd aan verbeterd omgaan met materialen en hoe hier in beleidsvorming rekening mee gehouden kan worden.
Een ander thema voor vervolgonderzoek betreft de veranderende rol van materialen in onze samenleving. In dit proefschrift wordt er vaak stilzwijgend van uitgegaan dat de diensten die door materialen worden geleverd ongeveer gelijk blijven. Er zijn echter verschillende trends waar te nemen die een grote invloed kunnen hebben op de toekomstige rol van materialen. Ontwikkelingen in de informatie- en communicatietechnologie (ICT) bijvoorbeeld kunnen grote effecten hebben op toekomstig materiaalgebruik. Enerzijds is misschien een substitutie mogelijk van bestaande materiaalintensieve producten naar materiaalextensieve diensten die ICT-ondersteund zijn. Aan de andere kant kan een voortschrijdende globalisering door ICT-ontwikkelingen leiden tot drastische toenamen in transportactiviteit. Veranderende consumptiepatronen kunnen gemakkelijk leiden tot veranderingen in de typen materialen die wij in onze samenleving gebruiken maar ook in de intensiteit waarmee de materialen worden gebruikt. Tot slot: nieuwe technologieën, zoals microchips in producten, kunnen ook helpen om informatie over de kwaliteit van het product en de hiervoor gebruikte materialen te presenteren op het moment dat ze het afvalverwerkingstadium bereiken. Dit type innovaties zou kunnen leiden tot effectievere materiaal- en productrecyclingsprogramma's.
De invloed van innovaties in de productie en het gebruik van materialen zou verder onderzocht moeten worden om de kansen en bedreigingen van deze innovaties op de efficiëntie van materiaalgebruik en op de mogelijke gevolgen voor het milieu te kunnen beoordelen. In dit proefschrift is een aantal van deze innovaties onderzocht. Verdere analyse is echter nodig om de bredere impact hiervan te analyseren op onze samenleving, zowel qua milieu als materiaalgebruik.

Curriculum vitae

Marko Hekkert werd geboren in Vianen (ZH) op 4 juli 1971. In de periode 1983-1989 behaalde hij het diploma VWO aan het Oosterlicht College te Nieuwegein. Na een jaar gestudeerd te hebben aan het Mesa State College te Grand Junction, Colorado, USA, studeerde hij scheikunde aan de Universiteit Utrecht in de periode 1990 - 1995. Hij studeerde af bij de vakgroep Natuurwetenschap en Samenleving op een studie naar energetisch efficiëntere vormen van afvalverwerking in Nederland.
Na zijn afstuderen werd hij aangesteld als onderzoeker-in-opleiding bij dezelfde vakgroep. Hij werkte gedurende zijn aanstelling op een door het Nationale Onderzoeksprogramma Mondiale Luchtverontreiniging en Klimaatverandering gefinancierd project, het zogenaamde MATTER project; dat door een samenwerkingsverband van ECN, RUG, UU, VU en bureau B&G werd uitgevoerd. Het doel van dit project was het bepalen van de impact van veranderingen in het materialen systeem op de uitstoot van broeikasgasemissies in West Europa.
Sinds september 1999 is hij werkzaam bij de disciplinegroep Innovatiewetenschap (Universiteit Utrecht) als docent-onderzoeker. Naast onderzoek naar verschillende aspecten van energie en materiaalinnovaties verzorgt hij onderwijs voor de studie Natuurwetenschap en Innovatiemanagement. Tevens coördineert hij een afstudeertraject van deze studie op het vlak van energie en materialen.

Als resultaat van zijn onderzoek werden de volgende publicaties geschreven:

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