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BUILDING MATERIALS AND CO_2

Western European emission reduction strategies

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Abstract

This report discusses the materials consumption in the Western European building and construction sector. The production, use, and the waste handling of building materials is analysed from a CO_2 emission point of view. Apart from the analysis of the current situation, technological improvement options are analysed and characterised by techno-economic parameters. The report serves as background document for the Western European MARKAL model that is developed in the framework of the MATTER project, ECN project number 7.7018.

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SUMMARY

The construction sector is an important sector from a materials consumption point of view. Significant CO_2 emissions can be contributed to the production of these materials. The estimates range for Western Europe range from 275 to 410 Mt CO_2 per year, representing 8-12% of the total CO_2 emissions in this region. The construction sector represents approximately one tenth of the Western European Gross Domestic Product.

The energy consumption for heating and cooling of buildings causes currently approximately one third of the total CO_2 emissions in Western Europe. This value can indicates the relative importance of the direct CO_2 emissions (heating and cooling) compared to the indirect CO_2 emissions (due to building materials production). The ratio of direct and indirect CO_2 emissions is approximately 3:1.

Within the construction sector, the ratio of indirect and direct CO_2 emissions does significantly differ for different products. A significant fraction of the building materials is used in applications where the direct CO_2 emissions are negligible, like in civil engineering and for storage facilities. For heated buildings, the ratio of direct and indirect CO_2 emissions is in the range of 5:1 - 10:1. This ratio will change in the next decades as the heating energy demand is gradually reduced due to improved insulation. As a consequence, the relative importance of building materials for the CO_2 emissions this sector will further increase.

The indirect CO_2 emissions encompass the emissions related to the fossil energy for production of building materials, the inorganic CO_2 emissions from cement clinker production and the CO_2 released during non-renewable wood production. The most important materials from a CO_2 point of view are cement, wood products, steel, bricks, sand-limestone, aluminium, plastics, and asphalt.

The number of buildings that are constructed is at this moment still four times as high as the number of buildings that are demolished. This ratio will change in the next decades, as the construction activity declines and the demolition activity increases. The renovation activity will also significantly increase. As a consequence of these developments, the demand for bulk materials is expected to decline.

A number of improvement options for the construction sector have been identified as important reduction options for the next 10-25 years:
- improved cement production: increased use of clinker substitutes, increased use of high strength cement, increased prefab production;
- use of higher strength steel qualities and improved control of steel quality;
- use of alternative reinforcement materials, which results in a decreasing steel reinforcement demand and decreasing cement requirements for concrete production;
- increased use of (engineered) wood products;
- substitution of non-renewable wood;

- substitution of structural cement and bricks in floors, walls and foundations by wood and steel;
- energy recovery from wood waste.

On the long term (>25 years), improvement options like redesign of buildings, more efficient utilisation of building space, and re-use of product parts may pose significant improvement potentials. However, these options may affect the product service. It remains to see whether the consumer will accept such changes in product performance.

A number of secondary effects complicate the analysis of improvement options:
- the weight of buildings influences the thermal mass, which influences the energy requirement for heating and cooling. As the insulation of buildings increases and the efficiency of cooling systems increases over a period of decades, the importance of this interaction decreases.
- the different climatological regimes in different parts of Western Europe influence the heating and cooling energy demand. Because of the interaction between direct CO_2 emissions and the thermal mass, this will influence the choice of the 'best' materials strategy.
- the energy source for heating influences direct CO_2 emissions. Because of the interaction between direct and indirect energy consumption, this will also influence the selection of a 'best' materials strategy.
- the foundation requirements depend on the building weight for soils with low carrying capacity. This interaction can in certain cases be substantial from a CO_2 point of view.

Because of the interactions between improvement options and the secondary effects, the 'best' solution from a CO_2 point of view is beforehand unclear. Preliminary calculations suggest that the 'light weight' strategy may be attractive. However, the improvement potential for cement is also substantial. The MARKAL analysis will provide more insight regarding the optimal strategy.

The price increase for building parts due to significant CO_2 taxes is for all structural elements below 10%. Such a limited cost impact poses probably insufficient incentive to switch from the current building practice to a completely different building practice. As a consequence, other policy instruments like legislation or covenants seem more attractive than the tax instrument.

1. INTRODUCTION

This report contains the results of a screening study for options to reduce CO_2 emissions that are related to building material production. This study is part of the MATTER project (MATerials Technologies for CO_2 Emission Reduction), a joint project of 5 Dutch institutes [1]. The project focuses on CO_2 emission reduction options that are related to the Western European materials system (which encompasses the use of materials, materials intensive products and waste materials). Three product groups are studied in detail: transportation equipment, packaging, and buildings and constructions. This report focuses on the current materials use for buildings and constructions, the analysis of autonomous developments in the period 2000-2040, and the analysis of technological improvement options in the construction chain. The report can be used separately, but its primary purpose is to serve as background document for the integrated MARKAL energy and materials model [2]. The actual model input will be discussed in a separate appendix.

MARKAL (an acronym for MARKet ALlocation) is a dynamic techno-economic cost minimisation model for the integrated energy and materials system. The cost-effectiveness of improvement options will in a later phase be studied with this model.

The construction sector shows all key features that makes it worthwhile to perform a dynamic MARKAL analysis:

- the materials consumption in this sector is relevant from a European CO_2 emission point of view,
- the products are relevant both because of their energy consumption during use and because of their materials intensity,
- the sector manufactures products with a very long life span,
- a significant potential exists for emission reduction.

These features will be elaborated in the following chapters. ‘Buildings and constructions’ encompass all man-made structures with a roof (buildings) and infrastructure like roads, harbours, air strips, sewer systems, pipelines, etc. (constructions).

While CO_2 is a relatively new topic in relation to buildings and constructions, energy use of buildings has been considered an important issue for a long time. Fortunately, both issues are closely related, and energy consumption data can be converted into CO_2 emission data. Energy data will in this report regularly be used as an indicator for CO_2 emissions.

The relevance of building materials in the total building life cycle

The construction sector encompasses a number of products. A division can be made into heated buildings like dwellings and offices, with significant energy consumption in the product use phase, and constructions like roads and waterworks without direct energy use. Certain building types like warehouses have also little or no heating energy demand.

Buildings account for a significant part of the total Western European CO_2 emissions. The major part of these emissions is related to energy use for heating (direct energy consumption). Many publications dismiss the indirect energy use, because they focus on heated buildings. The energy use for production of building materials (indirect energy consumption) is of lesser importance. The energy demand for heating of buildings in OECD-Europe (excluding industry) was in 1992 12.0 EJ, i.e. 20% of the total primary energy demand [3]. The total final energy demand for materials production was in the same year 13.0 EJ [4]. Approximately one quarter of these materials was consumed by the construction sector (see Chapter 3). As a consequence, the average ratio of indirect energy use (for materials production) and direct energy use (for heating) was 1:4 for the economy as a whole.

This crude estimate is based on a regional analysis. Data for individual buildings can indicate the validity of these figures and show the variation of this ratio for specific buildings.

Calculations for Swiss buildings in the 80's show indirect energy requirements of 3.2 - 6.0 GJ/m^2 useable floor area [5]. The direct energy requirements are in the order of 13.5-67.5 GJ/m^2 (for heated buildings), assuming a building life of 75 years. No clear relation was found between the direct and the indirect energy use. This results in a ratio of indirect and direct energy use for the whole building life cycle between 1:20 and 1:2.

Data for Swedish single family wood frame residences for the 90's indicate an indirect energy consumption of 2.6-3.2 GJ/m^2 useable floor area (excluding the heating value of timber). The ratio of indirect and direct energy consumption is 1:9, in line with the results for Switzerland [6].

These figures suggest that the indirect energy consumption is of secondary importance. The average Western European ratio is however lower. The average direct energy requirements are lower than in the Swiss and the Swedish case due to large regions with a milder climate. As a consequence, the ratio of indirect energy use and direct energy use will increase.

The direct energy requirements are lower in regions with milder climates, but the milder climate may also impact the indirect energy use. Studies in the 70's for the UK show for example indirect energy requirements of 1.25-3 GJ/m^2 [7]. This is significantly lower than the indirect energy use in Switzerland, and this difference is probably related to other building materials and other building designs.

The ratio of indirect and direct energy use will increase for new buildings, because the average direct energy use decreases due to improved building insulation and improved heating systems. Reduction of indirect energy use will be limited because industrial materials production is already relatively energy efficient. A reduction of the direct energy consumption through improved insulation and increased thermal mass can even result in increased materials requirements. This will result in a drop of the average ratio of indirect and direct energy use for new buildings, may be even to 1:2 or 1:3 in the next decades. Data for Danish buildings that illustrate this trend are shown in Table 1.1: the indirect energy use is significantly higher for the recent low energy residences. For very low energy residences, the indirect energy consumption becomes even more important than the direct energy consumption. For this reason, materials are relevant from a CO_2 policy point of view, not only with regard to constructions without direct energy consumption but also with regard to heated buildings.

Table 1.1 *Direct and indirect energy consumption for single family residences (building life 80 years) [8]*

	Indirect I [GJ/m^2]	Direct[1] D [GJ/m^2]	Ratio I/D [-]
Single family residence, built in 1974	3.2	23.7	0.14
Single family residence, built in 1977	2.8	22.0	0.13
Low energy residence, built in 1982	4.0	5.4	0.74
Very low energy residence, 1993	5.4	3.9	1.38

1 Assuming 100% heating efficiency

Apart from heated buildings, a large number of buildings and constructions are scarcely heated. Bridges, storage facilities, roads are examples of constructions with only indirect energy requirements. They raise the average ratio of indirect and direct energy requirements.

This study focuses on CO_2 emissions. Although energy use and CO_2 emissions are related, energy consumption is not proportional to CO_2 emissions. The inorganic CO_2 emissions for cement production add to the indirect CO_2 emissions (see Chapter 3). These emissions are not related to the energy consumption. Moreover, the indirect energy use shows on average a higher specific CO_2 emission than the direct energy use for heating. The materials production is to a large extent based on cheap energy from coal (with high CO_2 emissions), while residences are generally heated with the more convenient but more expensive energy carriers like oil and natural gas (with low CO_2 emissions). As a consequence, the ratio of indirect and direct CO_2 emissions is higher than the ratio for indirect and direct energy use.

The CO_2 emissions during different phases in the building life cycle are analysed in Table 1.2. The emissions due to heating have not been included in this analysis. The data refer to single family dwellings of a ‘wood type’ and a ‘brick type’. The CO_2 emissions for maintenance and in the demolition phase are small compared to the CO_2 emissions in the materials production phase and the building assembly phase. The emissions in the assembly phase encompass predominantly emissions due to materials transportation to the building site.

Construction activities account for a major part of the total Western European materials consumption. Materials like wood, cement, steel are in large amounts used for construction purposes. The production of these materials results in considerable CO_2 emissions. As a consequence, influencing material flows into and out of the building and construction industry poses an important strategy for reduction of CO_2 emissions. These options are discussed in this volume.

Table 1.2 *CO_2 emissions during the life cycle of Austrian single family dwellings (excluding heating, building size 137 m^2) [9]*

	Wood frame [t/bldg.]	Solid wood [t/bldg.]	Brick [t/bldg.]
Materials production	18.0	23.0	27.0
Assembly[1]	7.9	7.9	9.5
Maintenance	0.8	1.6	0.8
Demolition[1]	1.2	1.2	1.8
Waste separation	0.2	0.2	0.3
Total	28.1	33.9	39.4

[1] Including transportation

Structure of the report

This report contains the following chapters:

1. Introduction to construction and CO_2
2. Production
3. Material flow analysis
4. Demand scenarios
5. Improvement options
6. The construction and demolition process
7. Secondary effects of materials substitution
8. Costs
9. Life cycle analysis
10. Conclusions

The goal of the analysis in Chapter 2 and 3 is to combine data for construction and data for materials production and materials use to yield a coherent picture of the current material flows in the building and construction sector. Demand scenarios for the period 2000-2050 are generated in Chapter 4.

The key data for MARKAL modelling are improvement options that are discussed in Chapters 5 and 6. The production and demolition processes are discussed in Chapter 7. Chapter 8 discusses the impact of materials substitution on the foundation requirements and the impact of materials substitution on the direct energy use. Chapter 9 focuses on costs. This is followed by a static life cycle analysis in Chapter 10. The goal of this analysis is to identify key variables whore sensitivity will be analysed in more detail in MARKAL. In a later stage of the MATTER project, the results from Chapter 10 and the MARKAL results will be compared in order to show the impact of system dynamics on the life cycle analysis.

2. PRODUCTION

The construction sector accounts for a major part of the industrial activity from an economic point of view. The 600 billion ECU (European Currency Unit) construction market represents approximately 11% of the total GDP (Gross Domestic Product) in the region.

Table 2.1 *1994 construction activity in Western Europe [10]*

Sector	[10^9 ECU_{1993}/year]	[%]
New residential	156.7	26
Private non-residential	89.0	15
Public non-residential	33.7	6
Civil engineering	127.0	21
Renovation	196.3	32
Total	602.8	100

Table 2.1 shows that the renovation market is largest construction market in Europe, followed by new residential buildings. This is an analysis in financial units that cannot straightforward be related to material flows. The relevance of sectors will substantially differ if it is expressed in mass units. Unfortunately such data are not available. Based on common sense, the materials intensity [tonnes of energy intensive materials/ECU] is higher for the first four sectors in Table 1.1 than for renovation.

With regard to the national building markets, Germany deserves special attention, as this single country represents almost one third of the total construction volume.

Because of the wide range of product types, data concerning product use are scarce and scattered. The analysis is significantly complicated by differing definitions in many countries. The following analysis should be seen in the light of these shortcomings. The data on the materials side in Chapter 3 have higher reliability than the product data in this chapter because of relatively straightforward aggregation (in tonnes). Combination of both data sets results in a data set that is sufficiently accurate to serve as MARKAL input. Because the MARKAL analysis focuses on long term improvement options, the accurate analysis of the current material flows is not of primary importance. Use of these data for other purposes should however be considered from the viewpoint of these uncertainties.

The sections in this Chapter discuss sections of the construction market:

2.1 Residential buildings
2.2 Non-residential buildings
2.3 Civil engineering
2.4 Renovation and Do It Yourself (DIY)

A complete data set for a material flow analysis consists of data for new constructions, the existing stock of constructions and the demolition of constructions. This complete data set is not available for most construction types. In cases where these data for Western Europe are lacking, data for the European Union or for a number of important countries are extrapolated to the whole of Western Europe.

2.1 Residential buildings

New residential buildings and the existing building stock

Some key figures of the European residential building market are shown in Table 2.2. Not all data are available on an aggregated level for all EFTA countries, so the EU (European Union) data must serve as substitute. This substitution is valid because the EU-12 covers 90% of the total population of Western Europe, and probably a similar fraction of the building and production market.

Note that the residential building stock is larger than the number of households. This difference can be explained by vacant dwellings and by households that own more than one dwelling. The dwellings completed in 1990 make up 1.12% of the existing dwelling stock. The completed multi-dwellings (flats) make up 44.9% of the total number of completed dwellings in 1990.

Table 2.2 *Key figures for EU-12 residential buildings [11]*

Households (1990) [-]	126,731,000
Dwelling stock (1990) [-]	145,617,000
Dwellings completed (1990) [-]	1,638,000
Multi-dwellings completed (1990) [-]	735,600
Average size new dwellings (1992) [m^2]	86

Data concerning the new and existing Western European dwelling stock are shown in Table 2.3 and 2.4. The total number of newly completed dwellings is 1.55 million. The average size is 125 m^2 with a range from 75 to 200 m^2 in different countries. This difference is related to different national income levels, the age structure of the populations, lifestyle differences etc..

Table 2.3 *Dwellings newly completed, 1992 [12]*

	No. of dwelling [1000]	Useful floor space [m^2/dwelling]
Austria	41.4	99.4
Belgium	49.7	203.4
Denmark	16.0	75.0 (e)
Finland	37.0	110.0 (e)
France	299.0	na
Germany	374.6[1]	90.8
Greece	pm	pm
Ireland	22.4	87.1
Italy	211.5	158.2
Luxembourg	3.0	114.0
Netherlands	90.5	na
Norway	17.8	130.6
Portugal	pm	pm
Spain	206.2	93.4
Sweden	57.0	85.0
Switzerland	40.0	na
UK	179.0	na
Western Europe (est.)	*1550*	*125*

[1] Excluding former GDR

Table 2.4 shows the dwelling stock per 1000 inhabitants. The figure ranges from 300 to 469. The countries with higher per capita income seem to have higher per capita dwelling stocks. The variation in dwelling stock is relatively small, compared to other variations in this sector (e.g. construction costs, discussed in Chapter 9).

Table 2.4 *Dwelling stock per 1000 inhabitants, 1990/1992 [11,12]*

	Dwelling stock [Dwellings/1000 inhabitants]
Austria	382
Belgium	389
Denmark	462
Finland	400
France	463
Germany	428
Greece	350
Ireland	300
Italy	400
Luxembourg	pm
Netherlands	390
Norway	419
Portugal	423
Spain	413
Sweden	464
Switzerland	469
United Kingdom	408
Western Europe	*420*

Demolition and changes in use of residential buildings

Table 2.5 shows the decrease in dwelling stock due to demolition and changes in use for the EU-12 countries (e.g. because of the conversion into offices). The figures in Table 2.3 show that new dwellings make up 1.12% of the existing dwelling stock. Approximately 0.20% of the dwelling stock is demolished per year, so the number of dwellings has increased by 0.92% in 1990. The number of dwellings in the EU-12 was 132.8 million in 1980 and 145.6 million in 1990. The increase in this 10-year period was thus 9.6%, the average annual increase was 0.9%. Both figures agree well. It shows that the building stock has been growing steadily over decades. This is important from a materials point of view, because it indicates still increasing materials storage in buildings: 0.9/1.12 = three quarters of all materials that are used for dwellings are stored. The storage figure for other building types and constructions is probably of the same order of magnitude.

Table 2.5 *Decreases in dwelling stock (demolition + changes in use), 1990 [11]*

	Number of dwellings	% of dwelling stock
Belgium	5.8	0.15
Denmark	2.5	0.11
France	73.0	0.29
Germany	69.0	0.20
Greece	pm	pm
Ireland	10.0	1.00
Italy	48.0	0.20
Luxembourg	pm	pm
Netherlands	11.5	0.20
Portugal	pm	pm
Spain	123.0	0.72
UK	16.6	0.07

2.2 Non-residential buildings

New non-residential buildings

Table 2.6 lists the production of non-residential buildings in 1992. Data are not complete for all countries. A total estimate is made, where population numbers are used to extrapolate the available data to the whole EU+EFTA region.

Table 2.6 *Non-residential buildings completed in 1992 [1000 m^2] [12]*

	Total	Industrial	Commerc.	Educ.	Health	Other
Austria	pm	pm	pm	pm	pm	pm
Belgium	8304.3	1976.6	3339.1	219.2	107.2	2662.2
Denmark	4359.0	2486.0	898.0	112.0	71.0	792.0
Finland	4364.0	924.8	1403.8	219.0	236.5	1579.9
France	42648.3	12031.8	12014.0	3003.6	2579.6	13019.3
Germany[1]	38025	6431	9512	473	671	20398
Greece[2]	3434.6	759.9	968.4	17.6	2.7	1685.9
Ireland	pm	pm	pm	pm	pm	pm
Italy	17000.0	9542	2500	-	-	5300
Luxembourg	282.3	89.2	141.5	-	-	51.7
Netherlands	14055.0	2203.0	4770.0	504.0	393.0	6186.0
Norway	2518.5	356.6	776.7	140.9	113.9	1130.4
Portugal	2662.5	716.8	674.4	169.2	13.4	1088.8
Spain	pm	pm	pm	pm	pm	pm
Sweden	pm	pm	pm	pm	pm	pm
Switzerland	pm	pm	pm	pm	pm	pm
UK	pm	pm	pm	pm	pm	pm
Total	137654.5	37518.7	36997.9	4858.5	4188.3	53894.2
W. Europe	217500	59000	60000	7500	6500	84500
Fraction [%]	100	27	28	3	3	39

[1] 1993 figure
[2] 1991 figure

The UN-ECE statistics provide the following definitions for the building types in Table 2.6:

- *Industrial buildings:* All buildings which are used to house the production, assembly and warehousing activities of industrial establishments, viz. factories, plants, workshops etc.
- *Commercial buildings:* Office buildings and all buildings which are intended for use primarily in retail and service trade, viz. hotels, restaurants, warehouses, public garages etc.
- *Educational buildings:* All buildings which are intended for use directly in the instructional activities and courses, viz. schools, universities etc. as well as museums, art galleries, libraries etc.
- *Health buildings:* All buildings which are primarily engaged in providing hospital and institutional care, viz. hospitals, infirmaries, sanatoria etc.
- *Other buildings:* Buildings which are not included in any of the above classifications viz. public, religious, amusement, sport, recreational and community buildings, non-residential farm buildings etc.
- *Floor area of buildings:* The sum of the area of each floor of the building measured to the outer surface of the outer walls including the area of lobbies, cellars, elevator shafts and all the common spaces. Areas of balconies are excluded.

The existing non-residential building stock

Data concerning the existing stock of non-residential buildings are not available. An estimate can be made, assuming an average floor space of 30 m^2 per person. This results in a total of 10 billion m^2. This would imply that the floor space increases by 2.1% per year. Compared to the construction of 1.1% new dwellings per year and the dwelling stock of 14 billion m^2, these figures seem reasonable.

Demolition and changes in use of non-residential buildings

Data concerning demolition of non-residential buildings have not been encountered.

2.3 Civil engineering

The construction category civil engineering can be split into:
- roads, parking lots etc.
- harbours
- tunnels
- dykes
- bridges
- pipelines
- off-shore platforms
- other waterworks etc.

This is a very diverse group of constructions. As no common physical denominator exists for these constructions, data concerning product stock and product flow are not available. On a materials consumption level, data are however available and will be discussed in the next chapter. Only the group of roads, parking lots etc. will be discussed in more detail. They can be measured in m or m^2, so they are registered separately.

New roads and the existing road stock

The type of road structures is determined by the number and weight of the vehicles that use the road. The structure of a highway differs completely from the structure of low volume roads. For this reason, a subdivision is made into high volume and low volume roads. Data for both road types are shown in Table 2.7. Note that the two references indicate significantly different figures for certain countries. The difference may be accounted for by privately owned roads. One should add that the definition of high and low volume roads differs to some extent between countries.

The road length increased in the last 10 years by 0.4% annually. Significant differences exist between countries. Apart from the increasing road length, roads were also widened. Data concerning road widening are not available. It is estimated that the road widening added another 0.1% annually to the actual road surface. Apart from the increasing surface, the thickness of the asphalt layer increases: e.g. in the Netherlands, some roads contain an asphalt layer of 1 metre [13]. No data are available concerning the increasing thickness on a Western European scale.

An estimate of the increase can be made, based on the 30 Mt waste asphalt that is released per year (see Chapter 3). If the roads are on average repaired each 10 years, where the upper 5 cm is removed, 226 Mt waste asphalt would arise per year. The actual waste quantities indicate that most roads are only covered with a new layer. An average increase of 0.5 cm per year is assumed. These data should be compared to the asphalt consumption of 260 Mt. Assuming a density of 2.4 t/m^3 225 Mt new asphalt is used for increasing road thickness. The remaining production of 35 Mt equals 15 million m^3 pa. The average increase in road surface is 0.5% or $3768 \times 10^6 \times 5 \times 0.005 = 95 \times 10^6$ m^2 pa. This implies an average thickness of the asphalt layer for new roads of 16 cm, which seems quite feasible. These figures suggest that 87% of the asphalt is used for road maintenance, and only 13% is used for new roads.

Table 2.7 *Administrative + private road network [14,15]*

	Total network [1000 km]	Low volume roads [%]
Austria	200	80
Belgium	158	(est.) 70
Denmark	70	70
Finland	277	95
France	807	80
Germany (est.)	650	30
Greece	116	40
Ireland	92	90
Italy	298	(est.) 50
Luxembourg	5	(est.) 50
Netherlands	110	60
Norway	89	(est.) 70
Portugal	35	55
Spain	328	80
Sweden	306	90
Switzerland	71	80
UK	156	90
Total	3768	(est.) 75

Demolition of roads

Data concerning the complete removal of roads are not available. It is however thought that this amount is negligible. Road pavement is removed and renewed during maintenance operations. These materials flows are discussed in Section 3.7.

2.4 Renovation and the Do It Yourself (DIY) market

The renovation market is the largest construction market in monetary units (see Table 2.1). A significant amount of materials is additionally sold on the Do-It-Yourself market and used in private households. This market consists of a wide range of materials and products that range from paint and timber to floor cladding. More bulky products like new walls and floors, indoor and outdoor room additions, new outside cladding, garden sheds, garages, terraces etc. are also included. Data concerning materials use for such constructions are lacking for the European market. Data for the United States suggest that the bulk of the materials are used for structural applications that do not significantly differ from e.g. walls and roofs in new residence construction [16].

The materials intensity of renovation and DIY is lower than for new building construction, as the bulk of materials (in tonnes) are concrete and bricks that are used for foundations, structures and walls. These elements are generally not replaced during renovation. As a consequence, wood and plastics probably constitute a larger share than bricks and concrete. Due to the complicated market structure and the lack of data, the renovation market will not be considered as separate market.

3. MATERIAL FLOW ANALYSIS

3.1 Introduction

Materials use data for construction and related CO_2 emissions are shown in Table 3.1. These data for materials use will be elaborated further on in this chapter. A maximum and a minimum estimate for specific CO_2 emissions is provided. The CO_2 emission for metals refers to primary production from ores and scrap recycling, respectively. The CO_2 emission for non-sustainable timber represents a minimum and a maximum estimate for the emissions that can be attributed to tropical timber production (see Section 3.5). Fossil carbon feedstocks and energy recovery have not been considered in this table. Carbon storage through wood products in buildings and constructions has also been neglected.

Table 3.1 *Materials use for construction and related CO_2 emissions [17,18,19]*

Material	Use	CO_2	Total CO_2	
		Max./min.	Max.	Min.
	[Mt/year]	[t/t]	[Mt/year]	[Mt/year]
Steel	25	1.7/1.0	42.5	25.0
Aluminium	2	15.0/1.0	30.0	2.0
Copper	1.5	7.5/1.0	11.3	1.5
Zinc	0.8	2.0/1.0	1.6	0.8
Polyolefins	0.2	1.5/0.5	0.3	0.1
Polystyrene	0.4	1.8/0.5	0.7	0.2
PVC	2.2	3.0/0.5	6.6	1.1
Bitumina	17.1	0.4/0.2	6.8	3.4
Cement	185	0.85	157.0	157.0
Bricks+structural ceramics	89	0.15	13.3	13.3
Sand-limestone	40	0.15	6.0	6.0
Ornamental stone	18	0.1	1.8	1.8
Glass	5.6	0.7	3.9	3.9
Timber	35	0.5	17.5	17.5
Timber (non-sust.)	20	5.0/1.8	100.0	36.0
Particle board	10	0.7	7.0	7.0
Fiber board	5	0.7	3.5	3.5
Other fibres (paper etc.)	1	2.0	2.0	2.0
Total			412.8	279.1

As the emissions from the total materials production are approximately 700-800 Mt (excl. transportation), the emissions for building materials represent approximately 30-50% of total CO_2 emissions for materials production (excluding transportation), or approximately 8-12% of total Western European CO_2 emissions.

Note that the importance of the building and construction market from a CO_2 point of view is higher than from an energy point of view. Especially cement and non-sustainable timber are more relevant from a CO_2 point of view than from an energy point of view. Both groups of materials will be discussed in more detail.

The CO_2 emission for electricity production influences the CO_2 intensity of electricity intensive materials. The emission data in Table 3.1 are based on the Dutch electricity production. The average European CO_2 emission for electricity production is lower, so the average emissions per unit of material are lower for electricity intensive materials. This effect is important for e.g. primary aluminium and PVC.

The most important material flows (steel, aluminium, plastic, cement, bricks and timber) will now be analysed in more detail. Paragraph 3.2 discusses cement, 3.3 steel, 3.4 bricks, 3.5 wood products, 3.6 plastics. Data for materials consumption are combined with data for construction activities (Chapter 2) in order to show the material flows in the building industry. These data will serve as basis for the selection of improvement options that are detailed in Chapter 5.

3.2 Cement

Cement is used for a number of applications. A first division can be made into concrete and other applications (e.g. mortar, road base stabilisation). Concrete is by far the largest cement application. Table 3.2 provides data concerning cement use, divided into end-use markets.

Table 3.2 *Western European cement markets (based on [20])*

Market segment	Use fraction [%]	
New residential	30	
New non-residential	30	
amongst which:		
Public		7
Commercial		9
Agriculture		6
Industrial		13
Civil engineering	25	
amongst which:		
Transportation/paving		10
Hydraulic works		8
Others		7
Repair & Maintenance	15	
Total	100	

The estimates in Table 3.2 are based on an extrapolation of data for 60% of the total Western European cement market. They show that the market segments new residential, new non-residential and civil engineering make up 85% of the market. All three segments are almost equally important. Repair and maintenance represents approximately 15% of the total cement market.

Cement is not applied as structural material itself. It serves as bonding agent for other structural materials. Table 3.3 shows data concerning the cement content of different products. The cement content can vary, depending on the strength requirements and the cement application.

Table 3.3 *Cement content of products*

Type	Cement content [%]	Use
Ready mix	10-15	Foundations, waterworks
Prefab elements	20-25	Buildings
Blocks	10	Buildings, road construction
Mortar	24	Wall construction

Concrete

The bulk of the cement is applied in concrete production. Concrete is a mixture of cement, aggregates and water that stabilises due to a chemical reaction of the cement and the water. Steel reinforcements are often added to increase the flexural strength. Many concrete types can be discerned, ranging from 400 (light weight concrete) to 2500 kg/m^3 (reinforced concrete). Table 3.4 shows the composition of some concrete products. The specific weight of concrete products depends on the aggregate type (e.g. gravel, wood or polystyrene) and on the content of empty volume (gas concrete etc.).

Table 3.4 *Raw material requirements by concrete product (excluding reinforcement) [kg/m^3]*

	30MPa ready mix	Block	Hollow Deck
Cement	350	189	505
Coarse aggregate	1092	510	750
Fine aggregate	722	1191	744
Water	160	53	202
Total	2324	1943	2201

Concerning concrete quality types, strength and heat conductivity differ considerably; each type has its own market niche. A first subdivision can be made according to the production process: on site cast concrete and precast shapes.

Another subdivision is possible, based on the content of steel reinforcements. Steel reinforcements can significantly increase the specific CO_2 emissions per tonne of concrete. The amount of reinforced concrete can be estimated from the reinforcement steel sales: 13.3 Mt per year. The steel content ranges from 40 kg per m^3 to 200 kg per m^3 of concrete. In the following analysis, an average steel content of 50 kg per m^3 is assumed.

The reinforced concrete density is on average 2500 kg/m^3. The cement content is 275 kg per m^3. Based on these data, 13.3 Mt steel reinforcements equal a cement consumption of 74 Mt, i.e. 40% of all cement applications. Reinforcements are both used for precast and on site cast concrete, e.g. for hollow decks and foundations. Reinforcements are not applied for mortar and concrete blocks.

The subdivision into precast and on-site cast concrete will now be used for further analysis of the concrete market.

1. Precast concrete

Precast or prefabricated (prefab) concrete products are produced in industrial processes. The solid product is transported to the construction site. The following product types can be discerned:
- concrete elements for structural applications (foundations, beams, columns, floors, walls)
- concrete blocks and tiles
- concrete pipelines.

The main advantage of prefab concrete is the lower building time requirement. Prefab concrete is not widely used in Western Europe due to reasons that differ per country. Especially in structural applications, prefab concrete does not live up to its market potential [21]. The total amount is estimated to be around 10 Mt prefab structural elements. The application for floors and walls is more accepted, and is estimated to be in the range of 100 million m^2 (20 Mt). Total cement application in prefab elements is thus approximately $0.2\times30 = 6$ Mt.

Only limited data are available concerning the market for concrete building blocks, shown in Table 3.5. It is assumed that the average weight is 2 t/m^3, the average cement content 10% and the average block thickness 10 cm. The result of 9.5 Mt cement can be extrapolated to the whole of Western Europe based on population data: 17.3 Mt cement for building blocks.

Table 3.5 *Market for concrete building blocks, 1994 [22]*

			[Mt cement/year]
Germany	21,365,000	[m^3]	4.3
Austria	407,000	[m^3]	0.8
Finland	23,000	[m^3]	0.0
France	13,361,000	[t]	2.7
UK	86,308,000	[m^2]	1.7
Total			9.5

The cement content of tiles is in the order of 2 Mt. Concrete pipelines represent an estimated volume of 2.5 Mt cement (based on [23]). A total overview of the national precast concrete markets is shown in Table 3.6. The total market volume is 36.7 Mt cement according to statistics. The addition of the cement consumption for the previously mentioned product types covers most of this amount.

Table 3.6 *Western European precast concrete market, 1990 [Mt cement pa] [24]*

Belgium	1.2
Denmark	2.2
France	3.3
Germany	9.6
Greece	0.1
Ireland	0.4
Italy	5.6
Netherlands	1.9
Portugal	0.8
Spain	5.3
UK	3.3
Other (est.)	3.0
Total	36.7

2. On site cast concrete

On site cast concrete can be split into ready mixed concrete, and on site mixed concrete. Ready mixed concrete is prepared in industrial installations and is consequently hauled to the construction site. On site mixed concrete is produced at the building location. Table 3.7 shows the Western European market for ready mix concrete. Data concerning the on site preparation are lacking. It is assumed that this application is less important.

Table 3.7 *Western European ready mix concrete market, 1994 [25]*

	RM Production	Cement consumption	
	[10^6 m^3 pa]	[Mt cement pa]	[kg/m^3 RM]
Austria	9.0	2.3	260
Belgium	9.3	2.5	265
Denmark	1.2	0.3	230
Finland	1.6	0.5	290
France	30.4	8.1	268
Germany	74.1	21.8	294
Greece	11.5	3.5	300
Ireland	2.3	0.7	300
Italy	50.0	11.0	220
Netherlands	7.0	2.1	300
Norway	1.5	0.5	307
Portugal	4.1	1.2	300
Spain	26.2	6.4	245
Switzerland	9.7	2.8	287
UK	22.3	5.4	240
Total	260.2	69.1	266

Total cement market: an overview

A subdivision of the total cement market is shown in Table 3.8.

Table 3.8 *Western European cement market, divided into applications*

Application		[Mt]	
Precast		36.7	
amongst which:			
Building blocks	17.3		
Prefab structural elements		2.0	
Prefab floors and walls	4.0		
Tiles	2.0		
Pipelines	2.5		
Other	7.7		
Ready mix		69.1	
On-site mix + DIY[1]		69.2	(est.)
Mortar		10.0	(est.)
Total		185.0	

[1] Do It Yourself

Table 3.8 contains estimates for on-site mix, mortar and DIY. The amount of on-site mix/DIY seems rather high, compared to the amount of ready mix. Detailed European market figures concerning the renovation and DIY market are lacking. This market segment is the most uncertain one. Data for cement use, subdivided into applications and products, are shown in Table 3.9.

Table 3.9 *Western European cement use [Mt/year], 1992*

Cement [Mt/year] Total	Mortar	Walls	On-site cast Foundations	Floors	Pillars	Other	Pillars	Precast Floors	Walls	Foundations	Pipelines	Bricks/tiles	Other
Residential single family	4	0	5	8	0	0	0	2	4	1	0	2	026
Residential multi-story	2	4	8	8	4	0	0	2	4	2	0	2	036
Factories/warehouses	1	0	5	5	5	0	2	0	2	1	0	2	023
Agricultural	1	2	5	3	2	0	0	0	3	0	0	2	018
Other non-residential	1	2	5	5	0	0	0	0	2	0	0	2	421
Repair & maintenance	1	0	0	0	0	10	0	0	2	0	0	0	013
Waterworks	0	0	0	0	0	10	0	0	0	0	0	0	010
Roads	0	0	10	0	0	5	0	0	0	0	0	10	025
Sewers	0	0	0	0	0	6	0	0	0	0	3	0	413
Total	10	8	38	29	11	33	2	4	17	4	3	20	8185

3.3 Steel

Steel is in constructions used for structural elements, as a cladding material and for concrete reinforcements. Significant amounts of steel are used for equipment like heating systems or for drainage systems. The latter products are not considered as part of the construction industry but are allocated to the product group long life consumer products or production equipment.

The Western European building market for steel is traditionally relatively small as most residential buildings are built with concrete and bricks. Table 3.10 provides an overview of the structural steel applications. The bulk of structural steel is applied in industrial buildings (factories and warehouses) and in the non-residential sector (offices).

Table 3.10 *Western European use of structural steel, 1992 [26]*

Application	Use [Mt/year]
Industrial buildings	2.8
Non-residential	2.2
Residential	0.1
Agricultural	0.3
Bridges & dams	0.25
Power generation	0.09
Towers	0.35
Miscellaneous	0.08
Total	6.2

Table 3.11 shows that significant differences exist regarding the market share for steel structures in different European countries. The UK and Sweden show a very high market share for structural steel, while the market share in Germany and in Italy is still fairly low. Assuming that the high UK market shares represent the maximum steel penetration that can be achieved, the consumption can increase from 6 to 12 Mt steel per year.

Table 3.11 *European structural steelwork industry: market shares (number of buildings) [27]*

	Multi-storey buildings[1]	Factories/ warehouses	Single-storey non-industrial	Agric.	Bridges
Austria	5	20	n.a.	n.a.	20
Belgium	8	72	5	42	30
Denmark	5	20	-	42	30
Finland	15	47	n.a.	23	n.a.
France	21	83	52	64	n.a.
Germany	17	25	-	10	10
Greece	pm	pm	pm	pm	pm
Italy	11	20	7	12	30
Netherlands	26	80	-	-	40
Norway	27	27	27	n.a.	22
Portugal	pm	pm	pm	pm	pm
Spain	30	85	55	15	10
Sweden	50	80	n.a.	n.a.	50
Switzerland	15	20	-	-	-
UK	57	95	61	85	40
European average	25	50	25	30	25

[1] Both residential and non-residential

Apart from structural applications, steel is also used for concrete reinforcements and for cladding and sheet piles (Table 3.12). Sheet piles can be used for waterfront structures and for underground structures. The steel sheets are typically 10 to 13 mm thick. Data concerning their use were not available, but are estimated to be in the range of 1-5 Mt per year.

Table 3.12 *Aggregated steel use for constructions (EU+EFTA), 1992 (based on [27,28])*

Application	Amount [Mt/year]
Reinforcement bars	13.3
Constructional	6.2
Cladding (estimate)	1.0
Window frames, door frames	pm
Sheet piles	pm
Total	20.5

Data concerning steel use for constructions, divided into product categories, are compiled in Table 3.13.

Table 3.13 *Western European steel use for constructions, 1992 [Mt/year]*

Steel [Mt/year]	Reinforcements	Structural	Cladding	Total
Residential single family	0	0	0	0
Residential multi-story	5	0.1	0	5.1
Factories/warehouses	2	2.8	0.7	5.5
Agricultural	1	0.3	0.3	1.6
Other non-residential	5	2.2	0	7.2
Repair & maintenance	0	0	0	0
Waterworks	0	0.3	0	0.3
Roads	0	0	0	0
Sewers	0.3	0	0	0.3
Other equipments	0	0.5	0	0.5
Total	13.3	6.2	1.0	20.5

3.4 Bricks and ceramic products

The total brick and ceramic product consumption is approximately 89 Mt (see Table 3.14). The average weight is approximately 1.3 t/m^3. Bricks constitute the most important product group. Several types of bricks can be discerned. The main difference relates to the volume fraction of voids. This percentage can range from 0 to more than 40%. In the last decades, the use of light weight bricks increased in favour of solid bricks. Table 3.14 lists the main data concerning ceramic product use. Apart from the category bricks, it includes floor elements and roof tiles. It does not include sanitary stoneware and floor tiles. The use of ceramic products is slowly decreasing in favour of concrete, steel and plastic substitutes.

Table 3.14 *Ceramic products consumption in 1994 [Mt/year] [22]*

Solid bricks (<15% empty space, 1.6 t/m^3)	22
Perforated bricks (15-40% empty space, 1.05 t/m^3)	26
Hollow bricks (>40% empty space, 0.9 t/m^3)	13
Pavement bricks	5
Floor elements	16
Roof tiles	7
Total	91

Light weight bricks are especially used in southern countries (Italy, Spain). Pavement bricks are especially used in Germany and in the Netherlands. Because of the labour intensive brick laying process, the current practice is costly. Table 3.15 provides an estimate of the brick use. Note that detailed data concerning the use of certain brick types in certain product types have not been encountered.

Table 3.15 *Structural brick use in Western Europe [Mt/year], 1992*

Brick [Mt/year]	Solid brick	Perfora-ted brick	Hollow brick	Pave-ments	Floor elements	Roof tiles	Total
Residential single family	9	11	9	0	10	6	45
Residential multi-story	5	8	4	0	6	0	23
Factories/warehouses	3	4	0	0	0	1	8
Agricultural	0	3	0	0	0	0	3
Other non-residential	5	0	0	0	0	0	5
Repair & maintenance	0	0	0	0	0	0	0
Waterworks	0	0	0	0	0	0	0
Roads	0	0	0	5	0	0	5
Total	22	26	13	5	16	7	89

3.5 Wood

Wood products are used in different forms for the building and construction industry, amongst others:
- structural lumber
- plywood
- fiber board and particle board
- engineered wood products.

These products will be discussed in more detail. An analysis of the apparent wood consumption in Western Europe is shown in Table 3.16. Data for apparent consumption in m^3 are converted to m^3 roundwood equivalents in the rough, based on estimated conversion factors, so the amount of roundwood equivalents is an estimated figure. The structural wood consumption is still significantly higher than the wood consumption for pulp production. One should add that the standard conversion factors for m^3 structural wood to m^3 roundwood may be rather high for the current average European situation. The wood residues are either used in a cascade of material applications (e.g. chips and sawdust for chipboard or pulp applications), or they are used for energy applications.

Table 3.16 *Apparent wood product consumption in Western Europe, 1992 [29]*

	[10^6 m^3 r.e.]	[10^6 m^3]	[Mt pa]
Sawn wood	139.2	76.5	40.2
Particle board	24.3	24.3	14.6
Plywood	10.0	5.3	3.8
Fibreboard	3.6	3.6	1.1
Hardboard	3.0	3.0	3.0
Total structural wood	180.1	112.7	62.7
Pulp	105.4		38.7
Total wood products	285.5		101.4

[1] r.e. = roundwood equivalent. 1 m^3 sawn wood = 1.82 m^3 r.e.;1 m^3 plywood = 1.9 m^3 r.e.; 1 m^3 board = 1 m^3 r.e.

Table 3.16 shows that sawnwood is still the largest group of structural wood products, followed by particle board. Plywood, fibreboard and hardboard are less important groups.

Significant amounts of wood are used for applications that are not considered within this study: interior decoration, crates, pallets, furniture. Data concerning the wood applications are provided in Table 3.17.

The general trend in wood product consumption for the building and construction industry is from traditional sawn wood towards industrial wood fiber products and engineered wood products. There are several reasons for this trend. The width of sawn wood is generally limited to approximately 20 centimetres. The length is limited to approximately 10 metres. The availability of large size roundwood will be further limited in the future due to resource exhaustion and environmental policy constraints.

Another important reason is that the quality of industrial fiber products is more reliable, making it more suited for industrialised construction processes.

Table 3.17 *Wood applications*

Application	Amount [Mt pa]
Sawn timber	
Structural walls, floors, roofs	10-20
Civil engineering	5
Pallets & crates	5
Interior decoration & furniture	10
Other	0-10
Plywood	
Structural walls and floors	2
Furniture	2
Particle board	
Structural	5
Furniture	8
Other	2
Other fibreboard	
Structural	3
Interior decoration	1
Total	63

The wood product industry is more advanced in North America than in Europe. This is caused by the historical availability of good quality and large size timber which resulted in higher wood consumption for construction purposes in America. Because of ongoing depletion of large timber stands, prices for sawn timber are rising in the US. As a result, advanced wood products like oriented strand board (OSB), waferboard and glulam are nowadays rapidly developed in North America. An increasing use of these products can be expected for Western Europe.

The different wood type products and their applications will now be discussed in more detail. The discussion focuses on the properties of the products and the quantities that are applied. Finally, non-sustainable wood is discussed as separate topic.

Sawn wood

Natural wood exists in many qualities. The wood type, size, and growth history determine the quality. A general subdivision can be made into softwoods (from coniferous trees) and hardwoods (from broadleaved trees). Within these groups, several hundred wood types can be discerned. They differ in fiber length, fiber content and cell structure. These differences account for a major part of the difference in physical properties (see Table 3.18). Wood is a highly anisotropic material: properties differ considerably in different directions (axial, radial, tangential). Flexural strength is significantly higher than compressive strength, which is again an order of magnitude higher than the shearing strength. This phenomenon can be explained by the special structure: parallel fibres in a matrix of resins. One should emphasize that design strengths are one order of magnitude below the actual measured strength characteristics (e.g. 4.4 to 10 MPa design strength of flexure for Douglas Fir vs. 81 MPa measured average strength of flexure). This large safety margin is necessary because of variations in strength, creep and the occurrence of knots, shakes etc..

Apart from strength, durability is another important factor, especially the wood degradation in humid conditions. Several durability classes can be discerned, that depend on variables like silicium and natural toxin content. Durability can be enhanced by treatment with toxic substances, but this increases the environmental impact significantly. Durability is an important reason why foreign wood types like Western Red Cedar or Azobé (both currently produced in a non-sustainable way) are especially used for outdoor applications. As a consequence, straightforward substitution of these wood types by other wood types is not possible.

Table 3.18 *Variations in wood characteristics [30]*

Type	Density (12% water content) [kg/m^3]	Elasticity [MPa]	Flexural Strength [MPa]	Compressive Strength [MPa]
Spruce	460	10,800	77	49
Pine	500	10,800	79	47
Douglas fir	580	11,600	81	40
Oak	700	10,000	97	50
Robinia	770	14,200	133	71
Jarrah	860	13,000	114	62
Azobé	1,010	18,600	81	40

Many tropical hardwoods (e.g. Meranti, Merbau) are applied because their texture or their colour appeals to consumers. Replacement in applications where surface characteristics determine materials choice (window frames, doors, furniture) require other information than cost/benefit data, as the selection is not cost-driven.

Fiber board and particle board

The particle board market is analysed in Table 3.19. Furniture represents more than half of the total applications, followed by building applications with approximately one third. It is expected that particle board in the furniture market will face increasing competition from MDF board (Medium Density Fibreboard). Competition will focus on aspects like paint requirements etc.. Particle board in the building construction market faces competition from glulam and inorganic fibreboard (gypsum board, cement board), but no major market shifts are expected. Particle board is nowadays in buildings especially used for floor cladding and interior roof cladding.

Table 3.19 *European particle board market, 1990 [31]*

Application	Amount [%]
Furniture & interior decoration	54
DIY	8
Construction industry	29
Transportation	2
Packaging	3
Other	5

Engineered wood products

The use of engineered wood products is rapidly growing. Important products are:

1. Glue laminated timber
2. Laminated veneer lumber.

Glue laminated timber (Glulam) consists of layers of wood, 2-5 cm thick, which are glued together with phenol adhesives to yield wood products of almost any desired size. Glue laminated timbers of 10 metres long and 3 metres high have been produced. Manufactured sizes are primarily limited by the size that can be transported to the construction site. The main advantages of Glulam compared to conventional sawn timber is the availability of material in any size, the improved strength characteristics and the possibility to form Glulam into desired shapes. The strength characteristics are improved compared to average sawn timber because wood pieces with deflections can be removed.

Material made by parallel lamination of veneers into thicknesses common to solid sawn lumber (2-5 cm) is called Laminated Veneer Lumber (LVL) [32]. The industry presently uses veneers of 0.2 cm in thickness. These veneers are hot-pressed with phenol-formaldehyde adhesive into lengths from 2 to 20 metres. Strength-reducing defects are virtually non-existent.

Engineered wood products show less variation in strength characteristics, an important difference because lower safety margins are required, which results in higher design strengths and lower materials consumption (e.g. for Douglas Fir LVL, the design strength of flexure is 16-32 MPa. This value is 3-4 times as high as for the sawn Douglas Fir timber [33]). This allows the production of light trusses and I-sections. Current markets for these I-section beams are as joists and rafters in light-frame construction. The uses of this material are however still rapidly evolving.

Non-sustainable wood

Wood is often considered as ‘good’ material from a greenhouse emission point of view, because timber is produced from a tree that has previously converted CO_2 from the atmosphere into wood. The CO_2-wood-timber-CO_2 chain represents a closed carbon cycle. The validity of this assumption depends off course on the renewable character of the forest where the wood is harvested. The discussion concerning the sustainability of North American timber from the Pacific coast region, Siberian and Chilean coniferous woods and similar concerns about the tropical wood production in Asia, Africa and South America are well known.

Data concerning imports from non-tropical areas into Western Europe are shown in Table 3.20. The table shows that total imports from North America and the former USSR account for 12.9 Mt roundwood equivalents (based on an average density of 600 kg/m^3). The imports from other regions have not been analysed in detail, because their relevance is considerably smaller.

The major part of the imports consists of roundwood and sawnwood. The imports of other wood products is relatively small (note that pulp and paper are not shown in Table 3.20). The total import of structural wood products is considerable, compared to the Western European production: 12.6 Mt roundwood equivalents from Northern areas, 7.8 Mt roundwood equivalents tropical hardwood, 101 Mt r.e. apparent consumption of structural wood. 20% of the total apparent consumption is based in foreign wood resources that are partially non-sustainable.

Table 3.20 *Wood product imports from North America and former USSR*

Type	North America [Mt re]	Former USSR [Mt re]
Coniferous roundwood	0.05	1.12
Coniferous sawnwood	1.96	2.85
Non-coniferous roundwood	0.19	3.32
Non-coniferous sawnwood	1.02	0.07
Plywood	1.20	0.41
Particle board	0.00	0.04
Chips etc.	0.02	0.31
Fibreboard	0.03	0.07
Veneer	0.18	0.03
Total	4.65	8.22

Concerning North American woods, the recent US policies aim at salvaging the remaining rainforests along the West coast. Beyond 2000, US wood exports to Europe should decrease, given the still growing national wood demand in the USA. This may result in a shift toward European wood imports from Canada. The remaining Canadian resources (both Western and Eastern Canadian forests) are considerably larger; environmental concerns are less dominant. The Canadian harvesting practice of clear-cut is generally however not considered sustainable. Canadian sources state however that a difference should be made between virgin forests and logged forests in British Columbia, and more detailed studies suggest even a difference between coastal forests and inland forests (because of different intervals between forest fires, which affect the carbon balance) [34].

The major part of the imports comes from Russia. A large part consists of imports from Karelia into the Scandinavian countries, especially into Finland. This is a good example of the complicated discussion regarding the renewable character of wood. The forests in the Karelia region on the Finnish/Russian border have grown relatively undisturbed for 50 years, because economic activity was not allowed for security reasons. The recent political changes in Russia resulted in an opening of these forests for logging. These old forests are now rapidly being depleted to supply the Finnish wood processing industry. Within a timeframe of the next decades, this will result in a net CO_2 emission (apart from considerable other environmental impacts). However, replanting or natural regrowth will add to the supply of CO_2-free wood for a long period. In a timeframe of hundreds of years, the CO_2 impact of this logging practice is probably negligible.

The valuation of the CO_2 impact of certain timber production processes depends on the timeframe of the analysis. Given our timeframe of several decades, a net CO_2 emission will be modeled.

The harvesting practices in tropical countries are still for a major part considered to be non-sustainable. Notwithstanding the ITTO efforts to achieve more sustainable practices, it will take decades before the regrowth will match the harvest. This problem is closely linked to other development problems like a rapidly growing population, forest destruction for farming, mining, road construction and hydroelectric projects. The situation is different per continent, per country and even per logging concession. Generally speaking, it is difficult to find reliable statistical evidence for a close relation between logging and forest destruction [35].

Tropical logging is slowly shifting from the high yield natural resources (old forests with few tree types at easily exploitable locations, e.g. in South-East Asia) towards secondary forests, mountainous forest areas or less productive forests with fewer commercially attractive trees per km^2 (e.g. in the Amazon/Orinoco basin). As a consequence, the amount of waste wood during harvesting increases. Techniques to produce wood with limited environmental impacts are still in their infancy. This includes transportation of the trees out of the forest by helicopters or by aboveground cable transportation systems. It remains to see if such techniques will be adopted on a large scale, because they will significantly increase the production costs. One should add that wood plantations in tropical countries are rapidly increasing [36].

The current amount of biomass (relative to the harvested amount) lost beyond the commercial wood (roundwood) is between 75% of the actual roundwood production for undisturbed forests and 90% for logged forests [37]. This includes only aboveground biomass and includes only the actual logging: assuming a carbon content of 50%, the amount of CO_2 per tonne of roundwood is approximately 3.5 t CO_2/t roundwood. This estimate does not include the carbon in soils and/or losses due to road construction for logging etc. It is thought that the total emission will be in the range of 5-10 t CO_2/t roundwood.

The current use of tropical hardwood in Western Europe is estimated in Table 3.21. The total of 11.1 Mm^3 r.e. equals approximately 7.8 Mt tropical hardwood (roundwood equivalents). It can be divided into imports of saw and veneer logs (2.5 Mm^3), sawn timber (2.8 Mm^3) and imports of veneer (0.3 Mm^3) and plywood (1.3 Mm^3). The imported logs are predominantly used for timber (0.9 Mm^3), veneer (0.4 Mm^3) and plywood (0.5 Mm^3). One should add that these figures may contain some double counting because of exports of tropical timber products. The extent of double counting is thought to be limited. However detailed data have not been encountered.

Table 3.21 *European tropical wood imports, 1993 (extrapolated on the basis of [38])*

	$[10^6\ m^3$ r.e.][1]
Belgium/Luxembourg	1.06
France	1.64
Germany	1.34
Italy	1.48
Netherlands	1.75
Portugal	0.45
Spain	0.86
Switzerland	0.06
UK	1.46
Other (est.)	1.00
Western Europe	11.10

[1] 1 m^3 sawn wood = 1.82 m^3 r.e.;1 m^3 veneer = 1.9 m^3 r.e.;1 m^3 plywood = 2.3 m^3 r.e.

Significant amounts of sawn timber are used for production of window frames, doors and stairways. This is shown in Table 3.22. 1.4 Mt r.e. of the 4.7 Mt r.e. sawn timber, or 30%, is used for these four applications. The remainder is used for waterworks, furniture, interior decoration, cladding of buildings etc.. The 2.9 Mt r.e. plywood is used for cladding, interior decoration and furniture. The 0.9 Mt r.e. veneer is used for furniture and cladding.

Table 3.22 *Tropical hardwood applications [38]*

Application	Amount		
	$[10^3\ m^3]$	[Mt]	[Mt r.e.]
Exterior doors	280	0.20	0.36
Interior doors	60	0.04	0.07
Windows	600	0.42	0.76
Stairs	170	0.12	0.22
Total	0.78	1.41	

Table 3.23 provides an overview of the wood use for constructions.

Table 3.23 *Western European wood use for buildings and constructions (end use data) [Mt/year], 1992*

Wood	Sawn timber (sust)	Sawn timber (non sust)	Particle board	Fiber board	Plywood	EWP
Residential single family	3	0	2	2	0.5	0
Residential multi-story	2	0	1	1	0.5	0
Factories/warehouses	2	0	0	0	0	0
Agricultural	2	0	0	0	0	0
Other non-residential	5	1	2	1	0.5	0
Repair & maintenance	8	2	3	0	0.5	0
Waterworks	0	1	0	0	0	0
Roads	0	0	0	0	0	0
Sewers	0	0	0	0	0	0
Window frames	1	0.5	0	0	0	0
Other equipments	5	6	0	0	0	0
Total	28	10.5	8	4	2.0	0

3.6 Plastic

Plastic use in construction is dominated by PVC use. Other plastics are used to a much smaller extent. Table 3.24 shows major plastic applications. The total amount of plastic that is used for a Dutch reference residence ranges from 225-500 kg [39]. Note that plastic packagings are not considered in this analysis. They are included in the group product group packaging that is discussed in a separate report [40]. The current application of plastics in constructions is shown in Table 3.24.

Table 3.24 *Plastic use in Western European constructions, 1992 [41]*

Plastic	Application	Amount [Mt pa]	
PE	Pipes & ducts	0.457	
	Cables	0.226	
	Lining	0.179	
			0.862
PP	Pipes & ducts	0.073	
	Fixed floor coverings	0.200	
			0.273
PVC	Pipes & ducts	1.297	
	Fixed floor coverings	0.265	
	Cables	0.368	
	Windows	0.415	
	Profiles	0.300	
	Lining	0.081	
			2.726
PS	Insulation	0.424	
			0.424
PA	Floor coverings	0.172	
			0.172
PU/UP	Insulation	0.347	
			0.347
Others		0.332	
			0.332
Total			5.137

The total plastic consumption of 5.14 Mt per year represents 17% of the total use of plastics in 1992. The bulk of the plastics is used for pipes and ducts, insulation material, and for floor coverings. It is forecast that this amount will rise to 7.92 Mt in 2010. Growth figures will differ per product type: 4% annual growth for window frames, 3% for pipes, ducts and profiles, 2% for insulation, 1% for fixed floor coverings and 0.5% for cables. Note that not all applications in Table 3.25 are considered part of the construction industry in the sense of this report (e.g. floor coverings, cables).

3.7 Bitumen

The consumption of bitumen in the road industry in different European countries is shown in Table 3.25. The total bitumen consumption is 14.3 Mt, which equals 0.6 EJ or 48.4 Mt potential CO_2 emissions. A limited amount of bitumen is used for roof cladding (approx. 2 Mt per year, based on total bitumen consumption minus bitumen use for road construction). This application is not considered in more detail. The average bitumen content of asphalt is 5.8%, the addition of bitumen to recycled asphalt is not considered. The actual percentage warm recycling is currently 5.7% of the total production. The actual availability of old asphalt is approximately 30 Mt, i.e. 11.5% of the hot mix asphalt production. Again, closing the materials cycle is not possible for this product group because of the ongoing materials storage in products (see Section 2.3).

Table 3.25 *Bitumen consumption and asphalt production in the road industry in 1994 [42]*

	[Mt bitumen]	[Mt hot mix asphalt]	[Mt warm recycling]
Austria	0.33	8.0	0.1
Belgium	0.27	4.6	0.0
Denmark	0.18	3.1	0.2
Finland	0.37	4.1	0.1
France	2.70	40.0	0.4
Germany	2.90	69.0	11.3
Greece	0.30	5.0	0.0
Ireland	0.10	1.9	0.0
Italy	1.60	31.0	0.6 (est)
Netherlands	0.30	7.0	1.3
Norway	0.29	4.5	0.0 (est)
Portugal	0.46	6.0	0.0 (est)
Spain	1.44	26.4	0.0
Sweden	0.50	7.6	0.0
Switzerland	0.28	4.8	0.3
UK	2.30	37.7	0.6 (est)
Total	14.32	260.7	14.9

3.8 Conclusions

Detailed data concerning Western European materials consumption in the building and construction sector are scarce and incomplete. The large number of construction companies, the national character of the industry, and the significant construction activities outside the regular economy may explain these deficiencies. Given the inherent uncertainties of the long term trends that are analysed in this study, the precise data are fortunately of lesser importance, and the estimates in this chapter are sufficiently reliable. A final check is to combine materials consumption data and building construction and building composition data to check if both mass flow figures correspond. This check is not included in this volume. It will be a part of the MARKAL analysis.

4. DEMAND TRENDS

Trends in the building industry will influence material flows. The main issues concerning the building industry for the next decades are:
- sustainable development
- reduction of construction time
- building life cycle cost savings
- increased renovation activities.

A gradual trend exists towards increased industrialisation. The development wood products like particle board and fibre board or precast concrete can be considered as earlier developments that fit in the same trend. Combined with smart bonding technologies, standardisation can also improve the re-use potential of building parts. Increasing wealth may increase the demand for individual building characteristics, which may hamper industrialisation trends.

Decreasing European national barriers will result in more uniform building design and building practices. The total number of buildings will still increase because of increasing space requirements per person. The population stabilises in this period (a growth of 5% is forecast between 1990 and 2025). The age distribution changes towards more older people. It remains to see how this change will influence building requirements. Older people will in the future probably be more agile and wealthier. This trend can increase building requirements, e.g. if it results in a significant number of secondary residences for this part of the population.

The current residence stock is 420 per 1000 inhabitants (Table 2.4). It is assumed that this stock will increase to 550 per 1000 inhabitants in 2040. An increasing number will be multi-residence dwellings because of increasing environmental and spatial restrictions concerning land use.

The demand for offices and industrial buildings will stabilise, because the working force will decrease in the longer term, which compensates growing space requirements per labourer. The space requirements for agriculture remains at a constant level. The demand in the service sector increases, and space requirements for shops and vacation areas will further expand.

The demand for repair and maintenance and the DIY sector will increase significantly, both because the building stock becomes more mature and because of the increasing individualisation and wealth. Demolition will increase beyond 2025, when the post-war buildings reach their end of life.

Table 4.1 shows the assumptions concerning building activities that will be used for the MARKAL analysis.

Table 4.1 *Building activity forecast, 1990-2050*

Type	Unit	1990	2000	2025	2050
Residential single family	[mln. m^2]	100	90	75	50
Residential multi-storey	[mln. m^2]	80	80	80	80
Factories/warehouses/agric.	[mln. m^2]	135	125	100	100
Offices/government	[mln. m^2]	80	90	100	110
Repair/renov./DIY	[ECU/ECU_{1990}]	1	1.3	2	3
Roads	[mln. m^3 road]	100	110	125	140
Other	[ECU/ECU_{1990}]	1	1	1	1

Total dwelling demand is forecast to decrease due to the stabilising population and an increasingly satisfied demand. Limited building space, ageing population and decreasing household size will result in a shift in the ratio of single family and multi family dwellings in favour of multi family dwellings. The shifting economic structure towards a service economy results in an increasing demand for offices and governmental buildings, coupled to a decreasing demand for factories, warehouses and agricultural buildings. The demand for repair/renovation and DIY increases significantly. A tripling between 1990 and 2050 is assumed (measured in financial terms). For roads, the still increasing demand for road transportation will result in increasing traffic densities and increasing road demand. Concerning the group ‘others’, a stabilised demand is assumed because more detailed data are lacking.

5. IMPROVEMENT OPTIONS

5.1 General overview of improvement options

A wide array of improvement options exists in the building sector and has been documented in the literature. Technological, organizational, economical and legislative improvement options can be found. The main problem is that an overview of their significance, their scope and their cost-effectiveness is lacking.

This paragraph discusses first the general scheme of improvement options. This scheme is used as framework for improvement options in the construction sector. These improvement options are discussed in the following paragraphs.

Figure 5.1 shows the general life cycle of materials. The bulk of the CO_2 emissions is related to the production of primary materials. Options to reduce these emissions through changes in material flows can be divided into two strategies:
- doing the same with less (increased efficiency/enhanced resource productivity),
- substitution.

The ‘doing the same with less’ strategy includes:
1. less use of natural resources for the same materials production
2. less use of materials for the same product mix
3. less use of products for the same product service mix.

The 'substitution' strategy includes:
4. substitute feedstocks
5. substitute materials
6. substitute products.

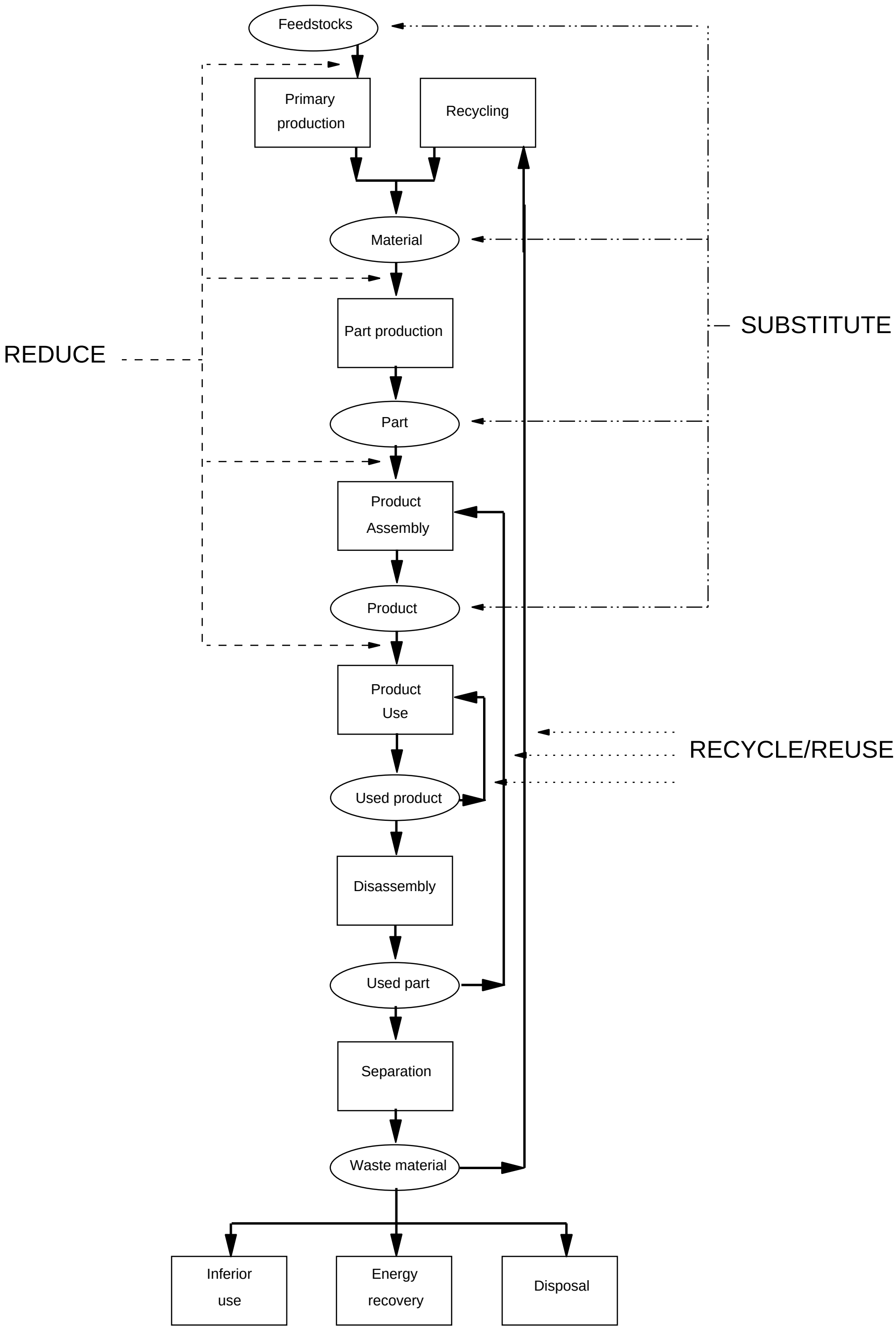

Figure 5.1 *Improvement options in the materials life cycle*

'Doing the same with less' can be achieved through the production of the same products with less materials (the 'reduce' strategy in Figure 5.1) and through the recycling of waste materials and waste products (while keeping the amount of material per unit of product at the same or even at a higher level).

The options that are elaborated for the construction industry in this volume are listed in Table 5.1. Note that substitution of products has been aggregated with substitution of materials, because a clear distinction is hardly feasible.

Table 5.1 *Improvement options related to the materials flow*

1	Less use of natural resources for the same materials production (Section 5.2)
A	Increased waste material recycling
-	Wood fiber cascading
-	Increased asphalt recycling
B	Improved waste collection systems
-	Building demolition waste separation
2	Less materials use for the same product mix (Section 5.3)
A	Product part re-use
B	Improved product design
-	Re-design of building structures with the same materials
C	Less materials losses during production process
-	Reduced losses of wood type materials
D	Increased average materials quality
-	Engineered wood products
-	High strength steel
-	High strength concrete
-	Hollow bricks
E	Less spread in materials quality
-	Engineered wood products
-	Steel
F	More diverse standardisation/reduced safety factors for design
-	Steel
-	Cement
3	Less products for the same product service mix (Section 5.4)
A	Increased product life
B	Design that matches quality requirements
-	More efficient use of office buildings
4	Substitution of natural resources (Section 5.5)
-	Increased slag use
-	Geopolymeric cement
-	Sustainable wood instead of non-sustainable wood
5	Substitution of materials (Section 5.6 and Chapter 6)
A	Without secondary effects
-	Substitution of steel reinforcements and steel wire
-	Substitution of insulation materials
-	Substitution of foundation materials
B	With secondary effects
-	Single family residences: concrete/brick vs. wood/steel
-	Multi family residences: concrete vs. wood/steel
-	Office buildings and other governmental buildings: concrete/brick vs. wood/steel
-	Factories, warehouses and agricultural buildings: concrete/brick vs. wood
-	Road constructions: asphalt vs. concrete

Apart from influencing material flows, the specific CO_2 emissions of processes in Figure 5.1 can also be influenced. Options like improved energy efficiency in materials production, substitution of energy carriers, or CO_2 removal and storage are included in the MARKAL model but will not be discussed in this volume. Their characteristics will be discussed in separate reports.

Caution is required concerning the estimate of potentials for materials substitution and decreasing materials intensity. Climate, building traditions and affluence are major reasons for the variation in building characteristics and the variation in building activity that has been discussed in Chapter 2. Use of certain building materials is often a result of national preferences and national standards.

For example wood frame buildings are more common in Scandinavia. Bricks are traditionally widely used in countries that lack natural stone like parts of the UK, Belgium, and the Netherlands. German building standards are comparatively rigid and result in higher materials consumption than e.g. Dutch building standards. Such factors limit the improvement potential. As the goal of this analysis is primarily to find important improvement options, only limited attention is paid to the implementation barriers for changes in materials use.

The improvement options will in the following Sections 5.2-5.6 be analysed in more detail. Their technological potential for reduction of CO_2 emissions and their costs will be discussed. Data are aggregated in Section 5.7.

5.2 Less use of natural resources for the same materials production

A. Increased recycling

Wood fiber cascading

The most significant potential exists probably for post consumer wood recycling into particle board, fiber board or maybe into fibres for paper production. The significance of this type of improvement options (from a CO_2 point of view) depends on the biomass availability. In the current situation, where Western European forest regrowth exceeds the wood harvest, recycling wood makes little sense from an energy/CO_2 point of view (because primary wood can be used as well). If future biomass availability becomes a limiting factor, efficiency can be increased through increased wood recycling. Such a situation can occur in future decades if significant amounts of biomass are used for energy production, or if a significant part of the materials system changes to biomass resources [43]. Competition between biomass for energy purposes and for biomass for materials purposes is expected, and cascading will make sense in order to increase the efficiency of biomass use.

A significant part of process wood waste and even post-consumer waste is already in e.g. Germany used for production of particle board. The use of post-consumer waste in other countries is less significant. It is possible to recycle sawnwood, particle and fibreboards into new particle boards by hydrolysis of UF-resins with steam at 110 °C. Surface coatings and edge materials are removed in the process. The fibres and particles can be separated. Particles recovered from particleboard can be defibrated to fibres. These fibres can be used to produce MDF or hardboard [44]. The main costs are for waste wood collection and transportation to the processing plant. These costs can range from 25 to 100 ECU/t. Shredding costs are approximately 10 ECU/t. The costs for the hydrogenation process are not known, but are probably in the range of 50-100 ECU/t, based on similar processes in other industry branches. This includes steam use of 1 GJ/t. The yield is in the range of 0.8 t particles and fibres per tonne processed wood waste. It is assumed that the residual waste fraction can be processed for 100 ECU/t, i.e. 20 ECU per tonne waste wood. As a consequence, the costs of this process are 100 - 230 ECU per tonne product (fibres and particles). The price of particles and fibres from production waste are 75 and 25 ECU per tonne, respectively. However, residue prices may rise in the future due to competition of energy applications.

The potential of wood material recycling is limited by the amount of waste wood that becomes available. Given the large amount of sawnwood that is produced compared to the amount of particle and fibreboard, complete substitution of primary wood residues by post-consumer wood waste seems feasible. This would allow more pulp production from primary wood residues, because the quality standards are higher for pulpwood. The potential contribution to CO_2 emission reduction is determined by the reference energy system and the biomass availability at that time. If the land availability limits the biomass production, cascading makes sense. Wood waste cascading can increase the availability of sawn timber. Concrete (20% Portland cement) can be substituted on a 1:10 mass basis by sawn timber [45]. The emission reduction potential is estimated to be 31 Mt CO_2 per year[1].

Increased asphalt recycling

The amount of asphalt recycling can be increased from 14.9 Mt asphalt that is currently hot recycled to the amount of waste asphalt that is actually released: 30 Mt per year. The main saving is in this case the reduced non-energy use of a heavy oil fraction. The CO_2-impact of increased recycling depends on the actual position and function of the refineries within the energy system. This heavy oil fraction can be hydrogenated to light fuel oils or gasified and used for energy recovery. If such alternative applications are not developed, asphalt recycling makes no sense from a CO_2 point of view. One should add that the amount of asphalt recycling could be significantly enhanced through ‘mining’ of deteriorated road pavements, instead of adding additional pavement layers. The potential for asphalt recovery could be increased to 100-200 Mt per year, resulting in 5-10 Mt bitumen savings, which represents 200-400 PJ. However, the high collection costs make such a scheme less likely. Only the remaining waste asphalt potential will be considered. The CO_2 reduction potential is in the range of $(0.094\text{-}0.073)\times15\times40\times0.055 = 0.7$ Mt CO_2 per year, if it is assumed that bitumen substitutes coal on a thermal par basis.

If costs for increased recycling are assumed to be 50 ECU/t asphalt, the CO_2 emission reduction costs are 1000 ECU/t CO_2[2].

B. Improved waste collection and separation systems

Demolition waste separation

The general practice in the Netherlands and Germany is careful deconstruction of the less valuable fraction in order to keep wood, concrete and bricks and other building materials separated. The current focus is mainly on energy recovery and materials recycling. The incentive for these

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[1] $17\times10\times0.2\times0.9 = 31$, based on 17 Mt additional residue recycling, 10 t concrete/t wood, 0.2 = cement content, 0.9 t CO_2/t cement

[2] $50/[0.094\text{-}0.073)\times40\times0.055]=1000$, based on 50 ECU/t asphalt recycling costs, 0.094-0.073 CO_2 saving per GJ bitumen; 40 GJ/t bitumen; 0.055 t bitumen/t asphalt

efforts are in some cases cheap resources (e.g. for metals), but in many cases the rising disposal costs are the main incentive. As a consequence, stone type building materials are downcycled as aggregate materials for concrete, an option that saves resources but is not important from a CO_2 point of view. Improved deconstruction processes may pose an option to achieve recycling of building parts instead of materials recycling. Used buildings are currently already stripped of valuable building parts for re-use or recovery. E.g. in the Netherlands, a thriving trade exists in antique building materials for renovation purposes. Increased building part reuse may be attractive from a CO_2 reduction point of view, e.g. for bricks, wood and steel beams, precast concrete elements, rooftiles or windows (see Section 5.3).

The main problem concerning reuse are the high labour costs for deconstruction. Improved bonding technologies could reduce deconstruction costs. The long time span between construction and demolition results however in a significant discounting effect (see Chapter 9): new bonding technologies that are introduced now will result in increased recycling in 50 to 100 years. As a consequence, future consideration of demolition in the construction phase through new bonding technologies seems only viable if the costs are not higher than for the reference construction. New bonding technologies are not considered as improvement option, increased recycling and reuse is further elaborated.

The experience in this field is limited. One reference was found to a complete deconstruction of a former traditional German hotel (1100 t material, 4950 m^3, 1500 m^2) [46]. The example shows that labour costs dominate the balance: 80% of the deconstruction costs are labour costs. There exists however a considerable range for certain building parts: labour costs make up between 30 and 100% of total deconstruction costs. Scale effects exist in deconstruction. While the deconstruction of the hotel resulted in average deconstruction costs of 15 ECU/m^3 (deconstruction + recycling/removal + transportation), estimates for smaller buildings (1000 m^3) are in the range of 20-50 ECU/m^3 (the Dutch reference dwelling is 322 m^3).

The costs for deconstruction will also depend on the building type. One example has been found: a German industrial building of 21,000 t near Dresden was partially deconstructed [47]. Costs for demolition (excl. transportation and recycling/removal) were approximately 60 ECU/t. Unfortunately, the process is not further elaborated, so the data can only serve to illustrate the range of deconstruction costs.

The advantages of deconstruction for materials recycling are not obvious. The increased quality of waste materials may result in increased recycling rates. Table 5.2 shows the estimates for current recycling rates of building waste (recycling of stone type materials is not considered). The emission reduction potential refers to a situation with 100% recycling. One must add that the emission reduction potential depends to a large extent on the reference energy and materials system (e.g. a coal based electricity reference or a hydropower based electricity reference).

Table 5.2 *Current recycling rates and remaining CO_2 emission reduction potential for building materials*

	Waste arising [Mt material pa]	Recycling rate [%]	CO_2 potential [Mt CO_2 pa]
Plastics	1[1]	10	3
Steel	10	90	1
Aluminium	0.2	90	0.3
Copper	0.4	90	0.2
Wood	25	20	5
Total			9.5

[1] 90% non-structural elements: e.g. floor coverings, cables, pipes and ducts

The data in Table 5.2 suggest that the remaining material recycling potential is rather limited.

5.3 Less materials use for the same product mix

A. Product part re-use

If buildings are demolished, significant parts of the structure are often still in good condition and can potentially be reused. Parts like steel beams, wooden beams, prefab concrete elements, bricks or sand-lime bricks can be re-used. German examples show for example the possibility to reuse prefab structural elements from multi-family buildings. Irreversible bonding technologies limit however the reuse potential, because they result in high disassembly cost and damaged building parts. Typical examples are glued parts, nail connections, rivets. Reuse is also impossible for building foundations or for on site cast concrete structures. In some cases, new separation technologies, eg microwave based systems or high pressure water spray guns, can be used to split problematic bondings. For future buildings, different bonding technologies can improve the reuse potential on the long term.

An estimate of the potential contribution of product part reuse to CO_2 emission reduction is shown in Table 5.3. The figures should be considered as high estimates of the emission reduction potential.

Table 5.3 *Current potential for CO_2 emission reduction through increased deconstruction*

Material/part	Waste amount [Mt pa]	CO_2-impact 100% reuse [Mt pa]
Bricks	25	8
Prefab concrete	10	9
Wood beams, floors etc.	25	10
Steel beams	5	3
Total	65	30

Comparison of the data in Table 5.2 and Table 5.3 suggests that the emission reduction potential of product part re-use is higher than the emission reduction potential of increased materials recycling.

Recycling costs (recovery+collection+re-manufacturing) are assumed to be 250 ECU/t material, the emission reduction costs are 540 ECU/t CO_2[3].

B. Improved product design

Improved design refers to improved shapes of product parts that allow the use of less materials to achieve the same product performance. Examples are honeycombed steel profiles, hollow bricks, gas concrete instead of common concrete blocks etc.. Identification of such improvement options requires detailed engineering knowledge and can only be checked for specific cases. Generally speaking, safety factors are applied to constructions in order to allow for quality variations and variations in the required engineering performance. The safety factors are currently completely revised in the course of European standardisation efforts.

The optimisation of structures can result in significant savings. Eg in timber frame construction, optimisation of the distance of loadbearing poles results in a reduction of the structural wood fraction per m^2 from 15% to 8.5%, a reduction in materials use of 43% [90]. Data for the United States suggest a similar potential: 15×5 cm wood studs are used nowadays instead 10×5 cm studs because of additional insulation potential. This would allow 60 cm spacing between the studs. However, the traditional 40 cm spacing is still applied. A materials saving potential exists of 50%, which is currently not applied because the closer spacing appeals to the consumers' perceptions of good building practices [48]. Similar situations exist probably in Europe, and can be extrapolated to other constructions and other materials.

New shapes of structural building elements can also save considerable amounts of material. Circular sections require considerably less material than rectangular sections: the savings are in the range of 50-80%. For loadbearing beams, the loadbearing capacity is proportional to the height of the beam to the order of three and proportional to the width of the beam.

3 (65×250)/30=540, based on 65 Mt material per year, 250 ECU/t material, 30 Mt CO_2 reduction per year

As a consequence, higher, narrower beams save up to 50% weight. The use of honeycombed steel beams is already widespread, but can be further enhanced.

This design saving potential is not exhausted because of lacking availability of special building element shapes, conservative building standards, the lacking knowledge regarding advanced calculation methods, and traditional consumer preferences. It is assumed that on average 10% material savings can be achieved through improved product part design. The costs of the building elements increase by 10% (1000 ECU per building). Assuming an emission reduction by 3 tonnes CO_2 (see Table 1.2), the emission reduction costs are 1000/3 = 330 ECU/t.

C. Less materials losses during production process

Significant amounts of material are lost in the building process (see Chapter 7). Improved standardisation and improved building design, that is based on readily available building product sizes, can reduce these losses.

Reduced losses of wood type materials

The losses are the highest for wood type materials: approximately 10%. Suppose these losses can be cut in half, the emission reduction potential is 2 Mt CO_2[4].

D. Increased average materials quality

- Engineered wood products
- High strength steel
- High strength concrete
- Hollow bricks.

Engineered wood products

The advantage of engineered wood products lies in the reduced variation in materials properties. The possibility to use strong pieces of wood on spots where maximum strength is required is another option to increase the strength of the engineered wood product, compared to average sawn timber with knots, shakes etc. (see Paragraph 3.5). As a consequence, the design properties improve significantly. In Chapter 3, the example for Douglas Fir LVL showed design strengths for flexural strength which were 3-4 times higher than for the sawn timber. Other design properties are similarly affected. Figure 5.2 shows the relative weight of different sizes of Douglas fir glulam floor and roof beams in comparison to the equivalent Douglas sawn timber beams (US quality grade no. 1).

[4] 35×0.1×1×0.5, based on 35 Mt sawn wood per year, 0.1=10% reduced losses, 1 t CO_2 reduction/t saved wood, 0.5 = 50%

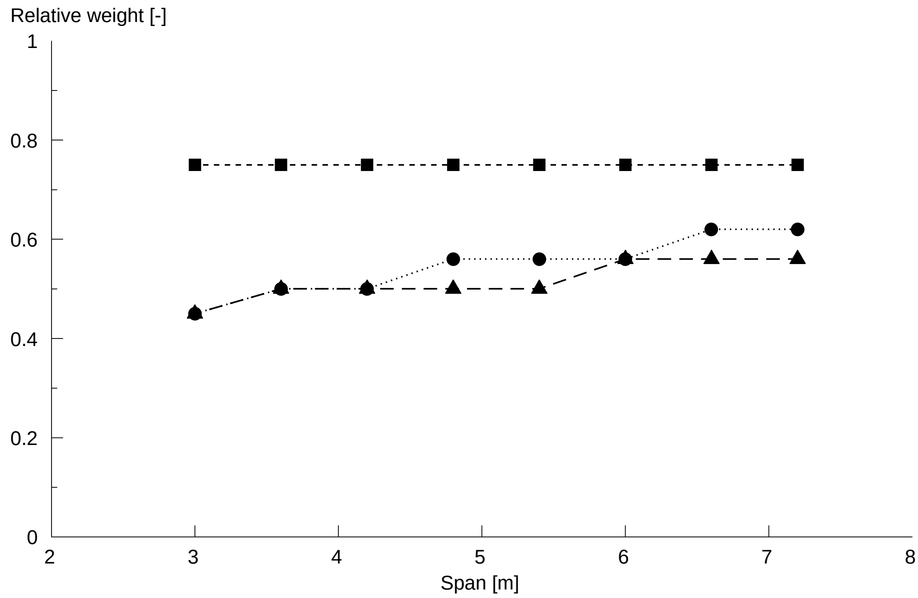

Figure 5.2 *Relative weight of equivalent Douglas glulams and Douglas sawn timbers no. 1 quality [49]*

It is assumed that an increased performance (or weight reduction) of 40% can be achieved for applications with bending loads. Because only a fraction of the applications are characterised by bending loads, it is assumed that the average saving potential is 40% for 50% of all material applications. The additional costs of engineered wood products are not known. Their labour intensity is generally significantly higher, so their cost price is generally higher than for sawn timber. However for large pieces of timber, the availability is limited and prices may be five times as high as for conventional sizes. In this study, it is assumed that the price of engineered wood products is 500 ECU per tonne.

The emission reduction potential is 4 Mt CO_2[5]. The emission reduction costs are 200 ECU/t CO_2[6].

High strength steel

Common reinforcement steel possesses a yield strength of approximately 300 MPa. Different types of reinforcement steel can be discerned. Their tensile strength ranges from 340 to 500 MPa. These differences are accounted for by different rolling and cooling treatments. Higher strength steel can be produced by more advanced steel treatment or by increased alloy contents. However the use of heavily alloyed steels is not considered in more detail because these steel qualities are 10 times as expensive as plain carbon steel.

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5 35×0.4×0.5×0.5 = 4, based on 35 Mt wood/year, 0.4 = 40% weight reduction, 0.5 = 50% of all applications,0.5 t CO_2/t wood

6 (500×0.5-200)/0.25 = 200, based on 500 ECU/t engineered wood

The amount of reinforcement steel is proportional to the tensile strength or the yield strength. Examples for e.g. reinforcement steels show that its strength can be increased (or its weight reduced) by 18% using an additional heat treatment after the hot rolling process (Tempcore 500 reinforcement steel) [50]. It is assumed that the use of high strength steel instead of steel FeB220 or FeB500 can result in a reduction of reinforcement steel use by 20%.

For structural steel, even higher weight savings can be achieved, compared to conventional carbon steel. Welding of steel structures can however destroy the increased strength. In cases where structural elements are designed for bending strength, the weight reduction is approximately proportional the ratio of yield stress to the order two-thirds. In cases where the design is based on bending stiffness (e.g. resistance to wind forces), the saving potential is negligible. On average, the saving potential of structural steel elements through increased strength is assumed to be limited to 10%.

The saving potential is 20×0.1×1.8 = 3.6 Mt CO_2. Assuming that the price for improved steel quality is a 50% price increase from 200 to 300 ECU/t, the CO_2 emission reduction costs are (300×0.9-200)/0.18 = 390 ECU/t CO_2.

High strength concrete (HSC)

Concrete strength can be significantly improved. The option high-strength concrete is discussed in the MATTER report concerning inorganic and ceramic materials [18]. In the modelling study, it is assumed that the increased cement content of HSC can be reduced to similar values as for conventional concrete. High strength concrete can on average contribute a factor 2 to the weight reduction of concrete columns with axial loads in a design with a constant amount of reinforcements, while the product part price increase (including material costs) is 25%. This application constitutes 25% of all concrete applications (see Table 3.9). For floor elements, it is assumed that the weight saving potential is 20%, while the material price increase is 25%. This application constitutes another 25% of all applications. These higher costs should be considered as high estimates. In many cases, the increased strength will result in net cost savings due to reduced transportation costs and reduced processing costs.

The costs of high strength concrete elements are determined by the costs of the additives and the cost savings for the sand and gravel use. Moreover, the secondary effects are also beneficial (less foundation requirements, increased floor space etc.). The costs of the fillers are however high: for silica fume 700 ECU/t, for finely ground fly-ash 400 ECU/t [51]. Assuming a 10% content results in additional costs of 40-70 ECU/t. However, the costs of reinforcements are reduced by 25-50 ECU/t. The costs of sand and gravel are reduced by 10-20 ECU/t. As a consequence, the additional costs are small or negligible.

The potential contribution is approximately 30 Mt CO_2[7]. Assuming additional costs in the range of 0-25 ECU/t conventional concrete and savings of 0.07 t CO_2/t concrete, the emission reduction costs are 0-350 ECU/t CO_2.

Hollow bricks

In the case of bricks, research results show that bricks with 40% perforation still comply with strength quality standards (compared to the conventional bricks with 20% perforation) [52]. They require however 40% additional mortar because of the large holes. The mortar requirement is approximately 20 weight% of the brick requirement. A 40% increase equals an increase in mortar requirements of 0.04 t/t bricks. The CO_2 saving 0.02 t CO_2/t bricks. This is a modest improvement of 0.02/0.15×100 = 13%. The potential contribution on a European scale is 0.13×16.5 = 2.1 Mt CO_2 per year.

E. Less spread in materials quality

Less spread in materials quality for concrete

Section 3.2 showed that the bulk of the cement is applied for concrete production. The concrete strength depends predominantly on the cement content and the water/cement ratio. Increasing cement content results in increasing strength, if the water content remains the same (Figure 5.1).

Cement strength has a dynamic aspect. The solidification can take up to several months before the final strength is achieved. The cement strength is in standardised tests measured after 4 weeks and is subdivided into 4 classes with minimum strength ranging from 35 to 60 MPa/m^2 [53]. This strength is the reference strength according to international standards. The final strength can be 50% higher in certain cases.

Two design problems can be discerned that limit the cement content. The first design consideration is the strength shortly after construction, when loadbearing forces are applied in constructions that have not yet gained their final strength. The second design consideration concerns the strength during the life of the building, when static and dynamic forces (wind etc.) must be considered. Only the latter one is considered in the following analysis.

Prefab production of concrete elements allows a better control of the spread in average strength: while the standard deviation is 5-7% for in-situ cast concrete, it is 3-5% for prefab concrete (estimates). Due to the reduced standard deviation, the design strength is 10-20% higher than for in-situ cast concrete with the same water/cement ratio.

There is some potential for decreasing cement use due to this increased strength. The total use of cement for floors and pillars is approximately 45 Mt. Assuming that on average 10% material savings are possible

[7] 180×0.5×0.35 = 30, based on 180 Mt cement, 0.5 = 50% of all applications, 0.35 = 35% average weight saving

through prefab construction, the total saving potential is 4 Mt CO_2 per year[8].

F. More diverse standardisation/reduced safety factors for design

Steel

Table 5.4 shows the design criteria for circular hollow sections and rectangular hollow sections according to the Eurocode, the US design criteria and the Japanese criteria.

Table 5.4 *Maximum design limits (d/t) for circular and rectangular hollow steel sections [54]*

	Circular		Rectangular	
	Axial	Bending (Yield limited)	Axial	Bending (Yield limited)
	d/t≤	d/t≤	d/t≤	d/t≤
EU	100 E^2	100 E^2	42 E^2	42 E^2
USA	97 E^2	268 E^2	41 E^2	41 E^2
Japan	100 E^2	100 E^2	48 E^2	48 E^2

d = diameter or side length, respectively [cm]
t = thickness [cm]

The factor E^2 is proportional to the inverse of the yield strength:

$$E^2 = \frac{235}{f_y}$$

where f_y = yield strength [MPa].

The data show that design safety factors do significantly differ. The difference is most extreme for bending loads for circular sections: the difference in the minimum amount of material between the US on one hand and the EU and Japan on the other hand is a factor 2.7. For rectangular sections, the Japanese design criteria result in a materials consumption that is 12% lower than in the EU and USA, both for axial and for bending loads. Note also that the data in Table 5.4 show that substantially less material (approx. 50% less) is required in case a circular section is used.

Hollow sections constitute only a limited part of the structural steel market, but similar differences exist probably for other designs. It is assumed that on average 15% structural steel can be saved through adjustment of the safety factors.

8 45×0.9×0.1, based on 45 Mt cement for floors and pillars; 0.9 t CO_2/t cement; 0.1 = 10% of all applications

Concrete
Even wider ranges of design criteria can be found for concrete. Table 5.5 shows the ranges of durability requirements for fifteen European countries that participate in CEN (European Committee for Standardization).

Table 5.5 *Ranges of durability requirements in Europe, depending on exposure class [55]*

Exposure	Minimum cover to reinforcement [mm]	Minimum cement content [kg/m^3]	Minimum strength [N/mm^2]
Dry environment	5-20	0-280	20-30
Humid without frost	15-40	200-340	15-35
Humid with frost	15-40	200-380	25-40

The concrete cover, the cement content and the strength requirements show a considerable range. Because the design strength may also differ between these countries, a clear conclusion about minimum cement requirements is not possible on the basis of the data in Table 5.5. It is assumed that on average 10% cement savings are possible through adjustment of the design criteria.

5.4 Less product use for the same product service mix

Two options will be discussed :
- increased building life
- design that matches quality requirements.

A. Increased building life

Materials life can be increased by re-use of complete buildings or by re-use of building elements. The latter option has been discussed in Section 5.3.

This section deals with increased building life. Buildings are demolished for various reasons. Longer life be achieved by construction of higher quality buildings. More expensive and larger residences tend to have a longer life than smaller and simpler ones. Buildings with large open floor areas are more easily adjusted to new user characteristics and desires. Buildings with high quality standards (insulation, noise levels, materials durability) can longer comply with technical standards.

Flexible building design
Re-use of large industrial buildings, storage facilities etc. for residential purposes has been practised in many cities. Building demolition is often a result of lacking comfort or inconvenient lay-out. Such problems can to a large extent be avoided through the use of adjustable constructions. This is one of the main advantages of steel: large spans can be covered without interior load bearing walls. As a consequence, the interior space partition can be easily changed, resulting in a more efficient space use and potentially a longer building life. Large spans without loadbearing pillars can also

be produced with concrete and wood, but at considerable additional cost and high material requirements. Flexible building design seems especially promising for short life buildings like offices, commercial buildings and industrial buildings. It is assumed that a more flexible building design can increase the average building life in 25% of all cases by 25%. As a consequence, the (long-term) saving potential is 19 Mt CO_2[9]. Again, the validity of this figure must be considered from the viewpoint of high uncertainties. Flexible building design will require high quality materials, while the ultimate re-use is still uncertain. Another problem is that how short-term additional emissions must be weighed against (potential) long-term emission reductions.

B. Design that matches quality requirements

More efficient use of office buildings

Buildings are often not used in an economical way. The most striking example are office buildings that are only used during 36-40 hours per week, 10 months per year. If the office worker is often outdoors, the actual use may drop below 10 hours per week. Assuming the use can be upgraded to every day 10 hours per day, this offers a potential for savings in the range of 80-90%. As the office buildings represent 15% of the total new building space and buildings represent tree quarters of the total CO_2 emissions in the construction sector, the saving potential is 30 Mt CO_2[10]. However, one must keep in mind that this option would have far-reaching consequences and will not be implemented just because of CO_2 policies. Office space is a status symbol, beyond the scope of techno-economic optimisation. This option is modeled for 50% of the office space, with a saving potential of 25%.

5.5 Substitution of natural resources

The following options will be discussed in this section:
- slag use instead of cement clinker
- geopolymeric cement
- sustainable wood instead of non-sustainable wood.

Slag use instead of cement clinker

The amount of cement clinker per unit of concrete has been reduced as a result of increased use of supplementary cementing materials like blast furnace slag, fly ash and silica fume. The total amount of supplementary cementing materials that is currently available in Western Europe is analysed in Table 5.6.

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[9] 300×0.25×0.25 = 19 Mt CO_2, based on 300 Mt/year is the CO_2 emission for the whole sector, 25% of all applications, 25% savings

[10] 300×0.75×0.15×0.85, based on: 300 Mt CO_2/year total emission building materials production; 0.75 = three quarters of all buildings; 0.15 = office building fraction of total buildings; 0.85 t CO_2/t cement

Table 5.6 *Availability of supplementary cementing materials in Western Europe [18]*

Type	Amount [Mt/year]	Current application
Blast Furnace Slag	24	Cement, roads
Fly ash	17	Cement, roads, disposal
Pozzolan/Trass	20[1]	Roads

[1] Local availability

Blast furnace slag is used for production of blast furnace slag cement. Fly ash can also be used for cement production. Its chemical composition does however influence the cement properties. Pozzolan and Trass (volcanic ashes) pose an alternative for cement.

The current clinker/cement ratio in Western European cement production (incl. Turkey) is approximately 82% [56]. Cement contains 5% gypsum, the remaining 13% difference between clinker and cement consumption consists of blast furnace slag, fly ash and pozzolan. The use of blast furnace slag is estimated at 11 Mt, fly ash consumption is estimated to be 5 Mt and pozzolan consumption is estimated to be 10 Mt [18]. From an availability point of view, there is still a potential for additional use of all three types of additives (total availability blast furnace slag and fly ash in EU + EFTA is 41 Mt, this suggests a potential of 25 Mt, equivalent to approx. 20 Mt CO_2 emission reduction). Pozzolan can be considered as back-stop option: high availability, but the resources are mainly located in Southern Europe and in Germany. As cement quality depends to some extent on the resource type, cement quality standards can pose a major obstacle. It is assumed at least 50% of the total cement market remains Portland cement.

On the long run, the availability of blast furnace slag and fly ash may decrease. Blast furnace slag and slag from other coal based steel production processes is considered to be suited for cement production. Slag from steel production and from EAF steel production is considered to be unsuited for cement production. As a consequence, increasing DRI use and EAF steel production may decrease the slag availability. With regard to fly ash, CO_2 reduction policies will decrease coal based power production. As a consequence, its availability may decrease significantly. This type of interactions will be analysed on the basis of MARKAL results.

Geopolymeric cement

Plain portland cement contains 65% CaO, the remainder being SiO_4 and AlO_4. This CaO can be substituted by a much smaller amount of Na_2O. The resulting product is called 'geopolymeric cement'. The production process has been described in [18]. Taking the additional energy use for Na_2O production into account, the saving is approximately 0.5 t CO_2/t cement clinker. The soda price is in the range of 100-200 ECU/t. The additional costs, compared to limestone based cement, are 10-20 ECU/t. The emission reduction costs are 20-40 ECU/t CO_2. If it is assumed that geopolymeric cement can be applied in 25% of all cases, the saving potential is $180 \times 0.25 \times 0.5 = 43$ Mt CO_2.

Substitution of non-sustainable wood

Non-sustainable wood can be replaced by substitution with sustainable wood. Especially tropical hardwood has a negative image in most European countries from an environmental point of view. The material is applied for a number of reasons:
- its durability
- its appealing structure
- its low price
- availability of large sizes
- availability in large quantities.

• *Different combinations of criteria are valid for different applications*
Competing options can generally not meet all criteria. E.g. European hardwood types like oak, chestnut, or robinia are significantly more expensive and generally not available in large quantities. Many softwoods cannot meet the durability criteria without environmentally problematic treatment with toxins. For interior decoration, the appealing structure may be a limiting factor. For this reason, a number of improvement options are required to substitute non-sustainable wood, each with special benefits.

• *PLATO*
PLATO (Providing Lasting Advanced Timber Options) is a typical option to substitute tropical hardwood in outdoor applications, where durability is the main criterion. Softwoods are heated for 30 minutes at 200 °C and 25 bar. Lignines are converted into phenoles, hemicellulose is converted into aldehydes. Cellulose is not affected. Because of these conversions, the durability is significantly enhanced. The wood can be formed after the cooking process. It is ultimately dried at 180 °C, where phenoles and aldehydes react to yield a bonding resin. The process is fairly new; detailed data concerning its performance and cost data are still lacking. The process seems in its current state less suited for large wood sizes. data concerning surface quality are lacking. The potential seems limited to 25-50% of all tropical timber applications. The option will be discussed in more detail in a separate volume [57].

• *European hardwoods*
European hardwoods like Oak, Chestnut or Robinia can be used as substitute for tropical hardwoods. Price and availability are generally the main problems. For some outdoor applications, eg in waterworks, oak of lesser quality can be used, which is significantly cheaper. One should add that all three alternatives show for outdoor applications less durability than the tropical hardwood alternatives. The durability class is II (life 15-25 years) vs. durability class I (>25 years) for tropical alternatives like Azobé or Iroko [58]. The price of European hardwoods ranges from 1500 to 2000 ECU/t.

• *Tropical hardwood plantations*
Efforts to plant tropical hardwoods in plantations are currently on their way in countries like Costa Rica. This option can only be applied for certain tree types. Teak is one type that is widely applied. Its structure is favourable for interior decoration, its durability is class II. The expectations concerning wood yield diverge and depend on the soil type,

rainfall and other climatological conditions. A conservative estimate is 100 t roundwood equivalents (r.e.) per hectare in a period of 20 years, an average yield of 5 t r.e./ha per year. Longer periods result probably in higher yields. A problem is that the diameter of the trees after 20 years ranges from 15 to 30 cm. This size is only suited for a limited range of applications. In the long run, this problem can disappear as larger size wood becomes available.

The expectations regarding production costs and product price are also very uncertain [59]. Assuming investment costs of 5000 ECU/ha, the teak production price from plantations is around 100 ECU/t (excluding sawing and transportation costs, additionally 200 ECU/t). Its market value depends to a large extent on the size and quality. This value may range from 100 ECU/t for small sizes with deficiencies to 1500 ECU/t for top quality sawn wood. This should be compared to current prices for tropical hardwoods in the range of 650 (Azobé) to 2000 ECU/t (Iroko) (for prime quality sawn timber). A comparison on a per tonne basis is probably not correct due to different wood densities, but should serve as indication. One should add that this type of resource substitution should be evaluated critically from an environmental point of view in order to avoid introduction of new environmental problems like erosion and ecosystem degradation. In the model calculations, the additional costs of sustainable tropical hardwood are estimated to be 200 ECU/t in 2020 (i.e. the first year such wood can be harvested if the investments are made before the year 2000, but the cost difference decreases to zero in 2050 due to the decreasing availability of non-sustainable tropical timber). A substitution on a weight par basis is assumed.

The CO_2 reduction potential of this option is 60 Mt CO_2 per year[11]. The costs per tonne CO_2 are 26 ECU/t CO_2.

- *Engineered wood products*
  Engineered wood products can serve as substitute for tropical hardwoods in case large sizes are required. Materials costs for large laminated wood substitute beams are 2 times higher than the costs for Azobé.

In conclusion, sufficient alternatives are available for tropical hardwoods. They require however long-term planning. On the short term, careful planning of the use of European wood can alleviate shortages in tropical timber substitutes. The life of substitutes for interior applications is not affected by the durability. For exterior applications, durability of substitutes is generally lower, resulting in a life that is approximately 30% shorter.

Interior substitution takes generally place on a 1:1 weight basis. For exterior applications, substitution of Azobé results probably even in some weight savings. The average saving is estimated to be 20%. As the average life is shorter, additional costs occur for earlier replacement (after 20 years instead of after 30 years). Installation costs are estimated to represent a similar sum to materials costs (2000 ECU/t) [60]. The additional costs must however be depreciated, so they are reduced to approximately 350

[11] $7.5 \times 7.8 = 60$, based on 7.8 Mt/year hardwood consumption; 7.5 t CO_2/t tropical hardwood

ECU/t. Materials costs are thought to be 500 ECU/t higher. The additional costs are thus for indoor applications 500 ECU/t, for outdoor applications 850 ECU/t. The CO_2 reduction is between 1.8 and 5 t/t, the costs for this reduction option are thus between 100 and 470 ECU/t CO_2.

5.6 Substitution of materials

The substitution of materials in buildings can be split into two categories:
1. substitutions of materials in building parts that do not affect the other building elements;
2. substitutions of materials in building parts that do significantly affect other building elements.

The first type of comparison can be used for materials with low weight but high CO_2 emissions per unit of weight. The second type is however far more common. Comparison of materials is not always straightforward. The building life may change due to materials substitution. The dimensions of foundations may change if the weight of walls and floors changes. Moreover, different materials may pose different options for building design. These complications are the reason that proper comparison cannot be made on the level of building parts, but should encompass the whole building system over its whole life. Because a building system can be split into a large number of components like walls, floors, roof, foundations etc., a vast array of combinations can be conceived. It is impossible to study such an array within the framework of this study. However, buildings are generally conceived based on one strategy: a steel frame building, a wood frame building, a brick building, a concrete building. Therefore, the comparison is based on extreme strategies, based on one or two materials. The data for the building systems are based on design studies or based on existing buildings.

5.6.1 Substitution options without secondary effects

Based on the material use data from Chapter 3, the following improvement options can be discerned that may have significant impact on materials use:
- substitution of steel reinforcements by steel fibres, synthetic organic or natural organic fibres,
- substitution of bricks or precast concrete by sand-limestone bricks, gypsum, clay or vice versa,
- substitution of concrete foundations by sand-limestone or brick foundations,
- substitution of insulation materials.

Substitution of steel reinforcements by steel fibres, synthetic organic or natural organic fibres

Steel reinforcement bars and wires are used as concrete reinforcements. The steel increases the bending strength of the concrete (the application is limited by the bending stiffness). With regard to steel, a division is possible between prestressed steel (for floors etc., especially used in prefab constructions) and reinforcements without prestress. As the bulk of the steel reinforcement is used without prestress, only this application will be used for modelling purposes. Other fibres with a high modulus of elasticity and high tensile strength can substitute steel in this application. Several technological problems have up till now limited the wide-spread application of alternative reinforcement materials. With regard to synthetic organic reinforcements, the long term creep of these materials poses a serious problem. Moreover, the rapid strength loss during fires is not acceptable for buildings. The use of synthetic organic reinforcements poses also structural problems. For example expansion due to climatological conditions can result in concrete cracking. With regard to glass fibres, the material cannot straightforward be added to concrete because the fibres would be damaged by the sand and gravel particles, and the high pH in concrete would dissolve the fibres. If the glass-fibres are combined to wires that are protected by coating materials, these problems may be solved. Nevertheless these problems, there is still a lot of research going on regarding the substitution of steel reinforcements. It is thought that these problems may be solved. The current research focuses on carbon fibres; the research regarding Arapree and other plastic fibres decreased in recent years [61].

Moreover, there is an important secondary advantage regarding the substitution of steel reinforcements from a CO_2 point of view. The cement content of concrete serves as a buffer to keep the pH above 10. At these pH levels, the steel reinforcements cannot be oxidised. For other reinforcement materials, oxidation poses no problem. As a consequence, the cement content can be lowered by 50 to 75%.

It depends on the application whether the modulus of elasticity or the tensile strength must be compared. It is likely that deflection, rather than strength, would be the governing criterion for many structures reinforced with non-ferrous material. Based on [62], it is assumed that the bending capacity of the concrete slabs is proportional to the reinforcement capacity and thus proportional to the tensile strength of the reinforcement wire or bars.

In prestressed hollow core concrete slabs, Aramide Prestressing fibres (Arapree) can be used as replacement of steel reinforcements [63]. Arapree consists of bundles of Twaron fibres that are bonded with an epoxy resin. Arapree has a tensile strength of 3000 MPa, vs. 300-500 MPa for steel reinforcement bars. The weight is only 1.25 t/m^3 vs. 7.2 t/m^3 for steel. The material weight saving for equal tensile strength is approximately 95%. However, the price is thirty times as high: 6000 ECU/t vs. 200 ECU/t. The CO_2-emission for Aramide is approximately 5 t/t; for steel, it is 1.5 t/t. The emission reduction costs are : $(6000 \times 0.05-200)/(1.5-5 \times 0.05) = 80$ ECU/t CO_2.

With regard to natural organic fibres, their strength is generally substantially lower than for the other materials (a tensile strength of 100-300 MPa). Their durability is limited, and they cannot withstand alkaline environments and humidity [64]. For this reasons, their application is limited and the long-term durability is still uncertain. They are not considered for further analysis.

There are also developments regarding the use of steel reinforcements. On development is the use of steel fibres in industrial floors. The reinforcement serves in this application as protection against cracks in the floor. The tensile strength is of lesser importance.

If steel fibres are used instead of rebars in concrete floors, less steel is required. The weight reduction is approximately 50%: 100 kg/m^3 vs. 50 kg/m^3 for reinforced floor slabs [65]. Further reductions are being planned, 30 kg/m^3 is currently used in Germany [66]. Undulated wire can improve the anchorage of the wire in the concrete matrix [67]. The concrete slab thickness can be reduced by 25% (from 25 to 20 cm), resulting in additional savings because less cement is used. It is however unclear if the fibres can be recovered in the demolition phase. In the calculations, it is assumed that recovery is not possible. The additional energy for steel fiber production compared to rebar production (approximately 5 GJ/t) is of secondary importance. It is assumed that the option can be applied in 25% of all reinforcement applications.

Substitution of steel wire by ceramic or organic fibrous wire materials

Steel wires are extensively used for their high tensile strength. In the construction sector, bridges are an example where steel wires are applied for tensile strength. Basically, the application is similar to the application of reinforcements. One difference is the absence of high pH values. The substitution may also be more attractive because the control of creep is much easier. In order to assess this option, the tensile strength of different fiber types is compared (Table 5.7).

Table 5.7 *Comparison of wire materials [68, 69]*

Material	Tensile strength [MPa]	Density [kg/m^3]	Equal specific strength [kg/kg steel]	Price [ECU/t]
Steel wire	1800	7800	1.00	200
Kevlar	1600	1440	0.20	2000
Carbon	2600	1750	0.15	3000

These data can be used for all structures where steel wire is used for its strength. In the building and construction sector, this steel application is probably limited to less than 3 Mt steel. The specific CO_2-emission of kevlar and carbon are in the order of 5 t/t material, vs. 1.7 t/t for steel. As a consequence, the saving potential is approximately 3 Mt CO_2[12]. The costs are 450 ECU/t CO_2[13]. These costs may significantly decrease in the next decades when the price of Kevlar and carbon fibres decreases.

Substitution of insulation materials

Different types of insulation materials can be used. Major current types and renewable substitutes are listed in Table 5.8. The data include only

[12] 3×(1.7-0.15×5) = 3

[13] (0.15×3000-200)/(1.7-0.15×5) = 450

substitutes that can be applied as blanket or as package. Loose cast variants like flax and waste paper are not included, but may in certain cases offer potentially higher insulation values at lower costs. These materials require a special structure into which the material can be cast.

The density of insulation materials will also depend on the processability. Low densities are favoured from an insulation point of view, but are often problematic in the building practice, resulting in the use of higher density materials. This problem is more important for mineral wool than for expandable polystyrene (EPS).

Table 5.8 *Insulation materials and sustainable alternatives [70,71,72]*

Material	Heat conductivity [W/m.K]	Density [kg/m^3]	CO_2 emission [t/t]	R=2.5 m^2.K/W [kg/m^2]	Cost [ECU/m^2]
Mineral wool	0.035	16-45	1.5	1.4	5.0
EPS	0.035	25	3.0	2.3	6.7
Hemp	0.064	100	0.5	16.0	7.0
Cotton	0.040	20	2.0	2.0	5.0
Sheep wool	0.034	12.5	0.5	1.1	8.0

Table 5.9 shows that the bulk of the insulation materials that is currently used in Western Europe consists of mineral wool and EPS.

Table 5.9 *Insulation material consumption in Western Europe, 1991 [73]*

Type	[10^6 m^3/year]	[Mt/year]
Mineral wool	52.7	0.8
EPS	20.2	0.5
Poly Urethane	3.5	0.1
Miscellaneous	2.8	0.1

Based on the CO_2 emissions in Table 5.8, the saving potential of renewable insulation materials like hemp and wool compared to mineral wool and EPS is in the range of 2-4 Mt CO_2. Problems regarding the processability and long term stability can pose a significant problem for large scale introduction.

Foundations

Buildings can be founded on concrete, wood, or steel. The choice of foundation material is determined by the soil type, the carrying capacity of the soil, the water level (wood foundations are only possible in case of high water levels) and by the foundation tradition. A large number of foundation types can be discerned that will not be discussed in detail. The bulk of the buildings is founded on concrete. Substitution of concrete by sand-limestone or bricks is an option. The weight is approximately proportional to the specific weight of the material (concrete 2.4 t/m^3, brick 1.8 t/m^3, sand-limestone 1.2 t/m^3). Costs do however differ. Table 5.10 shows material requirements and cost estimates for different alternatives.

Table 5.10 *Foundation material alternatives [74]*

	Weight [t/dwelling]	CO_2 red. [t/dwelling]	Material cost [ECU/dwelling]	Total cost [ECU/dwelling]
Concrete	24	Reference	1800	2000
Brick	18	4.5	2300	3200
Sand-limestone	12	5.4	1450	2200

The cost difference is accounted for by additional material costs (bricks) and by additional labour cost (bricks and sand-limestone). One should emphasize that such a substitution is only possible for a certain fraction of buildings. The costs for emission reduction range from 40 to 265 ECU/t CO_2.

5.6.2 Substitution options with secondary effects

The bulk of the materials are used for the walls and floors of buildings. Two wall structures will be discussed in detail in order to illustrate the scope of designs:
- exterior walls for single family residences
- exterior walls for multi family residences.

The actual MARKAL input will be based on aggregated designs for complete buildings. The aggregated data for the aboveground buildings will be discussed in Chapter 6. In this initial discussion, the secondary effects are neglected. A heavy weight building design requires heavier foundations, but may be beneficial in situations with high cooling energy demand. The actual input data for the MARKAL calculations are based on complete building system designs. The secondary effects will be discussed in Chapter 8.

Outside wall structures for single family residences

Two types of wall structures can be discerned. The first type has an outside cladding layer, outside insulation and an inside wall. The second type is the so-called cavity wall, where the insulation material is put into the cavity between two load carrying walls. The first type dominates eg. in Germany and Switzerland. The second type dominates in e.g. the UK and the Netherlands. Both types can be insulated up to an insulation thickness of 250 mm, well above the current standards. Only the double wall structure will be discussed in order to show the range of improvements.

An outside wall structure consists in both cases of 4 compounds:
1. Outside cladding or outside wall
2. Insulation
3. Inside wall
4. Inside cladding.

Table 5.11 lists wall construction material characteristics per compound (excluding additional structural elements in case of the wood and the PVC structure).

Table 5.11 *Exterior wall construction characteristics (R = 2.6 m^2.K/W) (excluding additional structural elements, based on [75,76])*

Type	Wood	Brick	Sand/lime	Plastic
Outside	Wood 27mm[1]	Brick 100 mm	Sand lime 100 mm	PVC 5 mm[1]
Insulation[2]	100 mm	100 mm	100 mm	100 mm
Struct. elements	Wood	No	No	Steel
Inside cladding	Board 25 mm[3]	Brick 100 mm	Concrete 100 mm	Gypsum 15 mm
Timber [kg/m^2]	35	-	-	-
Board [kg/m^2]	20	-	-	-
Brick [kg/m^2]	-	370	-	-
Steel [kg/m^2]	-	-	-	5
Concrete [kg/m^2]	-	50	280	-
SL-stone [kg/m^2]	-	-	180	-
Gypsum [kg/m^2]	18	-	-	25
PVC [kg/m^2]	-	-	-	7
Insulation [kg/m^2]	10	10	10	10
Tot. wght. [kg/m^2]	78	430	470	47
CO_2 [kg/m^2]	25	70	90	35

1 Additional 30 mm particle board
2 Mineral wool
3 Additional 15 mm gypsum for fire protection

Data in Table 5.11 show significant weight differences between wall constructions, ranging from 47 to 468 kg/m^2. Assuming an outside surface area of 6×10×6 = 360 m^2, the weight of the building walls ranges from 20 t to 175 t.

The brick and the concrete walls require no additional vertical loadbearing construction. The wood wall and the PVC wall (type 1 and type 4) require additional loadbearing structures.

The CO_2-emissions in Table 5.11 should be considered as crude estimates. The differences suggest lower CO_2-emissions for the wood structure and the steel structure than for the traditional brick and concrete structures.

Outside wall structures for multi-family dwellings

Table 5.12 lists material characteristics for non-loadbearing exterior wall characteristics, suited for residential multi-family and non-residential buildings. The inside cladding consists either of concrete or of sand-limestone. Steel and aluminium outside cladding are technologically feasible, but public acceptance poses a problem for the residential market. For the office building market, metal cladding poses an attractive option that is widely applied.

Table 5.12 *Characteristics for non-loadbearing exterior walls ($R = 3.6\ m^2.K/W$) [77]*

Material	Concrete type [kg/m^2 wall]	Brick type [kg/m^2 wall]	Plastic type [kg/m^2 wall]	Al type [kg/m^2 wall]
Steel	13.2	15	7.9	10
Aluminium	-	-	-	27.3
Brick	-	165	-	-
Concrete/mortar	180	28	-	-
Acryl stucco	-	-	6.0	-
Polystyrene	3.8	-	-	-
Gypsum	11.8	19.8	19.8	10.0
Fibreglass	-	5.4	3.6	5.4
Paint	0.4	0.4	0.4	0.4
Total	209.2	233.6	37.7	53.1
CO_2 [kg/m^2]	70	60	40	300[1]

[1] 40 kg/m^2 if secondary aluminium is considered

The figures for both wall types show that a difference of a factor 2-4 exists between the wall design with the highest CO_2 emission and the design with the lowest emission. Based on the data in Chapter 2, it is assumed that a total wall surface of 500 million m^2 is built per year. This suggests a technical saving potential in the range of 25 Mt CO_2 per year for walls alone. This is a crude estimate that does not account for potential differences in service life, recycling credits etc..

5.7 Summary of improvement options

The improvement options that have been discussed in this Chapter can be aggregated in order to show their contribution to the total emission reduction and their cost-effectiveness (Table 5.14). Because of the interaction of options, the figures in the list cannot be added straightforward. Many of the listed options may also be implemented in a situation without CO_2 emission reduction policies, because they are cost-effective or will become cost-effective.

For example, increasing average materials quality and improved product design are currently already actively pursued by the construction industry because they (potentially) increase the productivity. Increased product life and materials substitution in buildings is on the other hand less attractive from a construction industry point of view. These options might be pursued by the customers, but are often not taken into account by the industry and may pose a significant potential for policy making. Table 5.14 provides an overview of the improvement options. One should add that the figures represent the short-term technical improvement potential, based on the current reference energy and materials system.

Table 5.14 *Potential contribution of improvement options on the long term (current European reference energy and materials system)*

	Potential[1] [Mt CO_2 pa]	Range [Mt CO_2]	Cost range [ECU/t CO_2]	Status
1. Less natural resources				
A. Increased recycling				
- wood fiber cascading	30[1]	20-40	100-250	feasible
- asphalt recycling	0.7	0-1	1000	problematic
B. Improved collection systems				
- demolition waste separation and recycling	9.5	5-20	100	problematic
2. Less materials				
A. Product part re-use	30	10-50	540	problematic
B. Improved product design				
- re-design of buildings with the same materials	30	10-100	0-1000	feasible
C. Less materials losses in production				
- reduced losses of wood-type materials	2	1-3	-500-500	problematic
D. Increased average materials quality				
- engineered wood products	4	2-10	200	feasible
- high strength reinforcement steel	4	2-6	390	feasible
- high strength concrete	30	20-40	0-350	feasible
- hollow bricks	2	1-4	0	problematic
E. Less spread in materials quality				
- prefab concrete	4	2-6	0-500	problematic
F. More diverse standardisation				
- steel	6	4-8	0	problematic
- concrete	20	10-30	-50-0	problematic
3. Less products				
A. Increased product life	19	10-50	0-1000	problematic
B. Design that matches quality requirements				
- more efficient use of office buildings	30	25-35	-500-500	problematic
4. Substitution of natural resources				
- slag cement instead of PC	20	10-30	25-100	feasible
- geopolymeric cement	23	10-30	20-40	problematic
- sustainable instead of non-sustainable wood	60	0-100	25-500	feasible
5. Materials substitution				
- steel reinforcements	10	5-20	80	problematic
- steel wire	3	2-4	450	feasible
- substitution of structural materials (Chapter 6)	75	50-100	-100-1000	feasible
- substitution of insulation materials	3	2-4	100	problematic
- foundations/cellars	10	5-15	50-100	problematic
Total emission from construction materials	275-408			
Total W-European CO_2 emission	3500			

[1] The potentials should be considered as high estimates. All materials production in the reference situation is based on primary production with high specific CO_2 emissions (see Table 3.1). With regard to biomass, it is assumed that biomass availability poses a long term supply problem (because of the competition with energy production). Potentials in this

table cannot be added as the options interact. Some emission reduction, e.g. in the case of substitution of non-sustainable timber, is accomplished abroad.

There is both considerable uncertainty regarding the emission reduction potential and considerable uncertainty regarding the costs. These uncertainties are caused by the technological characteristics of the reference situation and the improvement option, by the development of resource prices and by the development of labour costs. The emission reduction potential for substitution of structural materials in Table 5.14 is based on the analysis in Chapter 6.

The calculation of the contribution of options is based on a comparison of a business-as-usual scenario (existing production processes, constant recycling rates, negligible re-use, constant materials quality, no substitution), for the year 2000. Current reduction and long-term impacts are separately listed. The current impacts refer to the current year, the long term impacts refer to the next 100 years. The long term impacts include the effects of increased or decreased recycling. On the longer term, there may be also significant impacts (eg concrete carbonation), but given the time horizon of the greenhouse effect, consideration of this long term seems less relevant. Because of the strong interaction between emission reduction in materials production and emission reduction through materials substitution, the estimates in Table 5.14 should be considered as high estimates.

The characterisation as ’problematic’ and ’feasible’ indicates the barriers for introduction because of building regulations, hidden technological barriers, public acceptance and acceptance within the current building culture.

5.8 Main strategies for emission reduction

The options from Table 5.14 can be further aggregated. An aggregation per strategy type is shown in Table 5.15. The aggregation shows that the total emission reduction potential considerably exceeds the total emissions. The interactions of improvement options will significantly reduce the potential of individual options. Based on a cost-effectiveness criterion of 100 ECU/t CO_2, all strategies seem to some extent cost-effective. The order of magnitude of emission reduction is the same for all strategies. It is not sensible to select one single strategy for policy making. Instead, a mix of options from al types of strategies will be required.

Table 5.15 *Aggregated contribution of improvement options per strategy type*

	Potential[1] [Mt CO_2 pa]	Range [Mt CO_2]	Cost range [ECU/t CO_2]
1. Less natural resources	40	25-61	100-250
2. Less materials	132	62-257	-500-1000
3. Less products	49	35-85	-500-1000
4. Substitution of natural resources	103	20-160	20-500
5. Materials substitution	101	64-143	-100-1000

Another type of subdivision is shown in Table 5.16. The options are categorised per actor. These data suggest architects, the building materials industry and the building industry as key actors in the chain. Each actor can be linked to different types of strategies, an issue that will be elaborated in a separate MATTER study [78].

Table 5.16 *Aggregated contribution of improvement options per actor*

	Potential[1] [Mt CO_2 pa]	Range [Mt CO_2]	Cost range [ECU/t CO_2]
Architects	79	45-185	-500-1000
Building materials industry	163	45-220	0-400
Building industry	103	65-132	-500-1000
Demolishers	70	35-110	100-1000
Legislators	26	14-38	-50-0

6. MODELLING MATERIALS SUBSTITUTION

Materials substitution requires an in-depth analysis of building structures in order to quantify substitution coefficients. The analysis in Chapter 5 was mainly based on a materials point of view, while the analysis in this chapter uses a product point of view. This chapter is structured according to construction types. Apart from buildings (Section 6.1), only roads will be discussed in more detail (Section 6.2). The goal of this chapter is to provide some insight regarding the variation in material requirements per unit of floor surface. These data serve as background for future sensitivity analyses.

6.1 Buildings

The whole building above ground will be considered as one ‘black box’, characterised by a certain materials choice. Substitution between e.g. single family residences and multiple family residences is an improvement option with major social consequences that exceeds the scope of this study and will not be included as improvement option. Office buildings, industrial and agricultural warehouses and residences all show particular characteristics and cannot be aggregated fruitfully. The following building types will be considered separately:

- single family residences
- multi family residences
- factories, warehouses and agricultural buildings
- office buildings and other governmental buildings.

For each building category, one type is modeled, characterised by a certain number of floors, a certain floor area and a certain loadbearing capacity per floor area. The general outline of the building types is shown in Figure 6.1. These buildings represent a wide array of building structures. The different building types that are modeled provide insight into the sensitivity of materials substitution for building characteristics.

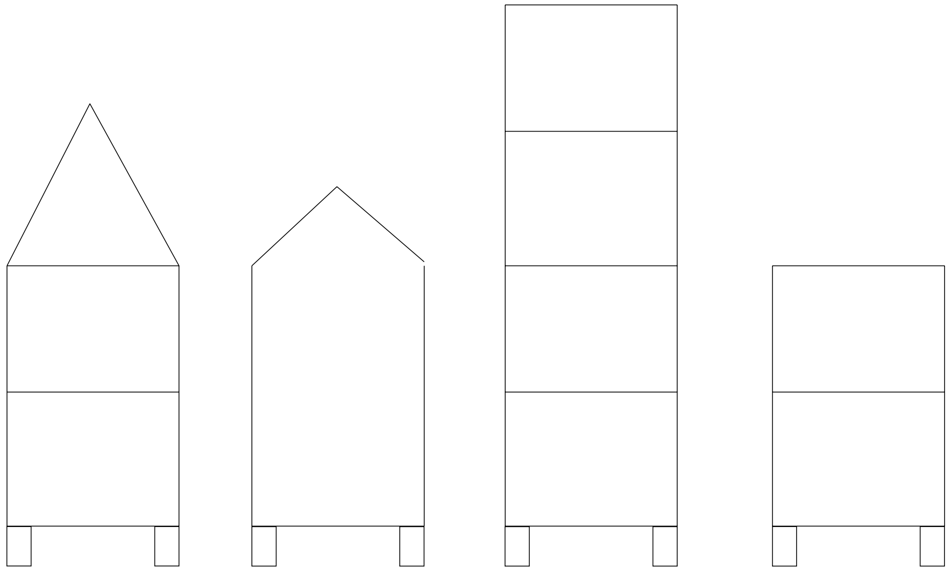

Figure 6.1 *Building structures*

The materials requirements will be expressed per square metre floor area. This will result in a dataset that allows a comparison of the materials requirements of different building types. Unfortunately, the data situation is not good. Data are available for individual cases, thorough studies about material requirements of buildings and constructions have not been encountered.

Two types of secondary effects of materials substitution will be considered. The first one is the interaction between the building weight and the foundation requirement. The second one is the interaction between the building weight and the heating and cooling energy demand in different regions. These secondary effects are discussed in Chapter 8.

6.1.1 Single family dwellings

Aggregated material requirements of buildings

Table 6.1 lists building material alternatives for typical New Zealand single family residences. The residence has a floor space of 94 m^2. The bottom section consists of a concrete slab on sand or a suspended timber floor, so no extensive foundations are included.

Table 6.1 *Building material requirements for different single family residences (New Zealand, including slab foundation) [79]*

Building part	Concrete/timber type	Total timber type	Concrete/steel type
Framing	Timber	Timber	Steel
Floor	Concrete	Timber	Concrete
Wall cladd.	Concrete block	Weatherboard	Brick veneer
Roof	Corrugated iron	Concrete tile	Corrug. iron
Material	[kg/m^2]	[kg/m^2]	[kg/m^2]
Wood materials	37	72	16
Steel (struct. + reinf.)	20	2	35
Concrete	575	170	383

Data for other types of single family residences are shown in Table 6.2, Table 6.3 and Table 6.4. These data are based on European designs. The data in Table 6.2 refer to terraced residences in the Netherlands. Data in Table 6.3 refer to Austrian detached single family residences. Data in Table 6.4 refer to Swedish detached single family residences. The comparison of data shows higher concrete requirements for the building designs in Table 6.2 and 6.3 that can be related to the additional foundations. Especially the concrete requirements for the additional basement in Table 6.3 are substantial. The datasets in Table 6.2 and 6.3 show the significantly reduced weight in case a wood frame construction is applied.

Table 6.2 *Building material requirements for different single family residences (Netherlands, including foundation, based on 120 m^2 useful floor area) (based on [80,81])*

Building part	Concrete/brick type	Wood frame
Framing	Brick	Timber
Floor	Concrete	Timber
Outside clad.	Brick	Timber
Roof	Clay tiles	Concrete
Material	[kg/m^2]	[kg/m^2]
Wood materials	23	80
Steel (struct. + reinf.)	19	3
Concrete	712	90
Brick	75	6
Gypsum	34	100
Sand-limestone	261	-
Heating [GJ/m^{2}pa]	0.28	na

Table 6.3 *Building material requirements for single family residences, Austrian situation [kg/m^2] [9]*

Material	Wood frame	Solid wood	Brick
Basement			
Reinforced concrete B25	657	653	657
Above ground			
Concrete B225	-	-	80.5
Concrete B15	-	-	70.0
Concrete blocks	45	40	44.5
Gypsum	17.5	-	35.0
Gypsum fibreboard	123	31	10.5
Hollow bricks	-	-	467.0
Timber	94	268	50.7
Mineral wool	7	4.8	2.3
Mortar	-	-	62.7
PE-foil	0.9	0.9	0.1
EPS	2.5	1.3	1.7
Particle board	8.7	7.8	-
Steel	4.0	3.2	15.3
Heating [GJ/m^{2}pa]	0.336	0.347	0.336

Table 6.4 *Building material requirements for single family residences, Swedish situation [kg/m^2] [82]*

Material	Type 1	Type 2	Type 3
Concrete	231	341	214
Gypsum	34	33	30
Roof tiles	60	62	61
Wood products	97	70	78
Plastics	6	7	4
Glass	3	2	3
Steel	3	6	2
Heating [GJ/m^{2}pa]	0.27	0.30	0.23

The data from Table 6.2, 6.3, and 6.4 will be used for the model because they refer to the actual European situation. The foundation and cellar requirements will be added separately.

6.1.2 Multi family dwellings and office buildings

Multi family dwellings and medium rise office buildings are similar in design. For this reason, they are treated together. Table 6.5 shows the material requirements for a five storey office building. The building size is 8568 m^2.

Table 6.5 *Materials requirements for a precast concrete and a steel structure medium rise office building (concrete cladding, incl. raft slab foundations, excl. interior decoration/hardware) [kg/m²] [79]*

Material	Concrete type	Steel type
Wood	10[1]	1
Steel (struct. + reinf.)	62	89
Concrete	1188	712

[1] Includes boxing

Table 6.6 shows the material requirements for a five storey office building, where the first two storeys serve as car park The total building floor area is 2400 m^2.

Table 6.6 *Materials requirements for a concrete and a timber medium rise office building (incl. foundations, excluding non-structural elements) [kg/m²] [79]*

Material	Concrete type	Timber type
Wood	0	55
Steel (struct. + reinf.)	37	11
Concrete	640	100

Table 6.7 shows the materials requirements for a six storey hostel. The total building size is 4032 m^2.

Table 6.7 *Materials requirements for a concrete and a timber structure hostel (including foundations) [kg/m²] [79]*

Material	Concrete type	Timber type
Wood	39	80
Steel reinforcements	22	9
Concrete	760	311

The data in Table 6.8 illustrate that the materials requirements depend to a large extent on the building height. The higher the building, the more material is required for the columns that support the weight. As a consequence, data can only be compared for buildings of similar height.

Table 6.8 *Comparison of different steel/concrete composite buildings [kg/m²] [83]*

Material	Type 1 12 floors	Type 2 5 floors	Type 3 5 floors
Steel (columns)	48	19	16
Steel (beams)	59	53	50
Concrete (columns)	150	25	21
Concrete (beams, est.)	300	300	300

The comparison of the data in Table 6.5-6.9 shows that the concrete requirements range from 325 to 1188 kg/m^2. Increased concrete use is balanced by decreased timber use and steel use. A concrete type, a steel type and a timber type multi family dwelling and office building will be modeled.

6.1.3 Factories, warehouses and agricultural buildings

Two New Zealand building types have been analysed. One is an auction hall of 2766 m^2, the other is a factory of 9995 m^2. Data concerning materials use are shown in Table 6.9 and Table 6.10. Note that the wall and floor structures are in both cases similar. The structural elements that are substituted constitute only a small weight fraction. However the difference is more important from an energy/CO_2 point of view.

Table 6.9 *Comparison of wood and steel frame auction hall (concrete floor, precast concrete wall, steel cladding/roof) [kg/m^2] [79]*

Material	Wood type	Steel type
Engineered wood products	8	0
Sawn timber	9	0
Steel (struct. + reinf.)	19	40
Concrete	450	450

Table 6.10 *Comparison of a wood frame and a steel frame factory (concrete floor, concrete brick wall, steel cladding/roof, excluding foundations) [kg/m^2] [79]*

Material	Wood type	Steel type
Engineered wood products	8	0
Sawn timber	8	0
Steel (struct. + reinf.)	13	36
Concrete	435	435

Data in Table 6.11 are based on a Dutch design study for industrial buildings. The aboveground section of the improved buildings can be dismantled and rebuilt elsewhere. Moreover, the heating energy requirements of the improved buildings is substantially reduced.

Table 6.11 *Comparison of three factory buildings [kg/m^2] [84]*

Material	Steel type	Improved 1	Improved 2
Above ground			
Concrete	286	336	336
Cement	2.6	2.6	2.6
EPS	2.8	6.8	6.1
PVC	1.9	7.0	0.1
Other plastics	0.3	0.3	0.9
Steel reinforcements/floor	2.5	20.1	20.1
Steel structural	44.1	72.1	50.5
Zinc	0.8	1.0	0.4
Aluminium	0.1	0.1	5.1
Particle board	3.1	-	-
Glass	0.4	0.4	0.4
Adhesives+coatings	0.7	0.3	-
Foundations			
Concrete	36.0	-	-
Steel (incl. reinforcements)	1.0	3.2	-
Heating energy [GJ/m^2]	0.308	0.179	0.179
Cost price materials [ECU/m^2]	71	83	115
Cost price assembly [ECU/m^2]	18	18	18

Comparison of the data in Table 6.9-6.11 shows actually little variation in material requirements for the steel type building. Concrete requirements range from 322 to 450 kg/m^2. Steel requirements range from 40 to 47.6 kg/m^2. A steel type and a wood type will be fed into the model. Moreover, the data in Table 6.11 will be used to model industrial buildings with longer useful life due to the potential for dismantling.

6.2 Road constructions

Heavy traffic roads and light traffic roads are separately modeled. Apart from traditional bitumen based asphalt pavements, materials like waste elastomers, waste plastic, and sulphur can also be used as bonding agent (see e.g. [85]). The application of these materials makes only sense from a CO_2 point of view if they require considerably less energy for production and if other applications exist for bitumina (currently a residual product from refineries). Given the slowly increasing C/H ratio of crude oil and the still significantly increasing demand for transportation fuels (with low C/H ratio), such a situation is not very likely. The energy demand for production of the bonding agents is in all cases low. Substitution of bonding agents is not further considered.

In Nordic countries, softer bitumen types (heavy oils) are used than in more Southern countries. The selection of the typical construction is of course very often an economic one. Minimised maintenance costs determine the optimal construction at average traffic densities above 600 passenger vehicles per day.

For high volume roads (highways etc.), an asphalt type and a concrete type will be modeled as alternatives. Data are shown in Table 6.12. The data refer to a 2-lane highway in the Netherlands, with 2 lanes of 11 metres width. Based on these data, a low volume road has also been modeled (see Table 6.12).

Table 6.12 *Material requirements for roads (based on [86])*

Material	High volume Asphalt type	High volume Concrete type	Low volume Asphalt type
Construction			
Asphalt [t/km road]	16,500	2,200	2,000
Bitumen [GJ/km road]	500	445	100
Cement [t/km road]	-	2,500	-
Steel [t/km road]	-	40	-
Transportation [GJ/km road]	15,000	15,000	2,500
Maintenance			
Asphalt [t/km road pa]	180	-	18
Cement [t/km road pa]	-	5.4	-

The use of sand and gravel for road bases and for concrete production, and the transportation on-site of soil and sand constitutes a certain CO_2 emission because of the transportation energy. An energy balance for a Belgian highway is shown in Table 6.13. Based on these data, the additional energy use for transportation in Table 6.13 has been estimated. In [86], the transportation energy is estimated to be 86,000 GJ/km for the concrete road and 14,000 GJ/km for the asphalt road. This difference can be explained by the assumption that the concrete road production uses low volume trucks, with a much higher energy consumption per tonne. However, as the bulk of the transportation energy is for soil movement for the road base, it is assumed in this study that the figure is the same for both high volume road types. The author in [86] acknowledges that the results regarding transportation overestimate the energy use.

Table 6.13 *Energy balance for the construction of a Belgian highway [85]*

	[GJ/km road]
Transportation of soil, sand and gravel	14,000
Reinforced concrete	12,000
Asphalt	20,500
20 years maintenance	1,000
Total	37,500

7. THE CONSTRUCTION PROCESS AND THE DEMOLITION PROCESS

Energy consumption in the building process

Energy use for various processes during the erection of buildings is listed in Table 7.1.

Table 7.1 *Energy use (primary energy) for various processes during the erection and demolition of buildings, Danish conditions [87]*

	[GJ/t]
Drying of standard concrete on building site	0.16
Drying of concrete element	0.09
Excavation and soil removal	0.08
	[GJ/m^2 useable floor area]
Lighting of construction object	0.09
Heating of construction object	0.09
Heating of sheds	0.05
Total	0.23

Diesel and electricity are the main energy carriers that are used. The total energy consumption for the building erection is in the range of 5-10% of the energy use for the building materials in the Danish conditions (see Chapter 1). This value excludes the building material transportation. This transportation accounts for 5-10% of the manufacturing energy for each construction material [87].

Building and Demolition waste

Few data are available concerning materials losses during the construction process. Two types of data will be discussed: bottom-up estimates from certain building projects and aggregated data from waste statistics. Table 7.2 lists data for the Netherlands, for the UK, and for Sweden. Notwithstanding the different period, the amounts are similar.

There seem to be significant differences in construction waste amounts during building processes. The design of the building project is important: if its sizes correspond to the standard building material sizes, the amount of waste is significantly reduced. Industrial standardised production results generally in less waste than unique building projects. Increased standardisation has not been considered as improvement option because of the current trend for individual design.

The amount of waste varies also per (group of) materials. For wood for example, the waste for wood studs and board materials is in the order of 10%, while the amount for engineered wood products waste is between 0 and 2% [88].

The amount of concrete waste in case of ready mixed concrete consist of returned concrete and truck washouts, amounting to a total of 2% of the concrete [89]. A German source indicates 2.5% waste for ready mix, a similar figure [90]. Ready mix concrete is nowadays in Germany often delivered in silos, which can be used at other sites of a surplus is delivered. This reduces the waste on site significantly. The amount of waste is smaller for precast elements because it is a factory bound operation with more process control (1-2% waste). The Swedish figures for concrete waste seem in comparison rather high.

The other materials in Table 7.2 will not be discussed in more detail.

Table 7.2 *Materials losses during construction [91,92,87]*

	Netherlands 1990 [%]	UK 1975 [%]	Sweden 1983 [%]
Concrete	4	8	10-20
Bricks	10	10	10
Metals	5	5	5
Plastic	7	n.a.	5-10
Wood	5	15	7-10
Glass	n.a.	9	0

An important category of building waste consists of packaging materials. These are not considered in this product group but in the separate product group packaging. An second important group is scaling material in case of on-site cast concrete. Wood is generally used for scaling purposes, sometimes plastic or metal scaling is used. The scalings are often multiple use in case of large, standardised building projects, but may be one-way in case of small, special constructions. In [90], the amount of scaling for a large building is estimated to be 2.4 m^2 per m^3 concrete. Assuming a wooden scaling with a thickness of 2 cm, the amount of material is 0.05 t/m^3 concrete. Assuming that the average scaling is used 5 times, the amount of scaling in Europe is 7 Mt per year[14]. The amount seems significant. Detailed data concerning the use of one-way and multiple-use scalings are not available.

Out of the total amount of construction and demolition waste, approximately 60% consists of concrete and bricks. The total of 225 Mt in Table 7.3 should be considered as a crude estimate. The range is ±50%. Approximately one third of this amount are building wastes, the remainder are demolition and renovation wastes. The main problems are the definition of waste (including polluted soil, removed soil etc.) and the definition of building and demolition (including or excluding civil engineering projects, roads etc.).

The 225 Mt building waste (excl. excavated earth and road pavements) can be compared to the materials consumption in Chapter 2. Assuming that the

[14] 675×0.05/5 = 7, based on 675 Mt on-site cast concrete, 50 kg wood/t concrete, 5 times re-use

cement content of concrete is 15% on average, the total building materials consumption, based on Table 2.1, is approximately 1450 Mt (excluding bitumina for roads). This indicates that the stock increase of materials in buildings and constructions is still 85% of the annual material consumption. This figure is well in line with the top-down estimates in Chapter 2 that were based on the building statistics. It does however also indicate that the estimates for building waste in Table 7.2 are rather high. For this reason, they will be reduced to 5%.

Table 7.3 *Construction and demolition waste arisings [90,93,94,95]*

	[Mt pa]
Belgium	7.8
Denmark	2.0
France	23.9
Germany	40.0
Netherlands	13.0
Switzerland	7.1
UK	50.0
Total	143.8
Western Europe	225

8. SECONDARY EFFECTS OF BUILDING MATERIAL SUBSTITUTION

8.1 The interaction between building weight and foundation requirements

Many types of foundations can be discerned, ranging from bearing piles that are founded in stable soil to strip foundations, pad foundations and raft foundations. Strip foundations are the most common type for Western European single family dwellings. This is the only type that will be included in the model. The foundation size depends on its construction, the construction weight, the soil type and the climatological conditions. In case a cellar is built, no additional foundations are required.

Rock, gravel or consolidated clay require less extensive foundations than peat or alluvial clay soils. The bearing value of soils can range from 25 (alluvial clay) to 5000 kN/m^2 (solid rock) [96]. Sand and gravel have a bearing value in the range of 100-800 kN/m^2. In case of a total building weight of 200 t (2000 kN), the required minimum foundation size ranges from 0.4 m^2 to 80 m^2. Table 8.1 shows the minimum strip foundation width according to the UK standards. The foundation width is not only determined by the loadbearing capacity of the soil, but also by the material quality and e.g. a minimum cover for steel reinforcements. In the Netherlands, the minimum width of strip foundations is in practice 2-2.5 times the width of the wall.

Table 8.1 *Minimum width of strip foundations for different soil types [mm width] [97]*

Soil type	Load 16 kN/m	Load 32 kN/m	Load 64 kN/m
Loose gravel/sand	300	600	-
Compact gravel/sand	225	300	600
Very soft clay	450	900	-
Firm clay	260	375	750

However the foundation width is often not determined by the bearing capacity of the soil but by the minimum width in which the bricklayer can lay the footing courses (450 mm). The width of the wall is also a limiting factor for the foundation width. For a heavily insulated wall, this width can even exceed 450 mm. As a consequence, the amount of foundation material exceeds the minimum requirements from a loadbearing point of view to a considerable extent.

The foundation requirements are a function of the size of the horizontal loadbearing beams that support the wall. The stronger these beams are, the larger the minimum distance of the vertical foundation beams.

The foundation depth is determined by the structure and the material properties. In the case of concrete, reinforcements are generally added to prevent cracking. These reinforcements reduce the minimum depth. Generally a safety factor of 2 or 3 is applied for the minimum foundation size. The minimum depth of foundations is 80 cm in the Netherlands. This prevents freezing of the ground below the foundation, as subsequent thawing can cause damage. In other climatological conditions, the minimum depth differs.

Most settlements are built at locations with soils with low bearing capacity. In the model it is assumed that the load bearing capacity of the soil is 100 kN/m^2 in 75% of the building locations and 1000 kN/m^2 in 25% of the building locations. A safety factor of 2 is assumed for building contents, wind forces etc.. The foundation material is reinforced concrete, thickness 25 cm. The minimum width is 45 cm. Table 8.2 lists for the reference single family dwelling the material requirements for foundation.

Table 8.2 *Foundation requirements [t concrete/building] for single family residences for different design weights*

Soil strength [kN/m^2]	100		1000	
	75% of all cases		25% of all cases	
Building weight	Foundation		Foundation	
[t]	[t]	[kg/m^2]	[t]	[kg/m^2]
50	8.6	60	8.6	60
100	12	85	8.6	60
200	24	170	8.6	60
300	36	260	8.6	60

The figures in Table 8.2 show that significant savings in foundation materials due to light weight construction are only possible in the case of low soil strength. The foundation weight increases proportional to the building weight in the weight range of 100-300 t, but is limited by the minimum width at lower weights. For stable soils, the building weight has no influence on the foundation weight.

Table 8.2 shows that 250 t weight reduction results in 25 t foundation weight reduction, representing a saving of approximately 5 t CO_2. This should be compared to the total CO_2-emission for the building in the range of 20 - 50 tonnes. This comparison shows that the secondary effect of reduced foundation weight can be substantial.

The analysis is further complicated by the thermal mass of the foundation. This mass can also be used for energy storage. This option has not been considered in the analysis. The impact of the above ground thermal mass is considered in the analysis. This effect is discussed in Section 8.2.

8.2 The interaction between building weight and energy use for heating and for cooling

Data in Chapter 1 showed that the direct energy consumption for heating and cooling is significantly higher than the indirect energy demand for the construction process and for building materials. The choice of materials can influence the direct energy consumption. Such interactions require special care because relatively small increases in direct annual CO_2 emissions can outweigh large gains in materials related CO_2 emissions.

The concrete industry states that concrete buildings show additional thermal mass, which reduces heating and cooling energy demand. The wood industry states that wooden buildings are better insulated, which results in even lower heating energy demand. Both statements will be addressed in this chapter.

Both issues require an analysis of direct energy consumption, which depends on climate conditions and building standards. The analysis starts with the analysis of regional differences in direct energy use.

Climate and building standards

A key variable for direct energy use is the climate. Three regions are discerned in the model: North, Middle and South. Each region has a different climate and consequently different heating and cooling requirements. Even within regions, considerable differences in heating energy demand for reference buildings (20-30%) exist between sub-regions, caused by temperature, wind and sunshine variations (see Figure 8.1).

However, building standards do also differ between regions. This is also shown in Figure 8.1, where the annual heating energy demand of a reference building according to different building standards is compared. Data are shown for the North (Lund and Oslo) and the Middle (Munich, Essen, Hamburg, Frankfurt) region. The figures show that the heating energy demand is the lowest in the North region (Sweden) with the harshest climate. This remarkable feature is caused by the more rigid insulation standards in the North region. The same feature is illustrated in Figure 8.2, where the energy efficiency standards of a number of Western European countries are compared. Unfortunately, data for the same building for the South region are not available.

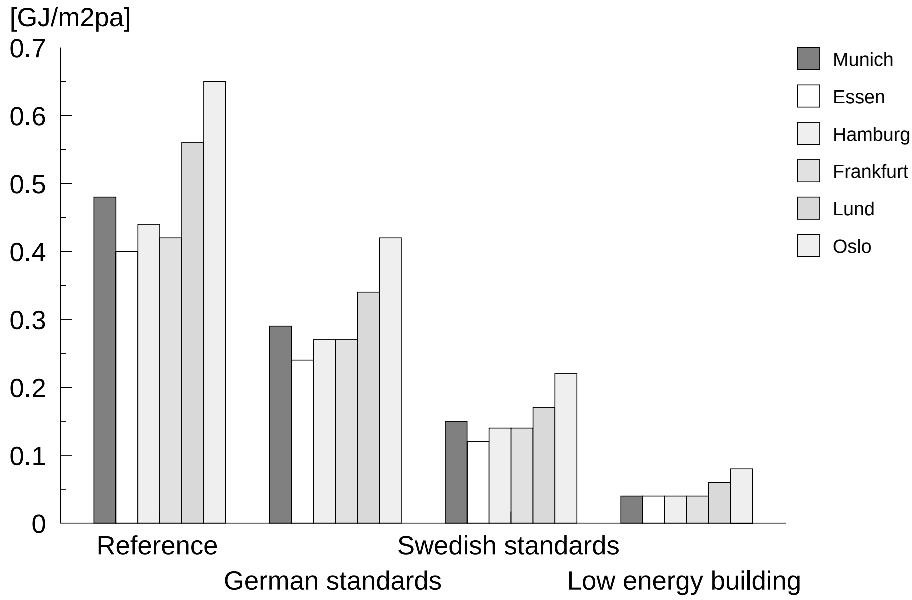

Figure 8.1 *Annual heating demand for 4 single family dwelling types at 6 different locations (German standard pre 1994) [102]*

The data refer to a dwelling in the middle of a row, 7.2×10.2 m inner size, 2 storeys, flat roof. Data for single family residences and multi-family residences show on average per unit of floor space other direct energy consumption (20% higher and 20% lower, respectively).

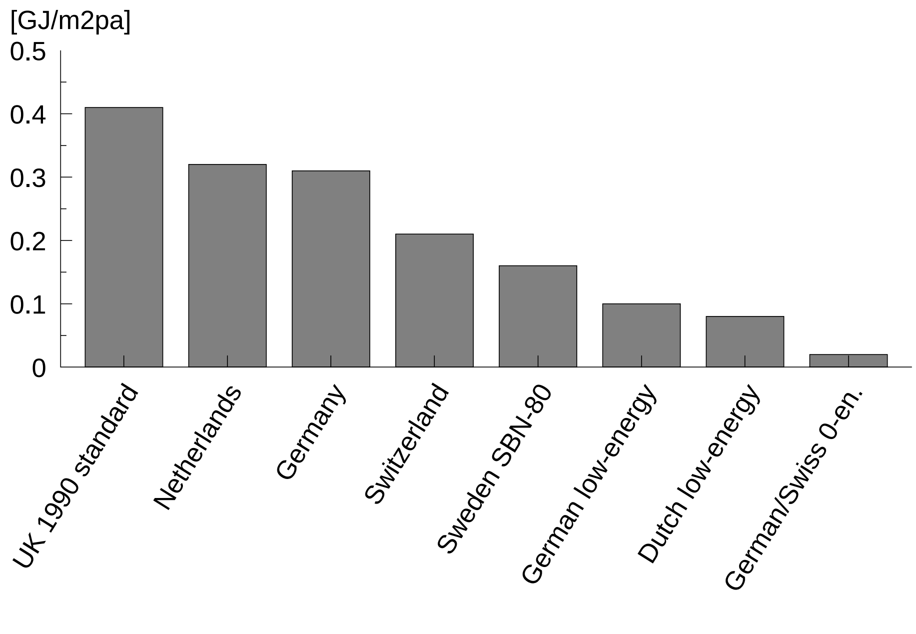

Figure 8.2 *Annual space heat consumption per unit of floor area according to different national energy efficiency standards and low energy alternatives, central UK climate conditions, situation 1992 (excluding Sweden, 1980 standards)*

Energy consumption of dwellings depends also to a large extent on the dwelling use. A dwelling that is heated day and night requires considerably more energy than a dwelling that is heated during the day or only during the evenings. The difference is in the order of 60-70%. This impact is significant, but it is hardly feasible to account for such differences in the actual building design process. Due to changing lifestyles (longer holidays, second residences etc.), the average heating energy demand may structurally change per building type. Such structural changes are not considered in the analysis. Average values of heating energy demand per building type will be used in the MARKAL analysis.

Direct building energy use

The energy consumption is highly dependent on the building type. Heating energy consumption data for average conventional buildings are shown in Table 8.3. The figures show a considerable difference between solitary dwellings and dwellings with less outer wall area. The bulk of the energy losses occur through ventilation. For the German dwellings in Table 8.3, the losses through ventilation are 59.4% for the solitary dwelling and 75% for the other two dwelling types. The remainder of the losses are transmission losses. These figures are important because they indicate that efforts to reduce direct energy consumption should focus on ventilation losses instead of increased insulation. Changing insulation has generally impact on materials consumption, changing ventilation has little or no impact on materials use.

Table 8.3 *Final energy use for heating different dwelling types [GJ/m²a] [98,99]*

	Netherlands, post 1981[1]	New, Germany
Solitary dwelling	0.49	0.32
2-Family dwelling	0.49	na
Row of dwellings	0.40	0.24
Multi-family	0.42	0.22

1 Based on 120 m^2 for solitary dwellings, 90 m^2 for row dwellings, 65 m^2 for multi-family dwellings (based on [100])

Three climate zones are modeled in MARKAL (North, Middle, South). The heating energy demand for these zones is compared in Table 8.4. The impact of the climate zone on the direct energy demand is very apparent. The impact of building materials choice on heating and cooling demand will differ per region.

Table 8.4 *Heating and cooling energy demand for three climate zones [GJ/m^{2}a] [101]*

Type	Zone	Heating	Cooling (est)	Total
Civic building	North	3.06	0	3.06
	Middle	2.34	pm	2.34
	South	0.72	0.25	0.97
Nixdorf office	North	0.36	0	0.36
	Middle	0.18	pm	0.18
	South	0.00	0.25	0.25
Grammar school	North	1.44	0	1.44
	Middle	0.90	pm	0.90
	South	0.18	0.25	0.43
Admiro warehouse	North	2.34	0	2.34
	Middle	1.62	pm	1.62
	South	0.54	0.25	0.79

Thermal mass

Thermal mass is often mentioned as a variable that depends on the building material characteristics, and deserves further attention, as it may influence energy use for both cooling and heating. This variable will be included in the analysis.

Thermal mass of buildings can influence direct energy use because it serves as cooling medium during the summer day, so cooling energy can be saved. On the other hand, additional thermal mass requires additional energy for heating in the winter, if the building is heated separately.

The impact of thermal mass is the highest for buildings with high direct energy consumption. The study shows for the reference building in Frankfurt in Figure 8.1 3.5% less energy consumption for a residence with 55 t additional mass in the form of interior walls. The reference building consumes 0.42 GJ/m^2 pa. For buildings with low direct energy consumption (<0.25 GJ/m^2 pa), the impact of thermal mass is small [102].
Other data concerning the impact of thermal mass are shown Figure 8.3. A light building is made from wood or plastic/steel, a middle weight building is made from gypsum and sand-limestone, a heavy weight building is made from concrete or (double wall) bricks. The thermal mass is only relevant if it is applied within the outside insulation: heavier external walls outside the insulation layer have little impact on the direct energy use.

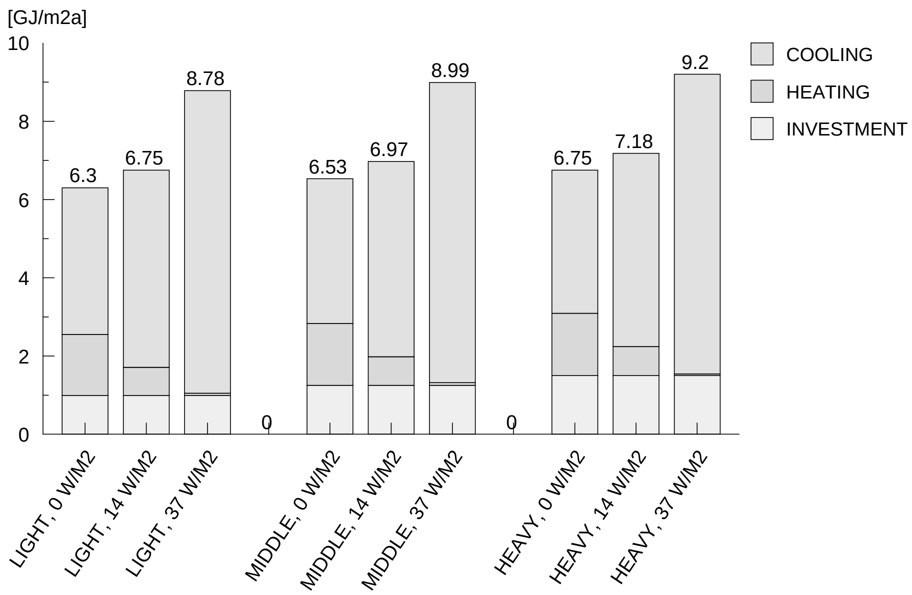

Figure 8.3 *Direct primary energy use for different building weights, office buildings, Dutch situation, with 3 levels of internal heating load [103]*

The difference between the direct energy use may seem small, but if a ratio of direct and indirect energy use of 10:1 is assumed, a 4% advantage in direct energy use for the heavy building represents 40% of the indirect energy use. These differences must be accounted for in order to achieve a valid comparison. They will be included in the MARKAL calculations.

The impact of thermal mass depends also to a large extent on the climate. The same building requires in the North more heating than in the South. Conversely, the same building requires more cooling in the South than in the North. This is illustrated with US figures in Table 8.5, where the reduction in space heating and space cooling is illustrated. Data refer to a Ranch type building (floor area 110 m^2) at different sites in the USA. It is assumed that similar climates do occur in certain regions of Western Europe (e.g. in parts of Spain and Italy).

The reference building in Table 8.5 has wooden walls, the alternative building has a 0.12 m thick masonry wall as interior wall. Partition walls were made from wood in both cases. The difference in building weight is approximately 13 tonnes (120 kg/m^2).

Table 8.5 *Reduction in space heating requirements due to heavier construction, Ranch type residence, USA [104]*

Location	Reference heating load [GJ/m^{2}a]	Reduction [%]	Reference cooling load [GJe/m^{2}a]	Reduction [%]	Reference primary [GJ/m^{2}a]	Reduction Primary[1] [%]
North						
Madison, WI	0.51	1.0	0.10	9.3	0.76	3.7
Central						
Washington, DC	0.26	1.7	0.20	3.1	0.76	2.6
South						
Lake Charles, LA	0.063	11.7	0.34	2.4	0.91	3.0
Los Angeles, CA	0.021	36.0	0.12	12.3	0.32	13.8
Charleston, CA	0.098	9.9	0.27	3.1	0.77	4.0

[1] Assuming 40% efficiency in electricity generation

In order to show the sensitivity of assumptions regarding building characteristics, data in Table 8.6 show the impact of thermal mass on the same Ranch type US house on the same location, but with a window area increased from 13% to 15% of the floor area, and the entire window opening placed on the South.

Table 8.6 *Reduction in space heating requirements due to heavier construction, High Solar Gain Ranch type residence*

Location	Reference heating load [GJ/m^{2}a]	Reduction [%]	Reference cooling load [GJe/m^{2}a]	Reduction [%]	Reference primary [GJ/m^{2}a]	Reduction Primary[1] [%]
North						
Madison, WI	0.48	2.5	0.12	11.7	0.78	6.0
Middle						
Washington, DC	0.24	4.7	0.23	5.2	0.82	5.0
South						
Lake Charles, LA	0.058	20.3	0.39	4.0	1.03	4.9
Los Angeles, CA	0.018	58.3	0.21	11.6	0.54	13.2
Charleston, CA	0.086	19.9	0.32	6.2	0.89	7.5

[1] Assuming 40% efficiency in electricity generation

The relative savings for the High Solar Gain residence are higher than for the reference residence. Such differences will not be accounted for, because only one single family residence will be modeled per region. A sensitivity analysis can be applied to study the impact of a variable heating energy demand.

In Appendix 1, the impact of the thermal mass on different building types is analysed in more detail for the Dutch situation. The results show that heavy inside structures and light outside walls are favoured for residences (the outside structure refers to the walls inside the insulation layer, the walls outside the insulation are irrelevant). Regarding the offices, the optimal solution depends on the use of cooling in the summer. If no cooling is applied, the best solution is a light outside structure and a heavy inside structure. In the situation with cooling, a combination of heavy inside structures and heavy outside structures is favoured.

The air tightness of different buildings

Literature sources indicate that the average air infiltration rates in ‘heavy, wet’ constructions (in-situ cast concrete) are lower than in ‘light, dry’ constructions (timber, masonry) [105]. This feature depends however to a large extent on the workmanship. It is possible to construct masonry and timber buildings with similar airtightness characteristics. For this reason, this difference is neglected in the analysis.

The wood industry argues often that their buildings show better insulation (lower U-values) than the reference buildings. This depends of course on the measures that are included in the structure. It is possible to insulate concrete or brick buildings to the same extent as wooden frame buildings. This implies however additional costs compared to the reference building (200 mm insulation and upwards). In order to achieve a balanced comparison, buildings with similar insulation characteristics are compared.

8.3 The modelling of secondary effects in MARKAL

Both the interaction between building weight and foundation weight and the interaction between building weight and thermal mass will be considered in MARKAL. Table 8.7 shows the model input data for different building types in the three regions North, Middle and South. These data are based on the forecast future aggregated energy consumption of buildings [106] and the development of the building stock. For industrial buildings, heating has been neglected.

Table 8.7 *Secondary effects for new buildings in MARKAL, 2020*

Building type	Location	Heating Final energy [GJ/100 m^2]	Cooling Final energy [GJe/100 m^2]	Foundation Sand/rock [t concrete]	Foundation Clay/peat [t concrete]
SF dwellings					
Heavy type	North	26	-	10	25
	Middle	19	-	10	25
	South	16	-	10	25
Light type	North	28	-	10	15
	Middle	20	-	10	15
	South	17	-	10	15
MF dwellings					
Heavy type	North	22	-	10	25
	Middle	20	-	10	25
	South	11	-	10	25
Light type	North	22	-	10	25
	Middle	21	-	10	25
	South	11	-	10	25
Office buildings etc.					
Heavy type	North	45	-	10	25
	Middle/small	60	20	10	25
	Middle/large	90	20	10	25
	South	20	40	10	15
Light type	North	47	-	10	15
	Middle/small	63	25	10	15
	Middle/large	94	25	10	15
	South	22	50	10	15

9. COSTS

9.1 General cost analysis

Production costs can be divided into fixed costs and variable costs. Fixed costs contain the interest of capital and the depreciation of production installations and other costs that depend on production capacity instead of actual production. Variable costs contain the labour costs, energy costs and materials that depend on actual production. The construction costs are dominated by labour costs. Table 9.1 shows for example a subdivision of production costs in the Dutch residential and non-residential building sector for 1991. The bulk of the payments to subcontractors are also labour costs. What is called materials in this table consists for a large part of semi-finished building products, where significant labour costs are added to the materials from primary production, so the dependence on labour costs is even higher.

Table 9.1 *Production costs in the Dutch residential and non-residential building sector, 1991 [107]*

Category	Amount [10^6 ECU pa]	Fraction [%]
Labour	8,989	23
Payments to subcontractors	12,970	34
Materials	11,296	30
Energy	62	0
Other	5,017	13
Total production	38,334	100

Differences in labour costs dominate construction cost differences. Table 9.2 takes the construction costs as indicator for the variation in national building characteristics. The figures indicate differences in building costs of a factor 2-3.

Table 9.2 *Construction costs of newly built subsidized rental dwellings (houses) per m² in 1991 and average size of new dwellings (1992) [11]*

	Construction cost Single family residence [ECU/m²]	Average size [m²]
Belgium	829[1]	82.1
Germany	983[1]	97.9[4]
Spain	534[1]	68.0
France	804[2]	96.9
Portugal	357[3]	84.0
United Kingdom	587[3]	69.0

1 Including land and value added tax
2 Including land, excluding value added tax
3 Excluding land, including value added tax
4 Former Western Germany

These cost differences can mainly be attributed to the different labour costs. This is illustrated in Figure 9.2, where the correlation between labour costs (including wages, additional costs and indirect costs) and the construction costs from Table 9.2 are shown.

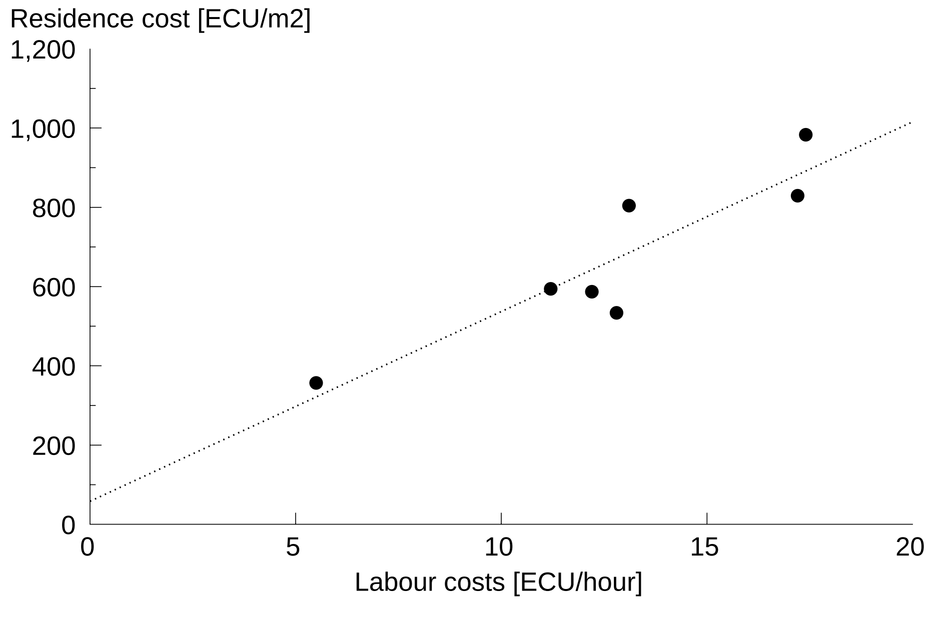

Figure 9.1 *Relation between labour costs and building costs*

Figure 9.2 shows a cost breakdown for a conventional single family residence (140m², the Netherlands). A conventional dwelling requires 814 labour-hours a 21.4 ECU per hour, a total of 17,400 ECU labour costs. Total costs are 57,150 ECU (1990 situation) [108, 81], so labour costs represent 14% of total costs. Land costs amount to 9,500 ECU (200 m² a 48 ECU/m²). Taxes amount to 17.5% VAT (only on building costs, not on land costs), thus 7,620 ECU. Profits and additional costs (architect, interest during the building period etc.) are 8,100 ECU. The remainder (18%) are characterised as material costs (14,300 ECU).

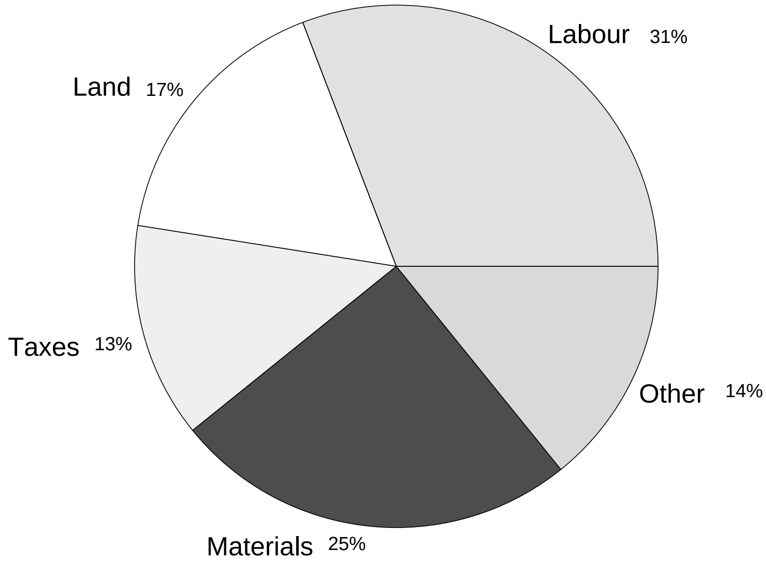

Figure 9.2 *Building cost structure [81]*

Combination of Figure 9.1 and 9.2 shows the importance of labour costs and the limited importance of material costs in the total construction costs. As a consequence, the impact of changing materials use on labour costs requires special attention, because small changes in labour costs can off-set large changes in material costs.

Materials costs for different structural materials are shown in Table 9.3. These costs include the transportation costs to the building site and exclude the processing costs on the building site. The data should be considered as indication. For example the value of bricks can significantly differ due to quality differences.

Table 9.3 *Materials and assembly costs (delivered, Netherlands, december 1995) [109]*

Bricks outside wall	[ECU/m^2]	27	
Bricks inside wall	[ECU/m^2]	13	
Cement (Portland/Blast furnace)	[ECU/t]	100	
Concrete cast-on-site (excl. reinf.)	[ECU/t]	75	
Concrete blocks outside wall	[ECU/m^2]	11	
Concrete blocks inside wall	[ECU/m^2]	40	
Concrete cellular inside wall	[ECU/m^2]	11	
Concrete hollow deck	[ECU/t]	100	
Construction steel	[ECU/t]	738	
Gravel	[ECU/t]	12	
Gypsum blocks	[ECU/t]	120	(11 ECU/m^2)
Mineral wool (100 mm)	[ECU/m^2]	6	
Roof tiles ceramic	[ECU/m^2]	14	
Roof tiles concrete	[ECU/m^2]	7	
Sand	[ECU/t]	8	
Sand-limestone outside wall	[ECU/m^2]	12	
Sand-limestone inside wall	[ECU/m^2]	8	

Apart from the construction costs, a life cycle cost approach for buildings provides again different insights. Total construction costs for the Dutch single family residence are approximately 57,150 ECU. Maintenance costs (excluding heating systems) are approximately 310 ECU per year. Assuming a building life of 75 years, the accumulated maintenance costs are 23,200 ECU. The demolition costs (assuming disposal) are 180 tonnes times 48 ECU per tonne, i.e. 8,570 ECU. Maintenance costs and demolition costs must be discounted for proper assessment. The discount correction after 75 years (assuming 5% interest rate) is $0.95^{-75} = 0.02$. Total life cycle costs are analysed in Table 9.4. The table shows that the life cycle costs are dominated by the construction costs. Maintenance and demolition costs constitute only 10% of total costs, if they are properly discounted.

As CO_2 emissions are in MARKAL valued according to their marginal costs, they are discounted with the same interest rate as capital costs. As a consequence, advantages in the demolition stage are of limited consequence in the life cycle assessment. The optimal solution will be heavily affected by the emissions in the construction stage. This characteristic is special to this type of long life products, and should be borne in mind in the analysis: easy recycling is no major benefit from a building lifecycle point of view.

The discounting approach yields considerably different results than the analysis without discounting. This should be borne in mind if MARKAL results are compared to e.g. LCA analyses of buildings. LCA methods use no discounting method. As a consequence, they value CO_2 emission reduction in later periods much higher.

Table 9.4 *Life cycle costs of Dutch single family dwelling (size 140 m^2)*

	Amount [ECU/m^2]	NPV[1] [ECU/m^2]
Construction + land	410	410
Maintenance	75 year × 2.2	41
Demolition	61	1.2
Land sale	-68	-1.4
Total		450.8

[1] NPV = Net Present Value = discounted value (5% interest rate)

Table 9.5 provides a cost analysis for the building sections of the Dutch single family residence.

Table 9.5 *Cost analysis for Dutch reference residence (140 m^2) [110]*

Element	Cost [ECU/m^2]	[%]
Foundation	26	5.9
Frame	41	9.3
Roof	49	11.1
Outside walls	26	5.9
Inside walls	35	8.0
Floors	21	4.8
Stairs	8	1.8
Roof decks	3	0.7
Window frames\doors\painting	33	7.5
Installations	46	10.5
Terrain	68	15.5
Additional	83	19.0
Total	439	100.0

Table 9.5 shows that the costs for materials intensive building elements (foundations to window frames) represent 55% of the total building cost. These elements can be analysed in more detail in order to show the fraction of actual building material costs for these elements. The material costs are in this case represented by the cost of materials from the factory (excluding transportation costs). These costs are shown in Table 9.6.

Table 9.6 *Building material costs (single family residence, brick walls, precast concrete floor, excluding installations/kitchen etc.)*

Assembly	Amount	Price	Materials cost [ECU/m^2]	Fraction of building element costs [%]
Foundation				
Reinforced concrete	150 kg/m^2	75 ECU/t	11	42
Frame				
Sand-limestone inside wall	52 m^2	13 ECU/m^2	5	
Storey floors concrete	75 m^2	75 ECU/t	19	59
Roof				
Roof tiles cement	90 m^2	7 ECU/m^2	5	
Outside cladding				
Brick outside	26 m^2	27 ECU/m^2	5	
Sand limestone inside	26 m^2	13 ECU/m^2	3	31
Inside walls				
Sand limestone inside	57 m^2	13 ECU/m^2	5	
Gypsum walls	200 m^2	5 ECU/t	1	17
Floors				
First floor	46 m^2	75 ECU/t	13	62
Stairs wood	2×200 kg	500 ECU/t	1	56

The figures in Table 9.6 indicate that the building material cost fraction differs significantly per building part. The building parts with a high fraction of materials costs are most affected by building materials price increases due to CO_2 reduction policies. Such an analysis, based on earlier MARKAL results for the Netherlands, is discussed in Chapter 10.

In order to provide some insight in the impacts of building type on construction costs, some building types are compared in Table 9.7. The differences in construction costs are mainly caused by the different shapes of the buildings. The spread in total building costs in Table 9.7 is relatively small. One should keep in mind that the costs in Table 9.6 do not encompass the total building costs. This is evident if the building costs for single family residences in Table 9.5 and Table 9.7 are compared.

Table 9.7 *Building costs comparison for different building types [ECU/m^2] [111,112]*

Element	Single Family	Multi family	Factory	Office (est.)
Foundation	26	15	30	20
Frame[1]	41	47	35	45
Roof	49	1	28	5
Outside cladding	26	23	32	25
Inside walls	35	32	-	30
First floor	21	10	30	10
Stairs	8	4	-	5
Roof decks	3	6	-	5
Windows/doors/paint	33	43	10	40
Total	242	181	165	185

[1] Storey floors, dwelling separation walls

9.2 MARKAL cost input data

Based on the analysis in the preceding paragraph and additional data for other materials, reference technologies and improvement options can be characterised. Labour costs are modeled as separate input variable for later sensitivity analysis. The costs refer to the construction costs, excluding materials costs, excluding land costs, excluding additional costs and excluding VAT. Because product parts are not separately modeled in MARKAL, labour and capital costs include production of prefab elements from the constituting materials.

Table 9.8 *Building construction costs [ECU/m^2]*

	Labour	Other	Total
Single family residence			
Reference brick/sand-limestone	125	50	175
Wooden frame	150	50	200
Steel frame	100	50	150
Multi family residence			
Reference brick/concrete	100	50	150
Wooden frame	125	50	125
Steel frame	85	50	135
Factories			
Reference steel frame	50	25	75
Concrete	75	25	100
Wooden frame	75	25	100
Office buildings			
Reference concrete	100	50	150
Steel frame	75	50	125
Wooden frame	110	50	160

The data in Table 9.8 should be considered as crude estimates, considering the significant spread of construction types in each group and considering the spread of labour costs in Western Europe.

10. LIFE CYCLE ANALYSIS

The direct and indirect CO_2 emissions of buildings can be analysed, based on the current building design and the current reference energy system. This life cycle analysis provides insight into the impact of materials choice, heating systems and building life on the life cycle CO_2 emissions. Input data for this calculation are shown in Table 10.1.

Table 10.1 *Direct final energy consumption of buildings [GJ/m^{2}a]*

	North	Middle	South
Single family dwellings	0.20	0.35	0.10
Multi family dwellings	0.15	0.25	0.08
Factories	0.05	0.10	0.00
Office buildings	0.40	0.40	0.40

Different building materials options that have been compared are shown in Table 10.2

Table 10.2 *Materials requirements for different building options (excl. foundations) [kg/m^2]*

	Wood	Steel	Concrete
Single family dwellings			
Heavy	37	20	575
Middle	16	35	383
Light	72	2	170
Multi family dwellings			
Heavy	10	62	1188
Middle	1	89	712
Factories			
Heavy	0	40	450
Middle	17	19	450
Office buildings			
Heavy	20	30	700
Light	55	11	100

The assumptions regarding the impact of the building weight (thermal mass) on the direct energy requirement is shown in Table 10.3. In all cases, it is assumed that heavy buildings show a reduced energy consumption. This assumption is biased in favour of heavy buildings, as the data in Appendix 1 show that light outside structures reduce the direct energy consumption for buildings without cooling system. However, heavy inside structures reduce the energy consumption for all buildings and are thought to dominate the total building weight. The interaction between the weight of the aboveground construction and the foundation requirements is not considered in this analysis.

Table 10.3 *The impact of the building weight on the direct energy requirement [-]*

	Light	Middle	Heavy
Single family dwellings			
North	1.02	1	0.98
Middle	1	1	1
South	1.01	1	0.99
Multi family dwellings			
North	1.02	1	0.98
Middle	1.02	1	0.98
South	1.02	1	0.98
Factories			
North	1	1	1
Middle	1	1	1
South	1.02	1	0.98
Office buildings			
North	1.03	1	0.97
Middle	1.03	1	0.97
South	1.05	1	0.95

Table 10.4 shows the specific CO_2 emissions per material. Different criteria have been used to establish the minimum and the maximum estimate. For steel, minimum and maximum estimates refer to scrap recycling and production from ore, respectively. For concrete, the use of Portland cement and blast furnace cement determines the maximum and minimum estimate, respectively. For wood, the minimum and maximum estimate respectively include and exclude CO_2 storage in wooden products.

Table 10.4 *Specific CO_2 emissions per material [t CO_2/t]*

	Minimum	Maximum
Concrete	0.2	0.9
Steel	1.0	1.7
Wood	-1.5	0.3

The direct energy consumption can be translated to CO_2 emissions if data are available how the building is heated. This ranges from electric heating (in countries with nuclear and/or hydropower) to natural gas, fuel oil and coal based heating systems. The specific CO_2 emission for the heating system ranges accordingly from 0 t CO_2/GJ to 0.094 t CO_2/GJ. The sensitivity of the total CO_2 emissions for the energy carrier for heating is shown in Figure 10.1.

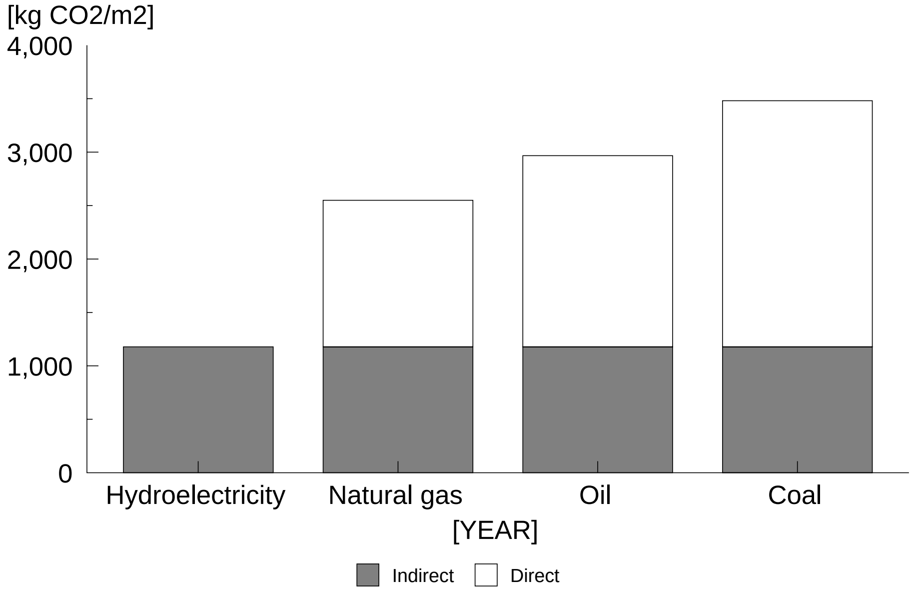

Figure 10.1 *Total CO_2 emissions for different heating systems, multi-family residence, middle region, high emission estimate, 100 years*

Figure 10.2 shows the accumulated direct and indirect energy consumption for the reference residence as function of time. The data refer to the middle region. Both the low and the high estimate for the indirect energy consumption are shown. It is assumed that the heating system is based on natural gas. Note that one minimum estimate starts in year 0 with a net carbon storage in wood.

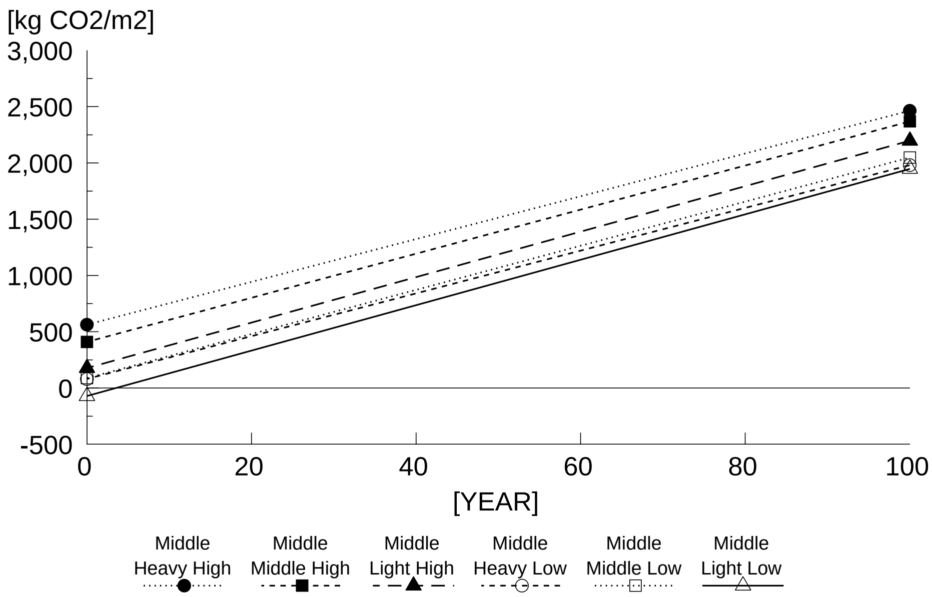

Figure 10.2 *Aggregated CO_2 emissions for the single family residence, heavy middle and low weight buildings, gas fired heating system*

The figure shows the highest aggregated CO_2 emissions for the heavy building design in case of the high estimate (Portland cement). In case of the low estimates, the difference after 100 years becomes rather small: the gains in direct energy consumption due to increased thermal mass compensate the increased indirect energy demand. Note also that the high estimate for the light (wooden) dwelling (assuming no CO_2 storage) and the low estimate for the concrete dwelling (blast furnace cement) favours the concrete dwelling.

Figure 10.3 shows the impact of the region on the total CO_2 emissions. The data refer to the multi-family dwelling according to the newest standards, which are more strict in the North than in the Middle region. For this reason, the total CO_2 emission is higher for the Middle region building. Note that the middle weight building is in all cases better than the heavy weight building. This conclusion remains valid (but to a lesser extent) for the low emission estimates (not shown).

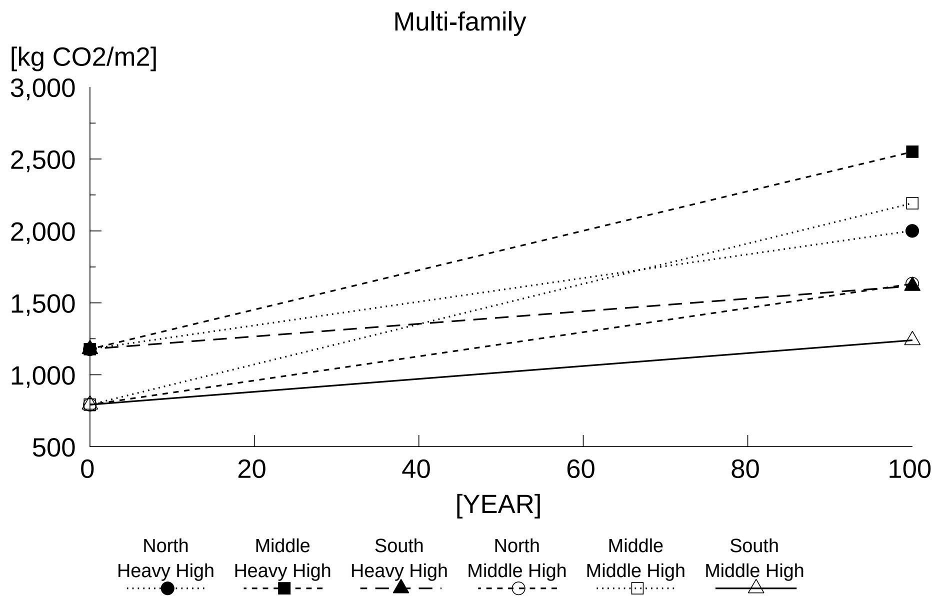

Figure 10.3 *The impact of the region on total CO_2 emissions, multi-family dwelling, heavy and middle weight buildings, gas fired, high emission estimate*

The optimal strategies may be influenced by the thermal mass effect. This impact is analysed in Figure 10.4. For four building types in the middle region, the relation between direct and indirect emissions is shown. The diagonal lines indicate a constant CO_2 emission. It is clear from the figure that the light weight solution is favoured in all cases. Only significantly higher direct CO_2 emissions (coal or bad insulation) can reverse the conclusion that the light weight solution is favoured. It seems quite viable to conclude that the light weight solution should be aimed for in the next decades. Note also the significant range of the ratio of direct and indirect CO_2 emissions in Figure 10.3: from 20 for the light weight office building to 1.3 for the factory building.

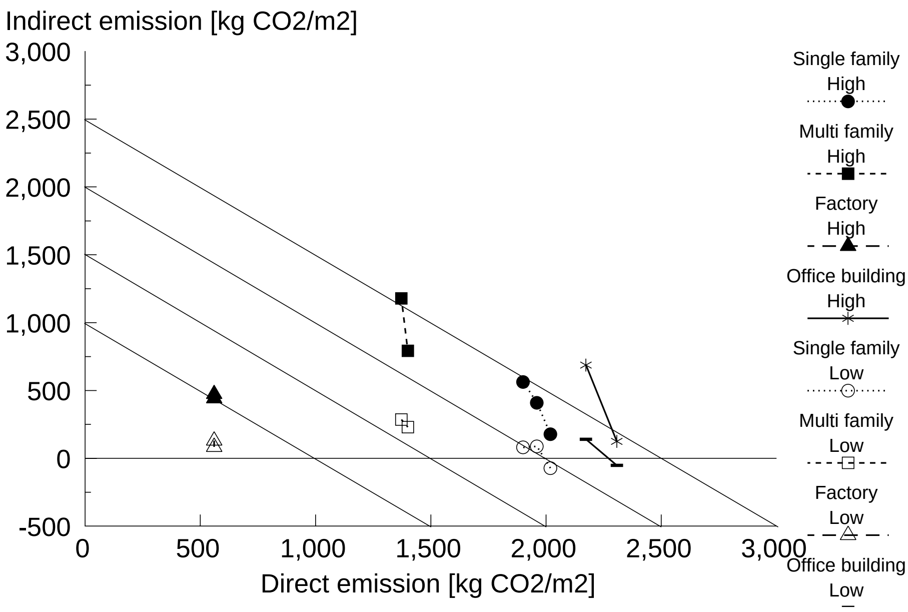

Figure 10.4 *The relation between direct and indirect CO_2 emissions, middle region, high and low emission estimate, gas fired, 100 years*

The conclusions can probably change favourably for cement if CO_2 removal and disposal or high strength concrete solutions can be found. On the other hand, improved cascading and energy recovery systems for wood must be considered for the competing options.

10.1 The impact of CO_2 policies on the building cost

Figures 10.1-10.3 show that a maximum CO_2 emission reduction can be achieved below 1 t/m^2. The value of such a saving is 50 ECU if a CO_2 penalty of 50 ECU/t CO_2 is assumed. This represents 5-15% of the current average construction costs per m^2 (see Table 9.1). The additional costs of substitution must be below this value to allow such substitution to take place.

The cost-effectiveness of the proposed measures depends on the reference situation. A static analysis is not meaningful because of the changing reference situation. Data from the integrated MARKAL energy and materials model for the Netherlands will be used to illustrate the impact of CO_2 policies on building costs. They can provide an indication of the effects in the Western European situation. Table 10.6 shows the price increase of materials due to 60% CO_2 reduction.

Table 10.5 *Price increase due to CO_2 reduction, 2025 (Netherlands, high economic growth scenario, no nuclear energy, including CO_2 storage option)*

	Base case 0 ECU/t CO_2 [ECU/t]	-60% CO_2 100 ECU/t CO_2 [ECU/t]	Increase [%]
Cement	68	87	28
Concrete	32	37	16
Bricks	60	77	28
Sand-limestone	25	35	40
Gypsum	138	142	4
Hardboard[1]	934	989	6
Sustainable timber[1]	387	387	0
Non-sustainable timber[1]	705	1690	120
Steel	355	485	36
Aluminium	1665	3335	100
Polyolefines	860	965	12

[1] No CO_2 storage is modeled

The comparison of price increases in Table 10.5 shows that the competitive position of non-sustainable timber is most affected, followed by aluminium. The significant price increase for sand-limestone is caused by the related inorganic CO_2 emissions and its relatively low price.

The price increase of the materials reflects the price increase in a perfect market economy where CO_2 emissions are internalised in the prices, and CO_2 emissions are reduced by 60% in 2030 compared to the 1990 emission level. This reduction equals a long-term CO_2 emission penalty of 110 ECU/t CO_2. The price increase is not the only relevant variable in the optimisation: if eg the emissions in the use phase are influenced by the materials choice (like for many building types, see the preceding paragraph), a life cycle approach is required. If this is not the case, the price increase of the materials is an indicator of the impact on the impact of CO_2 emission reduction on the competitiveness of materials. E.g. the competitiveness of steel compared to aluminium increases, wood becomes more competitive compared to concrete, concrete becomes more competitive compared to bricks. This does not imply that substitution is attractive. Materials processing into products and the substitution coefficient for materials must be considered for comparison of functional units. Table 10.6 shows the impact of CO_2 reduction on the current building practice in the Netherlands, divided into different building parts. In Table 10.6, the materials price increase (Table 10.5) is compared to the building materials costs (Table 9.5) and to the building part costs (based on Table 9.4, including construction costs).

Table 10.6 *Price increase for building elements due to CO_2 penalty 110 ECU/t*

Assembly	Materials [ECU/t]	Materials price increase [%]	Building part price increase [%]
Foundation			
Concrete	5	7	3
Reinforcements	130	36	6
Frame			
Sand-limestone inside wall	10	11	6
Storey floors concrete	5	7	4
Reinforcements	130	36	9
Roof			
Roof tiles cement	5	7	4
Roof trusses	0	0	0
Outside cladding			
Brick outside	17	11	5
Sand limestone inside	10	11	3
Inside walls			
Sand limestone inside	10	11	5
Gypsum walls	5	100	4
Floors			
Concrete floor	5	7	3
Reinforcements	130	36	2
Stairs wood	0	0	0

Table 10.6 shows that the price impact of such a significant CO_2 emission penalty is limited. The price increase for building parts ranges from 0 to 9 %. Reinforcements and heavy structural elements are most affected.

Similar values can be generated for the whole sector. The CO_2 emission is approximately 300 Mt (Table 3.1), the turn-over is 600 billion ECU (Table 2.1). As a consequence, a CO_2 tax of 100 ECU/t CO_2 will result in an average price increase of 5% for the whole building and construction sector. This value is in the range of the values for individual building elements in Table 10.6.

It remains to see if such a limited price impact poses sufficient incentive for materials substitution. The impact of CO_2 emission reduction is much more significant in the energy system (energy prices are multiplied by 2 or more). An active search for win-win situations (CO_2 emission reduction and reduced building costs) and an active R&D policy seems a better strategy than a focus on taxes and subsidies to achieve a changing materials consumption in the building and construction industry.

11. CONCLUSIONS

The construction sector is an important sector from a materials consumption point of view. Significant CO_2 emissions can be contributed to the production of these materials. The estimates range for Western Europe range from 275 to 410 Mt CO_2 per year, representing 8-12% of the total CO_2 emissions in this region. The construction sector represents approximately one tenth of the Western European Gross Domestic Product.

The energy consumption for heating and cooling of buildings causes currently approximately one third of the total CO_2 emissions in Western Europe. This value can indicates the relative importance of the direct CO_2 emissions (heating and cooling) compared to the indirect CO_2 emissions (due to building materials production). The ratio of direct and indirect CO_2 emissions is approximately 3:1.

Within the construction sector, the ratio of indirect and direct CO_2 emissions does significantly differ for different products. A significant fraction of the building materials is used in applications where the direct CO_2 emissions are negligible, like in civil engineering and for storage facilities. For heated buildings, the ratio of direct and indirect CO_2 emissions is in the range of 5:1 - 10:1. This ratio will change in the next decades as the heating energy demand is gradually reduced due to improved insulation. As a consequence, the relative importance of building materials for the CO_2 emissions this sector will further increase.

The indirect CO_2 emissions encompass the emissions related to the fossil energy for production of building materials, the inorganic CO_2 emissions from cement clinker production and the CO_2 released during non-renewable wood production. The most important materials from a CO_2 point of view are cement, wood products, steel, bricks, sand-limestone, aluminium, plastics, and asphalt.

The data availability regarding the material flows and the product characteristics is problematic. The MARKAL modelling study will be a balancing act between on one hand the limited data availability and on the other hand the required data for proper modelling.

The most important materials are analysed for their application in the construction sector. The data situation regarding materials consumption proves to be bad. Statistics use different definitions, measurements in weight units are scarce, incomplete, or non-existent. The data situation regarding product use (floor space etc.) is even worse. For the most important materials, data have been found representing between 50 and 80% of the total materials use in the construction sector. Data for a number of countries are in certain cases extrapolated to the whole of Western Europe. Data regarding materials use for DIY activities and renovations have not been encountered. Approximately 200 million m^2 residential buildings are completed per year. A similar floor production of non-residential buildings must be added to this figure. The growth rate of floor space is 1% for residential buildings and 2% for non-residential buildings. The road length increases with 0.4% per year. Data regarding the DIY sector and the renovation sector have not been encountered, but these activities seem to constitute an important fraction of the materials demand.

The construction sector is of paramount importance for the understanding of the materials system. It is recommended to develop improved building and construction statistics and dynamic models that try to match materials consumption data and product consumption data with the increasing product stock and waste release.

Regarding the autonomous development, the number of buildings that are constructed is at this moment still four times as high as the number of buildings that are demolished. This ratio will change in the next decades, as the construction activity declines and the demolition activity increases. The renovation activity will also significantly increase. As a consequence of these developments, the demand for bulk materials is expected to decline.

A number of improvement options for the construction sector have been identified as important reduction options for the next 10-25 years:
- improved cement production: increased use of clinker substitutes, increased use of high strength cement, increased prefab production;
- use of higher strength steel qualities and improved control of steel quality;
- use of alternative reinforcement materials, which results in a decreasing steel reinforcement demand and decreasing cement requirements for concrete production;
- increased use of (engineered) wood products;
- substitution of non-renewable wood;
- substitution of structural cement and bricks in floors, walls and foundations by wood and steel;
- energy recovery from wood waste.

A number of emission reduction strategies seem less relevant on the short term:
- re-use of building segments
- wood fiber cascading
- increased asphalt recycling
- hollow bricks
- substitution of materials in non-structural elements.

On the long term (>25 years), improvement options like redesign of buildings, more efficient utilisation of building space, and re-use of product parts may pose significant improvement potentials. However, these options may affect the product service. It remains to see whether the consumer will accept such changes in product performance.

Regarding materials substitution, the use of (renewable) wood is often considered a key option for reduction of CO_2 emissions. On one hand, the production of wood requires limited amounts of fossil energy. On the other hand, atmospheric carbon is stored in constructions for several decades. The latter storage will however result in increasing CO_2 emissions in future years, if the wooden building stock is demolished. Given the temporary character of the stock changes and the difficulties in emission accounting, it is not recommended to include the increasing wood stock in constructions into the CO_2 emission calculations. MARKAL sensitivity analyses will provide more insight regarding the impact of this issue on the attractiveness of wood for long life products.

A number of secondary effects complicate the analysis of improvement options:
- the weight of buildings influences the thermal mass, which influences the energy requirement for heating and cooling. As the insulation of buildings increases and the efficiency of cooling systems increases over a period of decades, the importance of this interaction decreases.
- the different climatological regimes in different parts of Western Europe influence the heating and cooling energy demand. Because of the interaction between direct CO_2 emissions and the thermal mass, this will influence the choice of the ‘best’ materials strategy.
- the energy source for heating influences direct CO_2 emissions. Because of the interaction between direct and indirect energy consumption, this will also influence the selection of a ‘best’ materials strategy.
- the foundation requirements depend on the building weight for soils with low carrying capacity. This interaction can in certain cases be substantial from a CO_2 point of view.

Because of the interactions between improvement options and the secondary effects, the ‘best’ solution from a CO_2 point of view is beforehand unclear. Preliminary calculations suggest that the ‘light weight’ strategy may be attractive. However, the improvement potential for cement is also substantial. The MARKAL analysis will provide more insight regarding the optimal strategy.

A model structure has been developed that is based on an analysis of individual products, their materials demand and their waste consequences. The most important applications that are analysed in detail are single family residences, multi family residences, offices, other utility buildings, and road constructions.

The cost-effectiveness of improvement options depends also on the development of labour costs and the life span of buildings and constructions.

The price increase for building parts due to significant CO_2 taxes is for all structural elements below 10%. Such a limited cost impact poses probably insufficient incentive to switch from the current building practice to a completely different building practice. As a consequence, other policy instruments like legislation or covenants seem more attractive than the tax instrument. A viable strategy may be to look initially for win-win situations, where reduction of CO_2 emissions can be coupled to sustainable development, cost reduction and increased competitiveness. There seems to be ample room for such strategies.

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APPENDIX 1: THE IMPACT OF THERMAL MASS ON THE DIRECT ENERGY CONSUMPTION

Based on TRNSYS building model calculations and literature study, the impact of thermal mass on the direct energy consumption has been assessed[15]. The results of this analysis are shown in Tables A1-A4.

'Heavy' refers to concrete walls and concrete floors, 'light' refers to wooden walls and wooden/ceramic floors and gypsum interior walls.

The results refer to offices, single family dwellings and multi family dwellings. All buildings comply with current standards for direct energy use. For residences, the orientation is important for the direct energy use. For offices, the relevance of the orientation is negligible.

The results show a considerable impact of the thermal mass on the direct energy use. The impact ranges from 6 to 15%, depending on the building type. The results show for all buildings without cooling an energy saving for light outside walls. Only for the office building with cooling (Table A2), the combination of heavy walls and heavy inside structure shows the lowest direct energy consumption. Regarding inside structures of buildings without cooling (Table A1, A2, and A3), the results are not the same. For offices, the light structure is the best solution. For residences, the heavy structure is favoured. The difference can be explained by the different use characteristics.

The results can be explained by the interaction between heat conductivity and heat capacity. Heavy materials possess a large heat capacity, but do also conduct heat more easily. For this reason, heavy materials are beneficial within the building, but not beneficial in the outside structure. A wooden building with a concrete floor and concrete walls would be the best option from an energy consumption point of view (for residences without cooling). The analysis if the structural feasibility is off course another consideration.

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Table A.1 *The impact of thermal mass on the direct energy consumption, offices, no cooling, Dutch situation, Rc = 3.0, internal heat load 35 W/m^2*

Wall	Internal mass	Direct energy use [m^3 gas equivalents/m^2][1]	Relative [%]
Light	Light	10.8-11.0	100
Light	Medium	11.2-11.4	104
Light	Heavy	11.3-11.5	105
Heavy	Light	11.1-11.3	103
Heavy	Medium	11.3-11.5	105
Heavy	Heavy	11.4-11.7	106

[1] Range indicates the impact of the building orientation

Table A.2 *The impact of thermal mass on the direct energy consumption, offices, including cooling, Dutch situation, Rc = 3.0, internal heat load 35 W/m^2*

Wall	Internal mass	Direct energy use [m^3 gas equivalents/m^2][1]	Relative [%]
Light	Light	21.3-21.6	100
Light	Medium	20.8-21.0	97
Light	Heavy	20.1-20.3	94
Heavy	Light	20.8-20.9	100
Heavy	Medium	20.4-20.6	98
Heavy	Heavy	19.8-20.0	95

[1] Range indicates the impact of the building orientation

Table A.3 *The impact of thermal mass on the direct energy consumption, terraced residences, no cooling, Dutch situation*

Wall	Internal mass	Direct energy use [m^3 gas equivalents/m^2]	Relative [%]
North-South orientation			
Light	Light	9.8	100
Light	Heavy	8.3	85
Heavy	Light	9.3	95
Heavy	Heavy	10.1	103
East-West orientation			
Light	Light	10.4	100
Light	Heavy	9.0	90
Heavy	Light	9.5	91
Heavy	Heavy	9.6	92

Table A.4 *The impact of thermal mass on the direct energy consumption, multi-family residences, no cooling, Dutch situation*

Wall	Internal mass	Direct energy use [m^3 gas equivalents/m^2]	Relative [%]
North-South orientation			
Light	Light	8.0	100
Light	Heavy	7.5	94
Heavy	Light	8.0	100
Heavy	Heavy	8.2	103
East-West orientation			
Light	Light	8.4	100
Light	Heavy	7.9	94
Heavy	Light	8.7	104
Heavy	Heavy	8.2	98

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