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Direction indirect

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2 Basic methods and reference data sets

2.1 Introduction

In this thesis, the freight transport modes rail, road and water transport are compared with regard to energy requirements and emissions. These environmental aspects relate to different parts of the system in which environment and society are linked (Moll, 1993). On the input side of the system one finds the resource flows, for instance the extraction of raw materials. On the output side, one finds waste flows such as emissions associated with the fuel use by cars or the electricity use by trains. These flows in and out society are linked by consumption and recycling in society. Such social processes can be split in processes with regard to the construction phase, the use phase and the waste phase. Each of these phases has its own input and output flows. Emissions from, for instance, fuel use can result from the construction of a road as well as from a truck ride.

In order to obtain an overall view of the environmental impacts of freight transport, one should consider impacts from vehicles in the use phase as well as impacts elsewhere in the freight transport chain, i.e in the production or waste phase. Such an approach in which a product or system is described from cradle to grave and is related to its performance is termed the environmental life cycle analysis (LCA) approach (cf. section 2.2). For each phase described above, both material use and energy use as well as emissions and other environmental impact are analysed.

A standardised method for the environmental life cycle analysis of a product developed by the Centre of Environmental Sciences CML is available (van den Berg, 1995). However, the freight transport system is a complex system which contains a large number of products. First, freight transport includes transport by train as well as by truck, boat, airplane or pipeline. Second, the main subsystems infrastructure and vehicles necessary for each transport mode subsystem consist of many different products. Nevertheless, the environmental life cycle analysis approach can be applied to freight transport systems. An analysis of the system includes *a product flow* analysis of all products involved next to a *material, energy and emission flow* analysis of each product.

Quite a lot is known about the environmental consequences of the use phase of transport, i.e. the energy use and emissions associated with driving vehicles. Relatively little is known about the environmental consequences of the construction of vehicles and infrastructure. Therefore, one of the main objectives of this thesis is the energy use and emissions related to the materials production and product fabrication of all products involved in the transport system, or, in other words, the indirect energy requirements and indirect emissions of freight transport.

The main issue of this chapter is to describe the energy and emission analysis methodologies to calculate indirect energy requirements and indirect emissions. The different analysis methodologies start alternatively from the investments costs of infrastructure and vehicles or from the material and energy balances of the products involved in these parts of the transport system. Outcome and goal of all analyses based on the methodologies are descriptions of the vehicles and infrastructure of the freight transport systems in terms of energy stocks and flows or so-called indirect emissions. This chapter discusses both basic methods and the application of these methods to freight transport systems in The Netherlands. The discussions and applications are descriptive and based on schemes which outline the structure of the methodologies. They consist of a few formal mathematical equations only. (For mathematical descriptions of the underlying basic methodologies, one can consult several sources referred to in the descriptions.)

Both energy and emission analysis are examples of system analysis with a rather specific scope. They describe an operation or a set of operations (a system) in energy and emission terms respectively. Therefore, general system theory concepts are applicable to them. Thus, concepts such as system boundaries play a role in energy and emission analysis theory as well as in system theory.

Basically, two types of energy and emission analysis are available, process analysis and input-output analysis. A third one, the hybrid analysis, combines elements of both methods. This section shortly outlines the basic characteristics of the methodologies. For extensive descriptions and formal definitions, see the sections of this chapter dealing with the separate methodologies.

A product energy analysis methodology based on input-output energy analysis (IOEA) combines the monetary value of the product and the energy intensity of economic sectors by which the product is produced. The *energy intensity* of an economic sector is the energy required to produce one monetary unit in that sector. The embodied energy of a product produced by a sector equals the investments costs of the product times the energy intensity of the sector. A process energy analysis (PEA) of a product is the calculation of its energy requirements based on a description of the product in mass and energy balances. The embodied energy of the product is the sum of the embodied energy of the production materials used and the (direct) production energy. A process analysis is relevant on a much more detailed level than input-output analysis. A hybrid energy analysis of a product combines PEA and IOEA elements. In most applications, the main processes (which are the processes which account for a high percentage of the products embodied energy) are analysed by means of PEA. Next, the remaining processes are analysed by means of IOEA.

The total embodied energy of a transport system is the sum of the embodied energy of all products involved in the system. For freight transport, it is the energy embodied in vehicles, infrastructure and other parts of the freight transport system.

The emission analysis methodologies resemble the energy analysis methodologies. The first methodology ’input-output energy emission analysis’ (IOEEmA) considers the energy requirements of the economic sectors divided over different energy carriers and the sulphur and carbon emission contents of these energy carriers. Based on the direct relation between sulphur and carbon emissions and the energy carriers oil, coal and gas, the so-called ’emission-intensities’ of the economic sectors are calculated. These ’emission intensities’ are comparable to the energy intensities of the economic sectors; they describe the emissions connected with the production one monetary unit. The emissions related to the manufacturing of a product equal the product’s investments costs times the emission intensities. These emissions are called the indirect emissions.

’A process emission analysis’ (PEmA) combines mass and energy balances and material, product and process-specific emissions. It considers emissions of different substances. Thus, contrary to IOEEmA, PEmA includes e.g. NO_x emissions which depend on technology used instead of on the energy carriers. The hybrid emission method ’input-output energy product process emission analysis’ (IOEpPEmA) has both process-analysis and input-output analysis characteristics. The method combines energy requirements for transport-related economic activities, such as the production of trains, and emission figures which are related to the energy carriers, such as gas, as well as economic activities. The energy requirements are comparable with the energy-inputs of the economic sectors which are used to calculate the ’emission intensities’ of the economic sectors in IOEEmA. The emission figures are comparable with the material, product and process-specific emissions in PEmA.

Structure of this chapter

This chapter focuses on the basics of life cycle analysis (cf. section 2.2), the basics of different energy and emission analysis methodologies and methodologies developed to calculate the energy requirements and emissions which result from construction and maintenance of the infrastructure and the vehicles of freight transport systems, the so-called indirect energy requirements and indirect emissions. Section 2.3 deals with energy analysis in general. It discusses the foundations of energy analysis (subsection 2.3.1) and the different types of energy analysis methodologies: Input-Output Energy Analysis (IOEA) (subsection 2.3.2), Process Energy Analysis (PEA) (subsection 2.3.3) and the Hybrid Energy Analysis (HEA) (subsection 2.3.4). Section 2.4 discusses comparable methods for emission analysis. The energy analysis methodologies of section 2.3 and parts of the IOEA-based and PEA-based emission analysis methodologies of section 2.4 have been introduced by other researchers. Inspired by these methodologies, the IOEA and PEA-based methodologies are developed further and a third new emission analysis methodology is introduced as well within the framework of this thesis.

The sections 2.5 and 2.6 describe the methodologies to calculate the indirect energy requirements and indirect emissions of freight transport systems in The Netherlands. They are applications of the methods described in the sections 2.3 and 2.4 and have been developed in the framework of this thesis. The sections also describe reference data sets for freight transport system analyses in The Netherlands in 1990. These data are generally applicable to all transport modes and are part of the analysis methodologies mentioned above. The data are used frequently in the transport mode specific analyses in the chapters 3 till 5 inclusive.

Finally, section 2.7 shows the set-up and basic structure of the energy and emission analyses which are performed for rail, road and water transport and which are described in detail in the chapters 3 till 7 inclusive. Section 2.7 is a general introduction to the following chapters.

2.2 Environmental Life Cycle Analysis

A Life Cycle Analysis (LCA) of a product is a systematic analysis and evaluation of the product with regard to certain aspects, which can range from physical flows to costs and employment. An environmental life cycle analysis focuses on environmental impacts. In principle, all these impacts in all stages of the life cycle of a product are studied. These include impacts resulting from the construction, use and waste phase, or, in other words, all stages from cradle-to-grave. This, however, is theory. In practice, an environmental LCA concentrates on the most relevant production parts with regard to for instance emissions, energy use etc. and the most important environmental aspects, e.g. global warming and acidification.

In The Netherlands, a standard method for environmental life cycle analysis was developed and is still under development at the Centre of Environmental Sciences (CML) of the Leiden University. This method, ’the environmental life cycle analysis of products’, is a tool for product comparison. The latest manual describing the method, definitions, rules and the backgrounds was published in 1995 (van den Berg, 1995). The methodology has been developed in an international context coordinated by SETAC (Society for Environmental Toxicology and Chemistry). In Europe, there is general agreement with regard to the framework of LCA.

Life cycle analysis is a static method. The method is suitable for state-of-the-art product studies but it is not suitable to study historical or future developments of for instance, technological innovation and political intervention and the like. For this purpose, Moll (1993) introduced the concept of dynamic life cycle analysis. With dynamic life cycle analysis, one can study changes in material flows, energy flows and environmental impacts.

Often the concept life cycle analysis is associated with the methodology developed at CML. In my opinion however, environmental life cycle analysis is more an approach than a tool. Nevertheless, the systematic way in which the tool is set up (and therefore also the tool itself), is useful to structure thoughts and to discuss the issues.

Other environmental decision tools exist besides life cycle analysis. Comparable other tools are substance flow analysis, technology assessment, environmental impacts assessment, environmental risk assessment, environmental audit (Udo de Haes, 1994) and chain analysis[1] (Udo de Haes, 1993). Parts of these methodologies are method specific, other parts overlap with other methodologies[2]. All such methodologies are very useful, each in its own way. They may contribute to the elaboration of the concept of ’integral chain management’ which is implemented by business nowadays[3].

The life cycle analysis approach can be used to analyse services (Moll & Bos, 1993), such as freight transport. Freight transport is realised through the availability of a collection of products, such as vehicles, infrastructure, computers, etc. and by several modes, such as rail and road transport. Therefore, a life cycle analysis of a service is defined as the collection of life cycle analyses of all products involved in this service. As a consequence, besides material and energy flows, product flows have to be analysed too. This is illustrated in figure 2.1.

Analogous to the standard method of environmental life cycle analysis, the

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[1] Chain management is in fact an LCA which concentrates on options for improvement with regard to both economical and environmental aspects.

[2] Udo de Haes et al (1994) compared the methodologies with regard to the two dimensions ’cradle to grave’ and ’global to site-specific’.

[3] Integral chain management is the management of substance cycles in the economic production cycle of ’raw materials - production processes - waste’ in order to close the cycle as much as possible in an environmentally acceptable and cost-effective way.

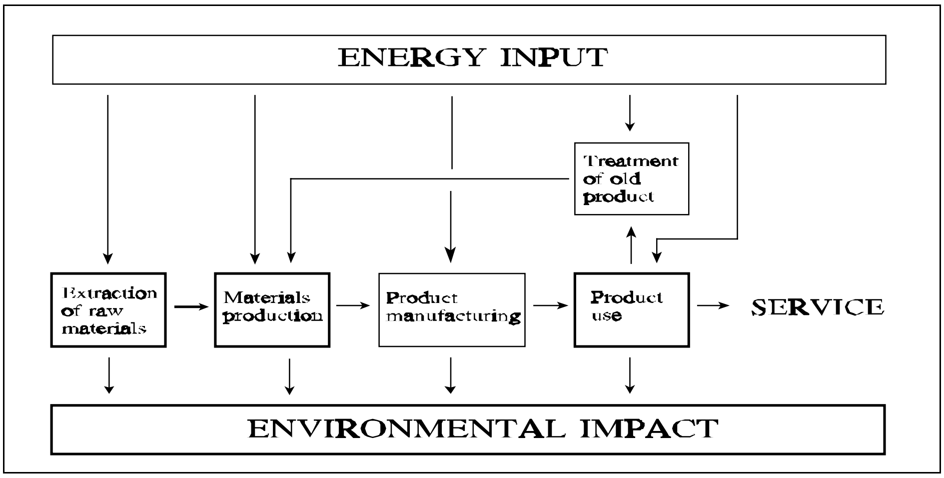

Figure 2.1 A life-cycle-analysis diagram of a service.

following steps can be distinguished in the analysis of a specific service: (1) goal definition, (2) inventory, (3) classification and characterisation, (4) evaluation and (5) improvement analysis. These steps are illustrated briefly below using examples from freight transport. (For a more extensive description of the life cycle analysis steps, cf. Van den Berg (1995).)

In step one, the product or system under study is described accurately, the system boundaries are set and a functional unit, the subject of study, is defined. For services, the functional unit is an important concept; the subject of study is primarily the function a product fulfils and not a physical unit. For instance, in transport system analysis, a relevant functional unit can be tons or ton kilometres (transported). Step two is an inventory of all relevant processes, the quantification of environmental loadings per process and the establishment of rules for the allocation of the environmental loadings to the functional unit. The classification section of an LCA is the arrangement of the environmental loadings of the inventory section in accordance with the (potential) environmental impacts. Translated to freight transport system analysis, for example, steps two and three concern the summary of the process emissions and exhaust emissions at the level of global warming and photochemical ozone depletion potential for the production and use of vehicles.

In step four, for different environmental themes, the results are discussed in relation to each other and, if possible, an overall conclusion is drawn. Next, step five discusses those parts of the system that have substantial influences on the results and in which changes can lead to improvements of the results, i.e. less environmental harm (per functional unit).

An LCA of freight transport is an integration of product LCAs. Each product

LCA concerns the construction, use and waste phase. The analyses of energy and emission flows with regard to the vehicles and infrastructure, the main issues of this chapter, only concern the construction phase. Besides, they concentrate on the LCA methodology steps ’goal definition’ and ’inventory’.

Results of the analyses (cf. chapters 3, 4, 5 and 7) can be used to construct a more complete LCA of freight transport. The model presented in chapter 8 is such an LCA. It combines the construction and use phase of the transport modes road, rail and water transport.

2.3 Energy analysis

2.3.1 Introduction to energy analysis

Important research carried out in the energy analysis area is summarised and reviewed by the IFIAS workshop (1974), Boustead and Hancock (1979) and Nieuwlaar (1988). This short introduction to energy analysis mainly discusses these sources.

Energy analysis can be considered as a system analysis with a limited scope. Therefore, elements from general system theory are worth considering carrying out an energy analysis. The following elements are under concern:

1 problem definition,
2 system definition,
3 the calculation of the energy requirements of the system,
4 allocation of the system energy requirements.

The problem definition is basically a description of the study objective. The system definition, which partly follows from the way in which the problem is defined, is described in terms of operations, system boundaries and time horizon. In this context, an operation or process consists of a number of inputs, such as *materials, capital goods and energy*, which are transformed into a number of outputs, such as *useful products, waste flows and energy services*.

A main system can be described in operations which, subsequently, can be described in material flows. Often, material flows into operations are products or outputs of an operation one step upstream in a production chain. Therefore, in defining system boundaries, one needs to determine which operations one wants to take into account and which operations should be excluded. Moreover, one has to decide how many steps upstream the production chain one wants to go. Capital goods inputs and energy inputs can be considered subsystems linked to the operations. For these subsystems, the same system definition problems are valid as for the main system. This general structure of inputs, outputs, the main system and subsystems as discussed is shown in figure 2.2.

Once the system is described and system boundaries are selected, the energy requirements of the system (and subsystems) can be calculated. In case some operations produce more than one output, energy allocation occurs: which part of the energy input has to be allocated to which parts of the outputs ? Different allocation methods are available. One often uses an allocation based on physical criteria, such as mass. The results are only valid within the selected system boundaries and under the assumptions made.

In order to structure communications on energy analysis, the definitions of the concepts GER and ERE are presented here.
GER - Gross Energy Requirements (for materials)
The gross energy requirements of a material expresses the total energy costs to produce 1 mass unit, e.g. kg, of this material.

For instance, the GER value of aluminium is 198 MJ/kg (van Heijningen, 1992a). That means that for one kilogram of aluminium, the energy requirements for the extraction of raw materials, the transport energy of these materials, the production of aluminium, the energy embodied in the capital goods required in the production, etc., are 198 MJ. This result holds for the specific choice of the extraction site, the transport mode and transport distance and the production processes and their related efficiencies.

ERE - Energy Requirements for Energy
The energy requirements for energy value (ERE) of an energy source expresses the total energy requirements to deliver one unit of energy to producers or consumers.

For instance, the ERE value of electricity for The Netherlands in 1989 equals 2.75 (Wilting, 1993). Thus, for the delivery of 1 MJ_e, 2.75 MJ of primary energy is required[4]. This is energy required for the extraction of gas or coal, energy for the production of electricity, energy for the transport of electricity to the consumer etc.

One way to qualify the results is to distinguish different orders of energy analysis. In an energy analysis, the order number indicates the number of steps upstream in the production chain. Therefore, the order expresses the completeness of the energy requirements estimate. The higher the order, the more processes or operations are taken into account. Both Boustead and Hancock (1979) and the IFIAS workshop (IFIAS, 1974) adopted order schemes. Since the order number in the IFIAS scheme reflects the sequence in the

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[4] For the delivery of 1 kWh_e, the primary energy required is 9.9 MJ.
(9.9 = 3.6 x 2.75; 1 kWh_e equals 3.6 MJ; ERE value of electricity = 2.75.)

contribution to the total system energy requirements, this one is used in this study. It is presented in figure 2.2.

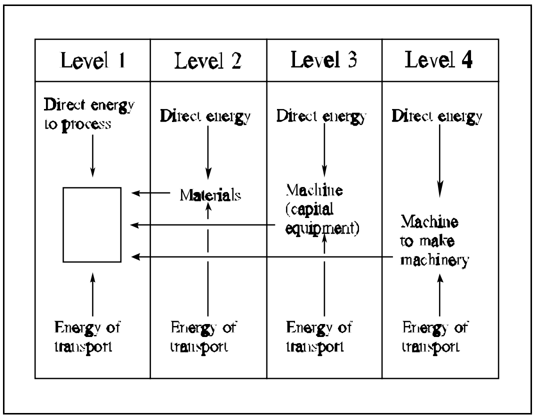

Figure 2.2 The energy analysis order scheme according to IFIAS (1974).

Both the order concept and the definitions of the GER and ERE value were originally defined in a process analysis environment. Since they are commonly used in energy analysis, they are discussed in this energy analysis introductory section.

2.3.2 Input-Output Energy Analysis (IOEA)

The foundations of economic input-output analysis as it is known today were laid by Leontief in the 1930s and 1940s. In such an analysis, the economy is desegregated in several sectors. The inputs and outputs of each economic sector, based on underlying physical processes, are represented by the monetary value of the goods and services flows.

Input-output *energy* analysis (IOEA) is an application of economic input-output analysis which relates energy flows to the value of the goods and services flows in the economic sectors. For each sector, this analysis results in the energy intensity of one unit of output (cf. figure 2.3, step 1). Bullard and Herendeen (1978) derived the foundations of the methodology of input-output energy analysis.[5] For a mathematical description of the basics of input-output energy analysis, see e.g. Wilting (1996).[6]

This section describes a 2-steps methodology which is the basis for this study. Step 1 contains the calculation of the (historical) energy intensities of economic sectors in The Netherlands based on the basics of IOEA as mentioned above (cf. figure 2.3, step 1). Step 2 combines the energy intensities of the economic

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[5] Also Wright (1974) published significant work in this field.

[6] For further reading cf. Peet (1993) and Miller (1985). In his article, Peet gives a short overview of both economic input-output analysis and input-output energy analysis. In his article, as Wilting does, Miller gives a thorough mathematical description of IOEA.

sectors and investments in these sectors. This results in an estimate of the embodied energy of capital goods stocks (cf. figure 2.3, step 2). Step 1 of the methodology is based on input-output energy analysis and has been developed by Wilting (1996). Step 2 is based on Noorman (1995) and Slesser (1990). In the following, both steps of the methodology are discussed. Figure 2.3 shows the way in which the steps are linked.

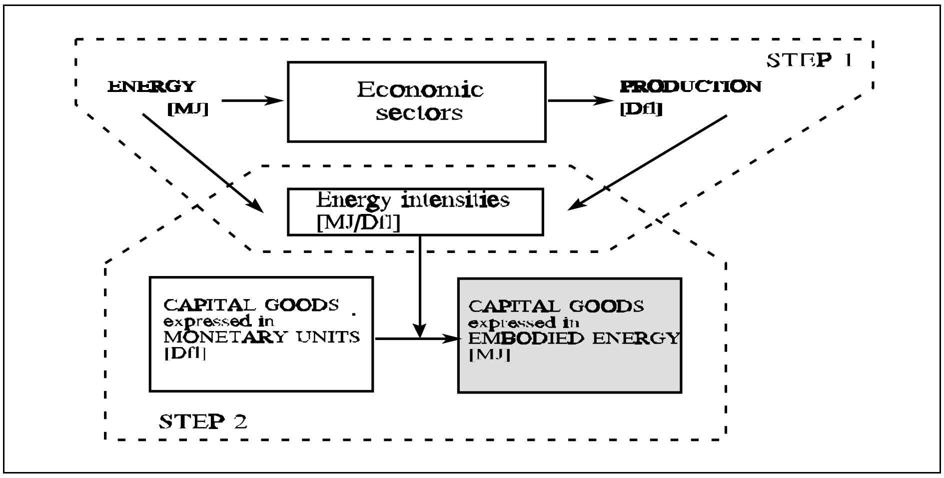

Figure 2.3 Overview of the application of IOEA in estimating the embodied energy of capital goods stocks required for a service or industrial activity.

Step 1: The energy intensities of the economic sectors

The economic sectors correspond to those considered in the Dutch input-output tables which are published in the National Accounts (CBS-NR, 1991) of The Netherlands[7]. These tables contain the mutual deliveries among the sectors, the primary costs (such as import, depreciation, salaries), the final goods and services (such as investments by consumers and government and export) and the production value of the economic sectors (cf. table 2.1).

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[7] The input-output tables distinguish 59 groups of economic activities; each of these groups of activities corresponds with one row in the input-output table. From now on, each of the 59 groups of economic activities will be referred to as sector ’X’ whereas ’X’ is the input-output table row-number.

To calculate a sector's energy intensity, the production value of an economic sector and the *total primary energy use* are combined. A sector with a X MJ primary energy input and Y guilders production output has an energy intensity of X/Y MJ per guilder (Wilting, 1993).

The total or cumulative energy input of a sector is the sum of the direct and indirect energy inputs. The *direct* energy flows into the different sectors, such as the gas and electricity consumption by the sector, are available expressed in primary energy carriers as well as in secondary energy carriers (Wilting, 1993).

Table 2.1 The basic structure of input-output tables as published in the National Accounts for The Netherlands (CBS-NR, 1991).

	Economic sectors 1 59	Final goods and Services	Total Production
Economic sectors 1 59	Mutual deliveries		
Total primary costs			
Total			

Nevertheless, the sector's energy intensity is expressed in *primary* energy per guilder. ERE (Energy Requirements for Energy) data are used to calculate the primary energy requirements from secondary energy requirements.

The *indirect* energy input of an economic sector includes the embodied energy of the products delivered by other economic sectors and some other factors such as the energy embodied in the import goods and the energy embodied in the sector's capital goods depreciation. The embodied energy of the imported goods is assumed to be equal to the embodied energy of the same products produced in The Netherlands. For the goods depreciated, the embodied energy is assumed to be the product of the depreciation value and the energy intensity of the Dutch investments. This investments energy-intensity, EI_{inv}, is the weighted sum of national investments in the different sectors times the corresponding energy intensities.

In formula:

$$EI_{inv} = \frac{\sum_{X=1}^{59} (INV_{sectX} * \ EI_{sectX})}{\sum_{X=1}^{59} (INV_{sectX})} ,with$$

INV_{sectX} = investments *in* goods produced by sector X

As indicated, the sum of the direct and indirect energy requirements and the production value of the sector lead to the energy intensity of this sector. Next, if such an energy intensity is known for a specified year, the historical energy intensities of the economic sector are calculated by use of the trend in the energy use per Dutch florin of the entire economy (Noorman, l1993). It is assumed that this trend in the direct energy use per unit GDP (Gross Domestic Product) for the entire economy also describes the developments in the energy intensities of the individual sectors and the investments. Since both the energy intensities and the GDP are expressed in constant guilders, the resulting time series of energy intensities are expressed in constant guilders.

In order to calculate time series of energy intensities expressed in current guilders, the sectoral deflators and the general deflator are used for the energy intensities of the sectors and the investments. The general deflator is calculated based on price index rates (of consumption) as published by the CBS (CBS-JB, several years). The sectoral deflators are calculated based on ’inland deliveries’ to these sectors expressed in both current guilders and prices of the previous years (Wilting, 1993).

Step 2: The embodied energy of the capital goods stocks

In order to estimate the embodied energy of capital goods stocks, IOEA combines the energy intensities time series derived in step 1 series and the values of capital goods (Noorman, 1995). CBS provides data on stocks of capital goods of many industrial or service activities in the economy (CBS-KGV, 1993). The general structure of the tables which contain values of these capital goods are shown in table 2.2.

Two fundamentally different embodied energy values of the capital goods stocks can be calculated (Noorman, 1995). The first embodied energy value, $EmbE_{CGS}(t)$, is the amount of energy required in year T for the production of the present capital goods stocks in year T. The second embodied energy value, $EmbE_{CGS}(h)$ (h=historical), expresses the amount of energy which was required

Table 2.2 Table structure of the statistics of the stocks of capital goods (CBS-KGV, 1990).

Type of capital goods	vintage period (years since 1950)						
Constant Dfl[*1] of 1990	<50	50-54	.....	80-84	85-89	1990	Total
Category 1							
.....							
.....							
Category 8							
Total							

[*1] Dfl = Dutch Florin

in earlier times for the production of the present capital goods stocks in year T. For the calculation of the first value, one combines the financial value of the capital goods stocks present in year T (and presented in table 2.2) and the energy-intensities time series of the economic sectors expressed in constant prices of the year T. For the calculation of the second value, one uses a table which contains the historical costs of the capital goods present in year T and the historical energy intensities time series expressed in current prices. A table which contains the *historical costs* of the stocks is derived from a capital goods stocks table as shown in table 2.2 by means of historical-costs indices provided by the CBS[8].

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[8] The historical costs indicators have not been published by the CBS officially, but are the result from additional operations carried out by the main division 'Statistics of the stocks and capital goods' of the 'Dutch Central Bureau of Statistics (CBS)'. Within the scope of the statistics on capital goods, the deflators are mainly used to convert historical costs to current values.

In formulas:

$$EmbE_{CGS}(t) = \sum_{time} \sum_{X=1}^{8} (VCG_{catX}(copr_t) * EI_{sectY(X)}(copr_t))$$

$EmbE_{CGS}(t)$ = Embodied Energy of the Capital Goods Stocks (CGS) present in year t if the capital goods are produced in year T

$EI_{sectY(X)}$ = Energy Intensity of the economic sector Y which produces goods belonging to the capital goods category X; each capital goods category X is related to one economic sector Y.

VCG_{catX} $(Copr_t)$ = Value of Capital Goods belonging to goods category X in constant prices of year t.

$$EmbE_{CGS}(h) = \sum_{time} \sum_{X=1}^{8} (VCG_{catX}(cupr_{time}) * EI_{sectY(X)}(cupr_{time}))$$

$EmbE_{CGS}(h)$ = Embodied Energy of the Capital Goods Stocks (CGS) present in year t taking into account they were produced in earlier times (h=historical),

$EI_{sectY(X)}$ = Energy Intensity of the economic sector Y which produces goods belonging to the capital goods category X; each capital goods category X is related to one economic sector Y.

$VCG_{catX}(Cupr)$ = Value of Capital Goods belonging to goods category X in current prices.

Theoretically, one can also calculate the historical energy requirements based on capital goods stocks expressed in constant Dfl of year T and energy intensity time series expressed in constant Dfl of year T. However, the methodology based on historical costs ánd energy intensities time series expressed in current Dfl is preferred since both the CBS historical costs indicators and the energy intensity time series in current prices express market price changes as well as the changing value of the currency. Since only deflation and nót market price changes are included in the methodology based on constant prices, an estimate based on this methodology is less correct than one based on the methodology based on current prices.

Reference data sets necessary to carry out an IOEA contain time series of energy intensities. These energy-intensities should preferably be expressed in $MJ/Dfl_{current}$. Besides, in order to calculate historical embodied energy values, one needs a reference data set which contains the historical costs indicators.

Next, to calculate the embodied energy of a defined group of capital goods, one needs to collect investments data of the capital goods stocks, or in other words, the monetary value of the capital goods stocks.

2.3.3 Process Energy Analysis (PEA)

The foundations of process energy analysis were laid at the IFIAS workshop in 1974 (IFIAS, 1974). A group of researchers discussed the methodology of energy analyses and proposed a number of conventions. This section describes the essence of the methodology. Some other results of the workshop, such as some relevant definitions (GER, ERE) and the analysis order scheme proposed were already discussed in section 2.2 since their meaning is important to energy analysis in general.

Instead of concentrating on energy flows among industrial sectors, as in IOEA, process analysis concentrates on *physical units and their related energy flows within* these sectors. A process energy analysis of a product is the calculation of its energy requirements based on a description of the product in terms of mass and energy balances. The materials used, the production energy of these materials and the direct process energy form the core of the methodology. In general, process energy analysis provides a tool at a much more detailed level than input-output energy analysis.

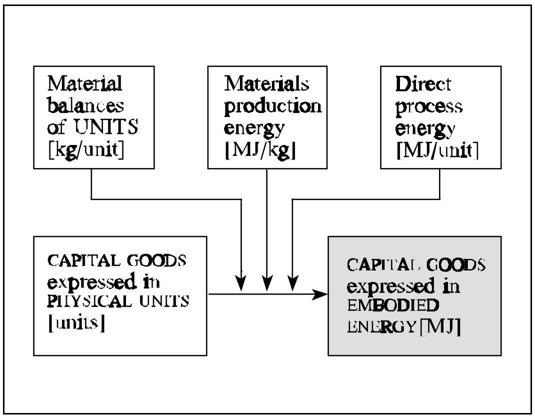

Figure 2.4 Overview of the application of process energy analysis in estimating the embodied energy of capital goods required for a service or industrial activity.

The embodied energy of a product is the sum of the embodied energy of the materials used and the direct production energy. Besides, the embodied energy of the capital goods required for production, the embodied energy to produce these capital goods and the direct energy to make these capital goods function can be part of the analysis. The more comprehensive the analysis, the higher the order of this analysis is.

As indicated in section 2.2, a life cycle analysis of a service or an industrial activity is *an integration of product analyses*. Each capital good which is part of the activity is a separate product and accounts for a separate analysis. The *products flows* present in freight transport systems are mainly the numbers of (different types of) vehicles and kilometres of (different types of) infrastructure.

The embodied energy of the system is the total sum of the embodied energy present in the vehicles and infrastructure, i.e. the embodied energy present in the physical units of the system. This general structure of a process energy analysis of a service is shown in figure 2.4.

One requires many data to carry out a process energy analysis. Already for a second order analysis one needs detailed mass balances, the gross energy requirements of all different materials in these balances and the direct energy requirements of the processes described.

The most important reference data set for this type of analysis contains the overall energy requirements of materials, such as iron and plastics. These energy requirements include the extraction energy of the raw materials, the energy required to transport the raw materials to the place where they are used etc. The most important data for a process analysis of a service or industrial activity to be collected by the user are the mass and energy balances of the products. Both mass and energy are expressed in physical units such as kilograms and megajoules.

2.3.4 Hybrid Energy Analysis (HEA)

Input-output energy analysis and process energy analysis need different input data and both have their own characteristics. The choice between these methods depends on the level of aggregation desired and the availability of data.

Sometimes, both methods are combined in a so-called hybrid analysis which is defined on the product level. A hybrid analysis starts with a process analysis and continues with an input-output analysis after a certain number of orders (Bullard et al, 1978). Often, the first and second order (according to IFIAS; cf. figure 2.2) of a product analysis are based on process analysis; the product is described in energy and material flows. Next, caused by a lack of detailed mass and energy balances, higher orders are worked out by use of IOEA. In these cases, the results of the hybrid analysis are mainly determined by the process analysis related part of the calculations since the first and second order generally account for the largest part in the total energy requirements.

The definition of a hybrid energy analysis is defined on the product level. Next, a hybrid analysis of a service or industrial activity is defined as the combination of a *product flow analysis* of a service or industrial activity and hybrid analyses of the products contributing to this service or activity.

2.4 Emission analysis

An emission analysis of a capital goods stock leads to a description of the emissions resulting from the production of the capital goods stocks. These emissions relate to the extraction of raw materials, the manufacturing of semi-manufactured products, electricity required for production, etc., or in other words, to all life cycle phases of all products are called indirect emissions. The emissions may concern different substances, such as CO_2, SO_2, NO_x and CO emissions.

The three emission analysis methodologies discussed in this section are based on IOEA analysis or process analysis. Method 1 is based on IOEA and calculates CO_2 and SO_2 emissions by means of the energy intensities of economic sectors. Method 2 is based on process analysis and calculates all kinds of emissions by means of product mass balances and process-specific emissions. Method 3 has characteristics of both IOEA and process analysis. It has been developed specifically for this study and it combines IOEA data with regard to *products* with relevant product and process-related emissions. All three methods are discussed below.

Input-Output Energy Emission Analysis (IOEEmA)

Input-Output Energy Emission Analysis (IOEEmA) as shown in figure 2.5 is derived from input-output energy analysis (Wilting, 1993). IOEA combines energy input flows and monetary output flows. The emission analysis IOEEmA adds an extra step to IOEA based on the relation between the chemical composition of energy carriers and CO_2 and SO_2 emissions. By means of the carbon and sulphur contents of the energy carriers such as gas, coal and oil, energy inputs are converted to associated emissions. Next, these CO_2 and SO_2 emissions are combined with the monetary output. The resulting emission rates expressed in kg per Dfl are values which are analogue to the energy-intensities in IOEA (cf. figure 2.5, step 1).

For separate years and for economic sectors distinguished in an IO table, emission rates can be calculated if the energy inputs divided over different primary and/or secondary energy carriers, the ERE values of the secondary energy carriers and the CO_2 and SO_2 emission rates of these energy carriers are available. Historical time series of emission rates can only be derived by calculating the emission rates for each separate year.

To calculate the indirect emissions of capital goods stocks, step 2 of IOEEmA is consistent with step 2 of IOEA.

Necessary input data for this method are CO_2 and SO_2 emissions per energy carrier next to the input data which are necessary for IOEA.

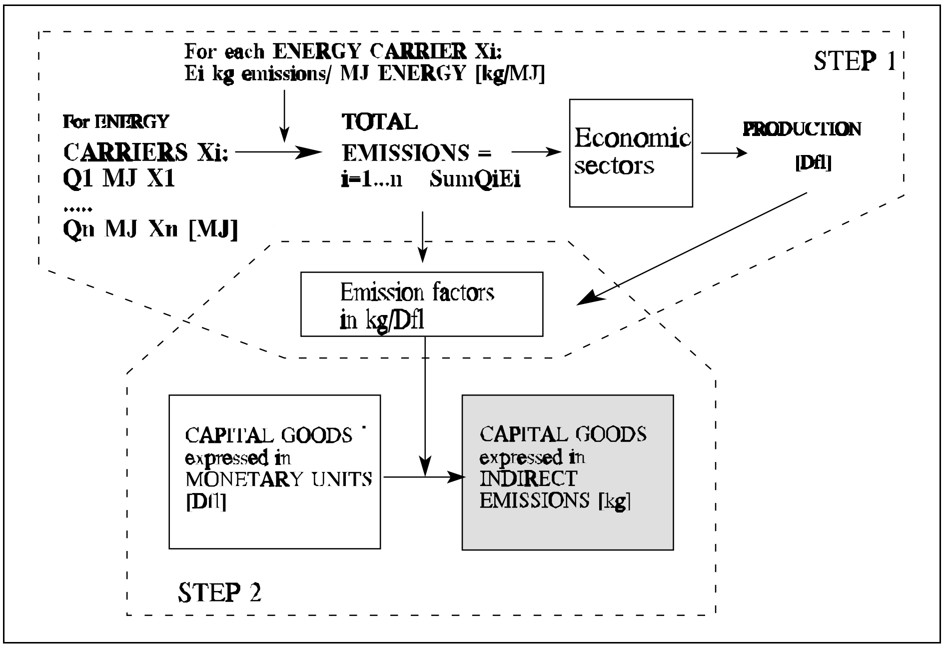

Figure 2.5 Overview of Input-Output Energy Emission Analysis (IOEEmA).

Process Emission Analysis (PEmA)

In manufacturing, most emissions strongly depend on the technology used instead of on the energy carrier used. For such emissions, an estimate of their magnitude can be made by means of process emission analysis instead of IOEEmA. The structure of a Process Emission Analysis (PEmA) of a product resembles the structure of a process energy analysis of a product (cf. figure 2.6). The indirect emissions of a product include the emissions related to the direct process energy, the emissions resulting from the manufacturing of the materials of which the products consist and the emissions resulting from the manufacturing of the capital goods required for the production. Analogous to the definition of energy orders in process energy analysis, these emissions are contributions of the first, second and third order.

The indirect emissions of a capital goods stock are the sum of the emissions that result from the production of the separate products. For a product, the emissions depend on its materials' composition and the technologies used for manufacturing. Thus, they can be energy-related emissions, such as CO_2 and SO_2 emissions, and process-related emissions, such as NO_x and CO emissions. A PEmA requires many input data, such as materials balances and the direct process energy divided over the different energy carriers. Besides, basic data sets need to be calculated for a PEmA since contrary to PEA, IOEA and IOEEmA no common basic data sets are yet available. No comparable values to the GER values of materials which concern the emissions per kg of material produced exist. For the relevant materials, one needs to calculate the emissions per kg and the emissions caused by the use of the direct process energy. A process emission analysis is thus a time-consuming and not yet well developed methodology.

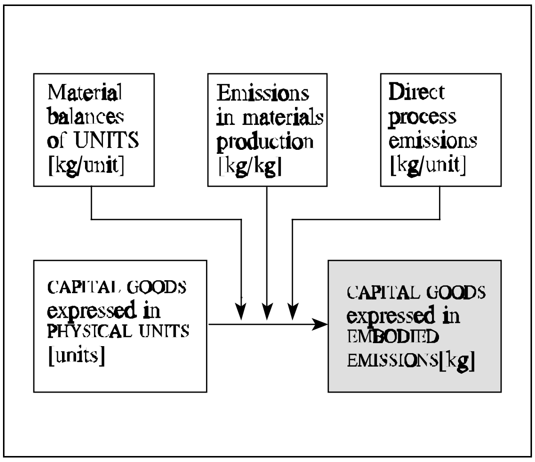

Figure 2.6 Overview of Process Emission Analysis (PEmA).

Input-Output Energy product Process Emission-Analysis (IOEpPEmA)

A product emission analysis is a method based on both IOEA and process analysis. The core of the method is shown in figure 2.7. For each product, it combines the cumulative energy intensities divided over different energy carriers and the emissions of different substances resulting from the use of these energy carriers. The cumulative energy requirements are expressed in MJ per Dfl of a product. The emissions related to the energy carriers are expressed in (kilo)grams per MJ. These parts of the analysis resemble IOEA and process analysis, respectively.

A product in a ’IOEpPEmA’ can be ’a truck’ or ’a product manufactured by the construction sector’, e.g. a road, track or bridge. ’A product’ in IOEpPEmA is in fact a group of products. (Also ’a truck’ is in itself a group of products since it can be a small or big one or consists of mainly steel or steel and a rather big share of aluminium, etc.) In general, the specification of the products in IOEpPEmA is more detailed than of those in IOEEmA, i.e. the products produced by the economic sectors. For instance, ’a truck’ is a more specified product than ’an average product of the automobile industry’.

The cumulative energy requirements of each energy carrier equal the sum of the direct and indirect energy requirements of the energy carrier. These calculations of the direct and indirect requirements are consistent with the calculations with regard to the economic sectors in IOEA. However, in this IOEpPEmA, the calculations are based on product-specific energy requirements

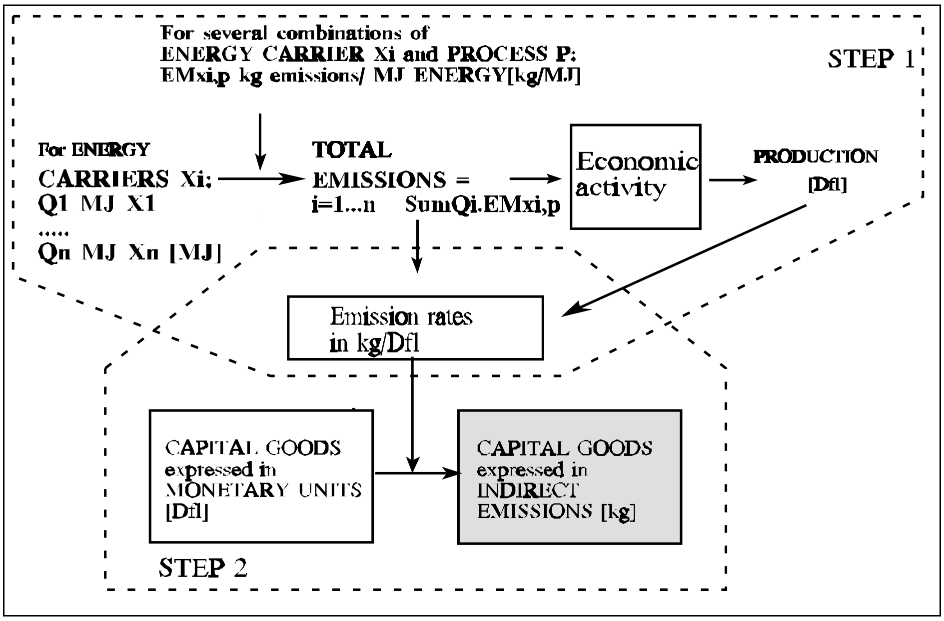

Figure 2.7 Overview of Input-Output Energy product Process Emission Analysis (IOEpPEmA).

(CBS, d1990), which again are based on IO tables which contains intermediate deliveries and production values which are *product specific*, ánd on direct energy requirements for the production of these products.

The emission factors used in this analysis depend on both the energy carrier and the process in which they are used (CBS, d1993).

For a specific product, well-chosen combinations of its cumulative energy inputs divided over different energy carriers and energy-and-process-related emission rates lead to an estimate of the emissions resulting from the manufacturing of that product.

The method combines knowledge with regard to the energy use per monetary unit with knowledge of processes. Thus, the method combines some advantages of the IOEA, i.e. the relatively simple way to calculate cumulative energy requirements of products or a group of products, with the advantages of process approach, i.e. detailed results and the possibility to identify product-specific emissions. As in process emission analysis, in IOEpPEmA, the emissions under concern can be of any kind.

The input data of this method are energy balances of the products under concern (or IO tables with monetary flows and direct energy use data on product level by which these energy balances can be calculated) and emission data which are product and energy specific.

2.5 Basic methodologies for freight transport energy analysis and the calculation of reference data sets

2.5.1 Introduction

Based on methodologies as described in 2.3, this section describes the methodologies developed specifically for this freight transport study. For each analysis method, it describes the crucial choices and assumptions and the resulting reference data sets. The basic structure of the energy analysis methodologies of freight transport systems is shown in figure 2.8. It combines the embodied energy of the system, the depreciations of the system and the transport performance belonging to the system (cf. figure 2.8, parts 1, 2 and 3). All energy analyses share the structure of the analysis parts 2 and 3. The methodologies differ with regard to part 1.

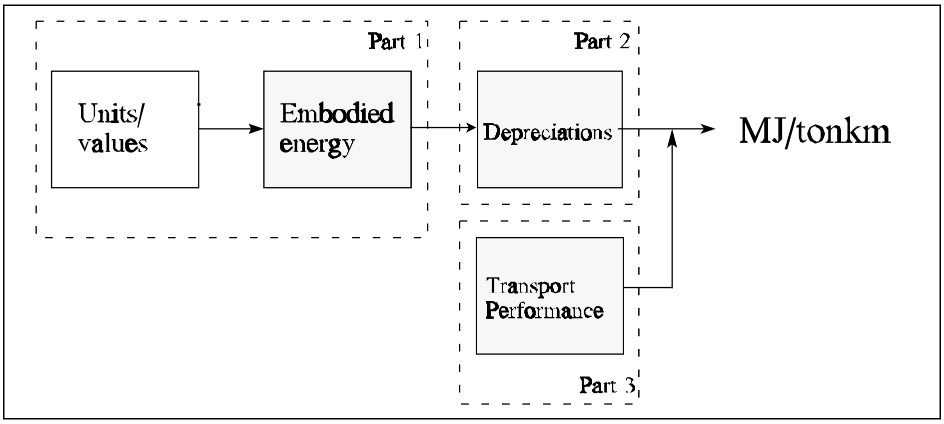

Figure 2.8 The common structure of all freight transport system energy analyses.

The reference data sets refer to The Netherlands anno 1990. This means that, for instance, the gross energy requirements of iron contain the transport energy of the materials from the place of extraction to The Netherlands and that the energy intensity of the economic sector ’industrial/commercial buildings’ describes the energy efficiency of this production sector in The Netherlands.

The reference data sets contain data with a *general* usefulness, that is, data which underlie all transport modes, such as the production energy of material or the energy intensities of the economic sectors. They are frequently used in the following chapters. Data sets in the chapters 3 till 5 inclusive contain mode-specific data with regard to the Dutch infrastructure and vehicle park, such as the amount of tracks and trucks.

Since the reference data sets refer to The Netherlands, results based on these data sets are primarily valid for the situation in The Netherlands. However, they may also have a more general applicability. This depends on the type of data and type of transport mode. Section 2.7 turns to this issue.

2.5.2 Input-Output Energy Analysis (IOEA)

As indicated in 2.3.2, the two steps distinguished in the Input-Output Energy Analysis (IOEA) based methodology are the calculation of the (historical) energy intensities of the economic sectors and the calculation of the embodied energy of the capital goods (section 2.3.2). This can be both the energy requirements necessary to produce the capital goods in 1990, i.e based on production technologies of 1990, or the energy requirements used for the production of the capital goods in earlier times, i.e. based on production technologies formerly used.

This section deals with the application of the two steps in the analyses for freight transport systems. Next, a third step consists of the calculation of the indirect energy requirements based on the embodied energy of the capital goods and the system's transport performance. The steps one, two and three lead to the methodology schematically represented in figure 2.9.

The different basic data required to carry out an IOEA for freight transport systems are data with regard to the value of the infrastructure and vehicle park and the energy intensity series of the economic sectors involved in the production of vehicles and infrastructure. For these data, long time series are necessary.

Step 1: The (historical) energy intensities of the economic sectors

Wilting (1993) described three methods to calculate energy intensities; two based on energy use flows expressed in primary ánd secondary energy carriers (source: van Engelenburg, 1991), and one based on energy use flows expressed in primary terms only (source: Kazemier, 1992). He concluded that the methods based on primary and secondary energy carriers are more accurate. The energy intensities in this freight transport study are calculated based on Wilting's method which includes all economic sectors excluding the energy production sectors (1993, page 55). The energy use of the energy-production sectors is allocated to the users, i.e. the energy use of the energy production sectors is allocated to the economic sectors which use their energy products. This method is the most suitable one for this freight transport study since the energy use of the sectors involved in the production of vehicles and infrastructure is the main interest rather than the energy-production sectors separately. The resulting energy intensities based on primary and secondary

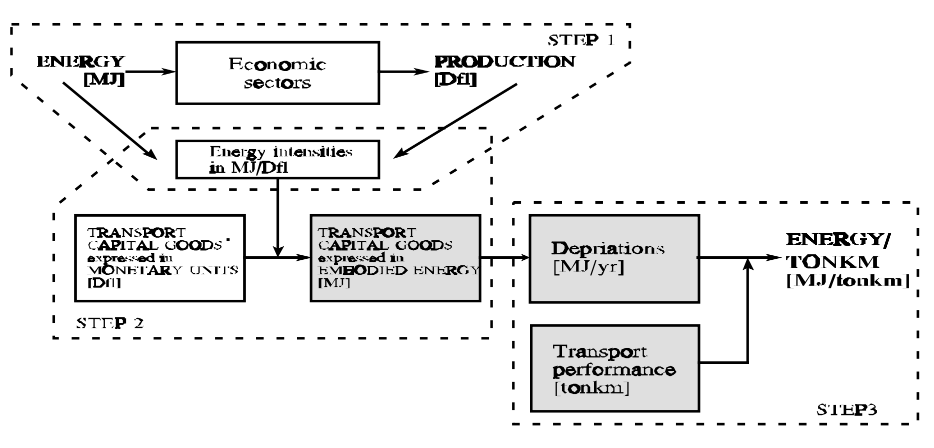

Figure 2.9 Overview of the IOEA based methodology for freight transport systems as developed for this study.

energy inputs are expressed in primary terms only by means of the ERE-values of the secondary energy carriers (cf. table 2.3).

The year 1989 is chosen as the base year in this study since in 1989, the Dutch Central Bureau of Statistics (CBS) improved their method of collecting and compiling data. For 1990[9], the energy intensities of the most relevant economic sectors for this study, i.e. the economic sectors related to transport systems, and the energy intensity of the investments are shown in table 2.4 (Wilting, 1993). A list containing the energy intensities and descriptions of all economic sectors is inserted in appendix B.

Table 2.3 The ERE values of secondary energy carriers (Wilting, 1993).

Secondary energy carrier	1970	1989
Coal products	1.25	1.25
Mineral oil products	1.11	1.11
Natural gas	1.01	1.01
Electricity	3.16	2.75

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[9] Since this study requires energy intensities through 1990, it is assumed that energy intensities of 1990 equal those of 1989.

Historical time series are calculated taking the base year 1989 as a point of departure. Since the capital goods stocks of transport activities even originate from the period before 1950, time series of energy intensities for the years 1945 up to 1989 included are calculated. These time series are expressed in both constant and current guilders. The historical energy intensities of all economic sectors are calculated under the assumption that the trend in the energy use per guilder of the entire economy (Noorman, l1993) also describes the developments in the energy intensities of the individual sectors and the investments.

Table 2.4 The energy intensities of the economic sectors belonging to the following input-output table row numbers: 1989.

Input-output table row number*1:	MJ per Dfl
32	4.11
34	5.18
35	4.00
40	4.41
Investments	4.03

*1 Sector 32 = machine industry; sector 34 = automobile industry; sector 35 = manufacture of transport equipment, such as boats, trains etc.; sector 40 = construction and installation, such as infrastructure projects.
For more detailed information of the input-output table row numbers, cf. appendix B and table 2.6.

This energy use for the entire economy is the direct energy use per unit GDP (Gross Domestic Product). The resulting time series of energy intensities are expressed in constant guilders of 1989 since both the energy intensities of 1989 and the GDP for the period 1945-1989 are expressed in constant guilders of 1989.

Next, for each economic sector, for the years 1950-1988, deflators which describe sector-specific price changes are calculated based on ’inland deliveries’ to these sectors expressed in both current guilders and prices of the previous years (Wilting, d1993). Data with regard to these deliveries are only available for the years 1950-1988. For the years 1946-1950 and 1988-1989, the trend in the sectoral deflators is assumed to be the same as the trend for the general deflators (CBS-JB, several years). The energy intensities for 1990 are assumed to be equal to those of 1989. Next, from the 1946-1990 time series, five years averages are calculated. These are shown in table 2.5.

Wilting (1994) calculated energy intensities of all economic sectors for each year in the period 1969-1988 (1988 is the last year the CBS used the old method of collecting their data). For the sectors considered in this study, the figures 2.10 and 2.11 show the time series as calculated by him and as calculated in this study. Wilting used the same methodology for the 1969-1988 series as the methodology used to calculate the energy intensities for 1990 for this thesis. However, in order to study energy use trends for such long time series, he simplified parts of the calculations. These simplifications did not effect the trends in the time series but they did effect the absolute values of the energy intensities. The absolute values of the energy intensities in the time series for the period 1969-1988 are significantly higher than the real energy intensities for the separate years. For a few years, Wilting (1993) calculated these real energy intensities based on the non-simplified calculations.

Thus, simplifications introduced by Wilting led to too high absolute values of the energy intensities in his time series for 1969-1988. These simplifications explain to a large extent the significant differences in the *absolute* values between Wilting's energy intensities time series and the energy intensities time series for the similar period 1969-1988 as calculated for this thesis. A minor part of the differences is explained by the difference in the methods of data collecting between the 1990 data and data of 1969 till 1988[10].

The *trends* in the time series of Wilting and the present study shóuld be similar and so they are. This shows that it is reasonable to calculate the historical energy efficiencies based on trends in the energy use per Dfl of the entire

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[10] Wilting studied the impacts of the difference in the methods of data collecting by the CBS. For 1987, he calculated two energy intensities series based on methodology 3 (cf. Wilting, 1993, p. 55; Wilting, i1996c). The first series is based on CBS input-output data that have been collected by the old method used up to 1988. The second series is based on CBS input-output data that are collected by a new method used since 1989. The energy intensities based on data sets collected by the old method are somewhat higher: 6% to 13% for the sectors 32, 35 and 36 and 25% for sector 34. The methodology used by Wilting for this comparison is comparable to the methodology used to calculate the 1990 energy intensities of this thesis ánd Wilting's own time series for 1969-1988. Therefore, the magnitude of the differences in his comparison for 1987 as described above, is assumed to be representative for the differences between results for the 1990 energy intensities of this thesis ánd Wilting's own time series for 1969-1988 if they would be worked out based on old and new data sets.

The 1987 values for the energy intensities out of Wilting's time series 1969-1988 are considerably higher than the separate results for 1987 based on old as well as new data sets. For the economic sectors 32, 35 and 40, the largest part of the differences found between the 1987-results calculated above and the 1987-results out of the 1969-1988 time series based is explained by the simplified calculations used to calculate the long time series for the period 1969-1988. Only for sector 34 is the difference caused by the way the data set is collected bigger. Therefore, the largest part of the differences found between the 1969-1988 time series of Wilting (based on old data sets) and the 1969-1988 time series for this thesis (and derived from 1990) is also explained by the simplified calculations used to calculate the long time series for the period 1969-1988.

Table 2.5 Historical time series of energy intensities of several economic sectors for the period '1946-1990' expressed in MJ per current Dfl.

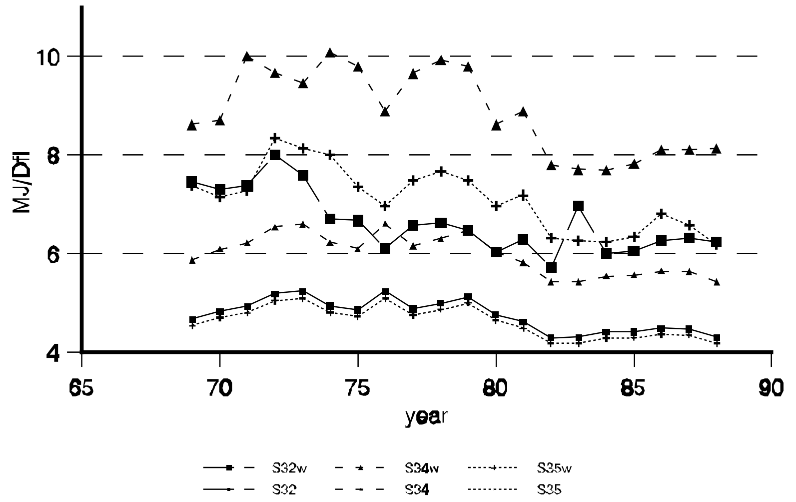
IOrn[*1]	vintage period (years following 1900):									
	46-50	-54	-59	-64	-69	-74	-79	-84	-89	1990
32	17.3	13.7	11.1	10.9	10.2	9.8	6.91	5.08	4.42	4.11
34	18.3	14.8	12.4	12.5	12.1	12.0	8.46	6.36	5.63	5.18
35	14.1	11.4	9.6	9.6	9.3	9.3	6.53	4.91	4.34	4.00
40	35.0	28.7	20.7	18.2	14.7	12.4	7.80	5.13	4.79	4.41
INV[*2]	22.8	19.5	15.9	14.5	12.1	10.7	7.23	4.95	4.32	4.03

*1 For explanation of the input-output table row numbers (IOrn), cf. appendix B and table 2.6.
*2 INV = investments.

economy. For *one* year, the year 1976, figures calculated by Wilting and data calculated in this study show extremely different trends. The increases in the energy intensities of the economic sectors in this study, compared to 1975, are due to an increase in the average national energy use. This increase in the national average is mainly explained by an increase in the energy use by the chemical basic products industry (with IO-table row number 26). The energy use of most other industries in the same year decreased (Noorman, 1995). Since Wilting calculated the energy intensities for all sectors separately, he actually found this decrease in the energy intensity for 1976 for other sectors than the chemical basic products industry (i.e. for all sectors shown in figures 2.10 and 2.11).

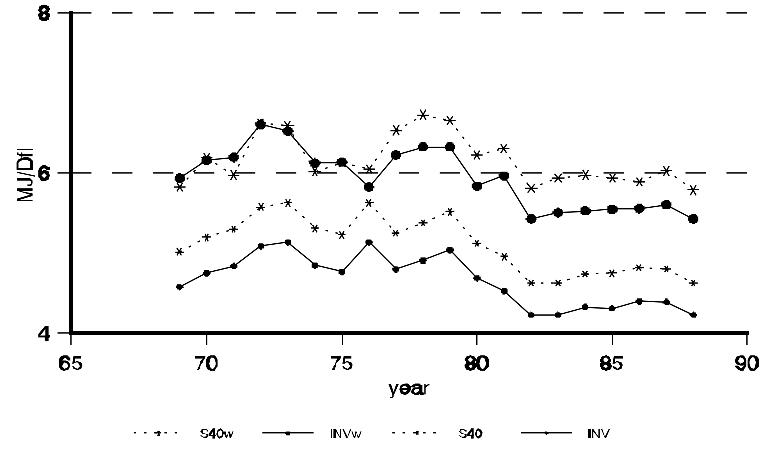
Step 2: The embodied energy of the capital goods stocks in freight transport systems

The embodied energy of capital goods stocks is the product of the monetary value and the energy intensity of the corresponding economic sector, i.e. the sector by which the capital goods are produced. An estimate of the monetary value is published in the statistics of the capital goods stocks (CBS-KGV, 1993). These statistics contain separate data for rail, road and water transport. A description of the different categories of capital goods considered in capital goods stocks tables of the different transport sectors is given in table 2.6 (see below). The main categories of capital goods for the transport activities are the 'external means of transport' which are mainly vehicles, and 'other building and earthwork' which is e.g. infrastructure. The values of the capital goods stocks in current prices are divided by type and vintage. They include



S32 refers to the energy intensity series of economic Sector 32 ; a' w' refers to series developed by Wilting'; no 'w' refers to the series developed for this study.
(For explanation of the sector numbers, cf. Table 2.7)

Figure 2.10 Comparison of the time series of energy intensities as calculated by Wilting (1994) and as calculated in this study - part 1.



S32 refers to the energy intensity series of economic Sector 32 ; a'w' refers to series developed by Wilting'; no 'w' refers to the series developed for this study.
(For explanation of the sector numbers, cf. Table 2.7)

Figure 2.11 Comparison of the time series of energy intensities as calculated by Wilting (1994) and as calculated in this study - part 2.

investments and expenditures on major maintenance, both on a replacement value basis.

In order to calculate the embodied energy of the capital goods involved in transport activities, for each category of capital goods stocks the corresponding Dutch economic sector must be defined. The categories and their corresponding sectors are shown in table 2.6.

Table 2.7 shows the for this study most important industrial activities which belong to these sectors. These activities are classes or groups of industry according to the Standard Industrial Classification (CBS-NR, 1991). A detailed list containing *all* groups of industry belonging to the different classes is given in appendix C.

The embodied energy of capital goods stocks equals the product of the monetary value and the energy intensity of the corresponding economic sector. For example, ’the industrial and commercial buildings’ (cf. table 2.7) are produced by the Dutch production sector 40 ’construction and installation on construction projects’.

However, not all products that are part of the transport system are produced in The Netherlands. Therefore, the energy intensities by which the products are produced might not be the energy intensities of the Dutch economic sectors by definition. However, since research results regarding energy intensities of economic sectors are relatively scarce, it seemed reasonable to start from the Dutch situation for which relatively many data are available. It was known, that depending on the part of the study, this choice would lead to errors in the estimates of the energy requirements. Consequently, energy requirements calculations based on these Dutch energy intensities have to be discussed with regard to this starting point.

The estimates of the value of the capital goods and the time series of the energy intensities of the relevant economic sectors are combined in accordance with the method described in section 2.3.2. This leads to estimates of the embodied energy (of parts) of a transport system. If 1990 energy intensities are used, the result equals the energy requirements necessary to produce the capital goods in 1990, i.e. based on technologies of 1990. If historical energy intensities are used, the result equals the energy requirements used for the production of the capital goods in earlier times, i.e. based on production technologies formerly used.

Table 2.6 Classes of capital goods (CBS-KGV, 1993) involved in transport activities and the economic sectors by which they are produced.

Category	Description	Produced by sector number
1	land	
2	industrial/commercial buildings	40
3	other buildings and earthwork	40
4	external means of transport	34/35
5	internal means of transport	32
6	computers	32
7	other machines, apparatus and installations	32
8	other types of capital goods	INV

Table 2.7 Input-output row numbers and the classification by type of economic activities (CBS-KGV, 1993, NV Databank, 1990).

Sector = IO table row number[*1]	Classes/ groups of industry	Description
32	35	Machine industry
34	37	Automobile industry
35	374/379	Manufacture of transport equipment (other enterprises)[*2]
40	50	Construction and installation on construction projects[*3]
INV	-	Investments

*1 As mentioned in footnote 4, sector ’X’ is in fact a group of economic activities which correspond to row number ’X’ in the input-output table.

*2 The ship building and train building industry belong to this sector.

*3 Road construction and the construction of other infrastructural projects belong to this sector.

Step 3: The indirect energy requirements of freight transport expressed in megajoules per ton kilometre

For each economic activity, the presence of capital goods is essential to produce output. Transport is such an economic activity. The vehicle park, the infrastructure network and other equipment are necessary to fulfil a transport demand. To keep the transport system functioning, new investments are continuously necessary in order to compensate depreciation.

In order to calculate the indirect energy requirements of the system, these replacement investments are related to the output of the system, the transport performance.

For each type of capital goods, based on its life span and the vintage structure of the goods, the depreciation of the capital goods *expressed in embodied energy* is calculated. Subsequently, the replacement investments of the transport system are defined as the sum of the depreciations of all capital goods involved.

The transport performance of the system is measured in ton kilometres.

Finally, the indirect energy requirements of freight transport are defined as the embodied energy necessary to fulfil one unit of transport performance. In other words, *the indirect energy requirements of freight transport are defined as the replacement investments in energy terms necessary to perform one ton kilometre*.

Since transport performance is the last step in this methodology described, it is easy to change the transport performance unit, if necessary.

2.5.3 Process Energy Analysis (PEA)

A process analysis of a service activity such as transport is *a collection of product process analyses* (Moll & Bos, 1993). Each capital good involved in the service ’freight transport’, that is each vehicle, each kilometre of infrastructure and each computer for the use of freight transport, is a separate product which is part of the activity. The embodied energy of the freight transport system is the sum of the energy embodied in vehicles and infrastructure and all other capital goods serving the transport system. In other words, a process analysis of transport includes a product flow analysis and material and energy flows analyses of the products involved (cf. also section 2.2).

The application of process energy analysis in freight transport system analysis is summarised in figure 2.12. Mass balances of vehicles and infrastructure form the core of the analysis. The embodied energy of a single

product, vehicle or kilometre of infrastructure, is the embodied energy of the production materials used, the direct production energy, and the embodied energy of the capital goods required for production.
Based on the embodied energy of the transport system, the indirect energy requirements of freight transport are calculated in a similar way as in IOEA.

The transport depreciation is calculated based on the lifespan and the vintage structure of the goods. Next, the combination of depreciation and transport performance leads to the indirect energy use of freight transport.

The energy requirements calculated by PEA are energy requirements necessary for the production of the vehicles and infrastructure in the year 1990, i.e. based on production technologies of 1990.

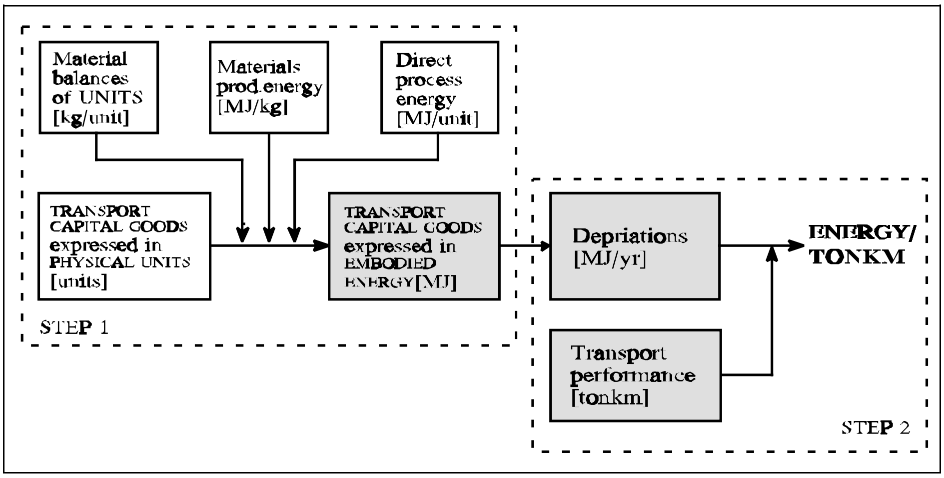


Figure 2.12 Overview of the process energy analysis based methodology for freight transport systems as developed for this study.

The mass balances of several parts of the transport system contain similar materials. This section presents a standard database for this study which contains the relevant materials and their GER values (cf. table 2.8). These values are used in the analyses presented in chapter 3 till 5 inclusive.

The most important sources for the GER values of the materials are two publications by Van Heijningen et al (1992a, 1992b). For 1991, these reports contain the calculations of the GER values of many materials used in this study. (The values are supposed to be equal to those of 1990). Van Heijningen published the energy requirements for the raw materials and the first, second and third order GER values. These orders refer to the IFIAS order scheme (IFIAS, 1974; cf. figure 2.2). For the materials discussed below, the third order energy values are presented if not explicitly stated otherwise.

Table 2.8 GER data of the relevant materials for this study (1990).

Material	GJ/ton	Material	GJ/ton
Iron/steel raw material	20.2	SBR[*1]	59
... plate production	10	Plastics	75
Cast iron raw material	16.7	Wood	30[*2] 36[*3]
... casting	10.9	Glass	50
Aluminium	198	Paint	50
... plate production	10.05	Sand	0.1
Copper	90	Ballast bed	0.25
		Concrete	2.5
		Asphalt	2.6

[*1] SBR is Styrene Butadiene Rubber.

[*2] The value, 30 GJ/ton, refers to wood used in sleepers. This wood originates from France; energy requirements of drying and transport to The Netherlands are not included.

[*3] This value, 36 GJ/ton refers to 'average' European hard wood. This wood originates from different countries; energy requirements of drying and transport to the Netherlands are included.

The GER values include production technologies of 1990 and materials recycling rates of 1990. Thus, by means of these GER values, the embodied energy of capital goods stocks based on the state-of-the-art in 1990 can be calculated. *Material* recycling rates of 1990 are discussed if recycling is put into practice to a sufficiently large extent. *Product* recycling is discussed in the chapters 3 till 5 which deal with the products made from these materials.

Steel and steel plates

There are three main routes by which primary steel is produced, the Basic Oxygen Furnace process (BOF), the Open Hearth process and the Electric Arc Furnace (EAF) process. Worldwide, the first one is the dominating process. The third one is rarely used in Europe but becomes more and more common practice in the United States.

The Dutch primary steel production at Hoogovens applies the BOF route and may be considered representative for the European steel production. In most cases, steel used in The Netherlands is obtained from the European market. The Gross Energy Requirement (GER) of Dutch steel according to Worrell and de Beer is 23.4 MJ/kg (van Heijningen, 1992a). This value includes the input of

12% of secondary steel in steel processing.

The truck, train and ship construction industry uses steel plates which are produced from steel blocks. The energy requirements for the production of steel blocks is 20.2 MJ/kg. These steel blocks are flattened out. Next, in some cases the steel is galvanised and finally the plates are pressed. For these processes 7.2 MJ/kg, 1.5 MJ/kg and 1.27 MJ/kg respectively is needed (Cornelissen, 1993). For a galvanised steel plate, the production energy is 9.97 MJ/kg. The total energy requirements for steel plates used in the truck, train and ship construction industry amounts to 30.2 MJ/kg.

Cast iron and cast iron products

For the production of cast iron, very often secondary steel (scrap) is used. In average, the input of primary steel is between 0 and 30 percent. To mould cast iron products, about 10.9 MJ/kg (Cornelissen, 1993) is needed. The electro oven necessary for the cast iron production uses 1.61 MJ/kg (Cornelissen, 1993). Finally, in order to derive the total energy of cast iron products, the energy needed to collect and transport iron scrap and to make it suitable for cast iron production (assumed to be 5 MJ/kg) also has to be taken into account.

In trucks, the quality of iron has to be rather high (Daf, 1995). Therefore, the primary steel content in cast iron is assumed to be 50%. Based on a 50 percent primary steel content, the GER value for cast iron products is about 27.6 MJ/kg (0.5*23.4+10.9+5).

Aluminium and aluminium plates

With regard to aluminium, this study concentrates on the production of aluminium plates. The production processes for aluminium are processes which are world-wide standardised. The energy requirements of aluminium in The Netherlands are 198.2 MJ/kg (van Heijningen, 1992a). This value refers to 100% primary aluminium. (Secondary aluminium is only used in cast aluminium.) According to Cornelissen (1993), the energy requirements for the production of aluminium plates is 10.5 MJ/kg of aluminium.

Copper

According to ’van Heijningen’ (1992b), the energy requirements for the production of copper in The Netherlands are 90 MJ/kg.

Plastics

The GER values of plastics varies by type of plastic. The GER values of plastics range from 62 to 85 MJ/kg (van Heijningen, 1992a, 1992b). Plastics used in cars are mostly ABS (Acrylonitrile Butadiene Styrene, 83.5 MJ/kg), which is used in dashboards, and PVC (62 MJ/kg). The average energy requirements for plastics used in cars are assumed to be 75 MJ/kg.

Styrene Butadiene Rubber (SBR)
Tyres are made of SBR (van Heijningen, 1992a, Koeneman, 1995). Since this material plays an important role in the process analysis calculations it is distinguished from other plastics. The energy requirements of primary materials are 79 MJ/kg (van Heijningen, 1992a). In The Netherlands, about 35% of the tyres is recycled as material. The energy use for the collection and the transport of the tyres is estimated at 5 MJ/kg. Thus, the energy requirements for the production of SBR based on a 35% secondary material input is 56 MJ/kg.

Another 25% of the tyres is recycled as useful products, generally outside the transport sector. Therefore, this recycling rate is not included in this study.

Wood
Wood is used in sleepers in rail infrastructure and in vehicles. Sleepers are generally made of tropical hard wood imported from France. This wood is transported to The Netherlands and is used in the rail infrastructure as soon as the wood reaches a 30% moisture degree. According to Van Heijningen (1992b), the energy requirements of European hardwood *exclusive* the transport energy and the energy requirements for drying, i.e. the energy requirements of the raw materials, are 30 MJ/kg. (In calculations based on this figure, the energy requirements of the transport of wood to The Netherlands has to be added.)

For the energy requirements of wood used in vehicles, the energy requirements are assumed to be those of ’average’ European hard wood originating from different countries. These energy requirements of 36.1 MJ/kg include the energy requirements for drying and transporting to the Netherlands.

Glass and paint
For glass and paint, no separate data are available. Therefore, the energy requirements are estimated at 50 MJ/kg which are the energy requirements of the rest products in cars according to Moll (1993). In the process analysis calculations, this estimated value will be of limited influence since the share of these materials in the material balances of the vehicles is very low. Often, this share is not even considered separately.

Sand
Sand used in The Netherlands originates from the south of The Netherlands (Limburg and Brabant), Belgium or Germany. The energy requirements are 0.1 MJ/kg. This value includes transport energy to one of the inner harbours in The Netherlands (van Heijningen, 1992b). Transport to the client is not included.

Ballast subbase materials
Ballast subbase materials are made of materials such as gravel or granite. The

energy requirements of broken gravel are 0.2 MJ/kg. Those of broken natural stone are 0.37 MJ/kg (van Heijningen, 1992b). For ballast subbase materials in The Netherlands, the energy requirements are assumed to be 0.25 MJ/kg. This value includes transport energy to one of the inner harbours. Transport to the client is not included.

Asphalt

The energy requirements of asphalt as derived from Gerardu (1983), i.e. the energy requirements of GAB[11], are 2.64 MJ/kg. These energy requirements include the extraction of raw materials, the transport of these materials to the asphalt installation, the preparation of asphalt, the transport of asphalt to the place where needed and the process energy for the construction of asphalt layers[12]. For each of the phases just mentioned 1.95, 0.16, 0.42, 0.08 and 0.03 MJ respectively per kg of asphalt are needed. Of the 1.95 MJ for the extraction of raw materials, 98 percent is embodied in bitumen which makes up only 4.5 percent of the total weight of the materials used for the production of GAB. In other words, bitumen makes up 73 percent of the total energy requirements of GAB.

The re-use of asphalt in 1990 is neglected. Several sources mention input-rates of secondary materials in the production process of asphalt between 7% and 14%. Since the decrease of the GER value of asphalt due to re-use would be compensated by an increase due to the energy required to collect and transport the secondary material, the input of secondary materials is neglected.

In spite of the fact that GAB is not the only type of asphalt used in the Dutch roads, the energy requirements of GAB are assumed to be representative for all asphalt layers on the Dutch roads. This seems reasonable since other sorts of asphalt also consist of sand, gravel, filler (although in different ratios) and bitumen (of which the amount is more or less constant). Other types of asphalt layers frequently applied in the Dutch roads are DAB, OAB and ZOAB[*11]. The upper asphalt layers, and therefore maintenance materials for roads, usually consist of DAB of ZOAB.

Concrete

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[11] GAB stands for Grind (gravel) Asfalt (asphalt) Beton (concrete); DAB stands for Dicht (solid) Asfalt Beton; OAB stands for Open (open) Asfalt Beton; and ZOAB stands for Zeer (highly) Open Asfalt Beton.

[12] In Gerardu (1983), the energy requirements of a ton of asphalt are expressed in litres of oil. To calculate the primary energy requirements, this study uses the ERE value 1.037 for ’oil extraction and transport to The Netherlands’ and the ERE value 1.12 for ’oil distribution in The Netherlands’ (Wilting).

The energy requirements for the production of concrete are deduced from the composition of the raw materials used to produce concrete. The weight percentages of the input materials gravel, concrete, sand, cement, water and steel are 37, 9, 32, 14, 4 and 4 percent respectively. These percentages, together with a GER value for cement of 4.5 MJ/kg (van Heijningen, 1992a), GER values for gravel, sand and steel as mentioned above and a negligible embodied energy contribution of water, the embodied energy of the raw materials input of concrete is estimated at 2 MJ/kg. Next, the process energy for the production of concrete is estimated at an additional 25%. This leads to an estimate of the GER value of concrete of 2.5 MJ/kg.

2.5.4 Hybrid Energy Analysis (HEA)

The energy requirements of freight transport consist of a calculation of the energy requirements of both infrastructure and vehicles. For both infrastructure and vehicles, process analysis can be applied since the material and energy balances of products such as a truck, one kilometre of infrastructure, etc. are available. However, for a complete process analysis of freight transport, the data sets are insufficient.

Relevant data with regard to the direct energy requirements, i.e the first-order energy data, lack and materials and energy data with regard to the orders three and higher are not easily available. The energy requirements of order 1 and 3 and higher are therefore calculated based on IOEA. Besides, for energy contributions of the orders higher than two, less time-consuming methods than process analysis such as IOEA make sense anyway since these parts of the system contribute little to the overall energy requirements.

In the analyses of the chapters 3, 4, 5 and 7 , the process energy analysis based calculations are in fact hybrid calculations. However, the second order contributions contribute most to the overall energy requirements in PEA.

2.6 Basic methodologies for freight transport emission analysis and the calculation of reference data sets

This section describes the application of the emission analysis methodologies described in section 2.4 and the resulting reference data sets. As in the case of the reference data sets for energy analysis, the data sets presented in this section refer to The Netherlands and underlie all transport modes.

The structure of the application of the emission methods in freight transport emission analysis is the same as in freight transport energy analysis (cf. figure 2.13). The methods differ with regard to part 1, i.e. the part in which the indirect emissions of the capital goods stock concerned is calculated. In emission and energy analysis, all methods share parts two and three. This section only discusses part 1 as the parts two and three have already been discussed in the sections 2.5.

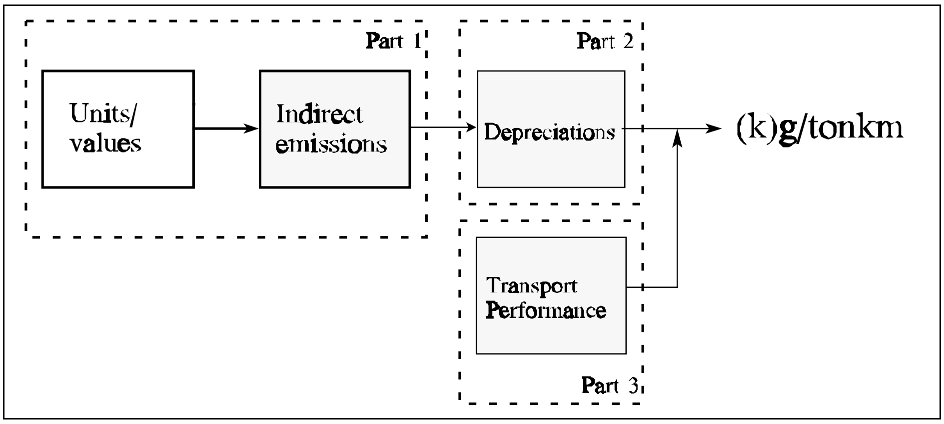

Figure 2.13 The common structure of all freight transport emission analyses.

Input-Output Energy Emission Analysis (IOEEmA)

For the relevant economic sectors for this study (cf. table 2.7), this method calculates the carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions per Dfl based on the direct energy inputs of all sectors and the monetary flows among the sectors.

As in IOEA, the energy carriers selected are the secondary energy carriers such as coal products, mineral oil products, natural gas and electricity. For these energy carriers, table 2.9 shows the assumed related CO_2 emission factors (Wilting, 1993). These CO_2 emissions factors include emissions related to the extraction, the transport and the distribution of the energy carrier. Next, the CO_2 emissions of the economic sectors are calculated by means of these emission factors, shown in table 2.9, by means of the cumulative monetary deliveries to the sectors and by means of the ERE values of the secondary energy carriers (Wilting, 1996a).

SO_2 emissions per energy carrier are derived from an emission table which contains the direct SO_2 emission factors of several economic sectors and several energy carriers (CBS, d1993). Since SO_2 emissions are mainly fuel related, the emission factors for the different energy carriers are equal for almost all economic sectors. For the energy carriers concerned in this IOEEmA, this study uses the average emission factors of the economic sectors distinguished by the CBS. Next, to include SO_2 emissions related to the extraction, transport and distribution of the energy carriers, the direct emission factors are multiplied by the ERE value of oil products (cf. table 2.3). Finally, the emissions of the economic sectors concerned in this IOEEmA are calculated by means of the SO_2 emission factors, the cumulative monetary deliveries and the ERE values of the secondary energy carriers. Table 2.10 shows the CO_2 and SO_2 emissions of the economic sectors as used in IOEEmA.

Table 2.9 CO_2 and SO_2 emission factors of the secondary energy carriers (1990).

	CO_2 ^{*1}, g/MJ_{pr}	SO_2 ^{*2}, g/GJ_{pr}
Coal products	133	198
Mineral oil products	79	97
Natural gas	56	2.1
Electricity^{*3}	525	226

*1 The CO_2 emissions per MJ primary energy (pr) are derived from Wilting (1996). The emissions from coal products equal the emissions of cokes since cokes are the coal products most frequently used by the economic sectors.

*2 The SO_2 emissions per MJ primary energy equal the direct emissions derived from the CBS (CBS, d1993) times the ERE value of oil products.

The electricity emission factor of SO_2 = (0.45 X coal products emission factor
+0.48 x natural gas emission factor
+0.07 x nuclear energy emission factor(=0))
divided by 0.4 (efficiency power plant).

An estimate of the indirect emissions of capital goods stocks present in 1990 is made by means of the emission values in g/Dfl and the values of the capital goods stocks, i.e. the values of vehicles and/or infrastructure. This calculation is analogous to the calculation of the embodied energy of the capital goods stocks in IOEA. The indirect emissions are the emissions that would result from the production of the capital goods stocks according to the technology of 1990. A calculation of the emissions in earlier times resulting from the production of the capital goods present in 1990 (which is a calculation analogous to the calculation of the historical embodied energy of capital goods stocks) is not possible since no historical emission data are available.

Process Emission Analysis (PEmA)

For the relevant materials in this freight transport study, the present study calculates the cumulative emissions for the production of one kilogram of these materials. The cumulative emissions include emissions related to the extraction of raw materials as well as emissions related to the production of the material and include emissions produced in The Netherlands as well as emissions produced in foreign countries. The cumulative emission factor of a material is defined as the emission variant of the GER value of the materials. It is indicated as the gross emission factor (GEm).

Table 2.10 CO_2 and SO_2 emission factors for the economic sectors under concern in this study expressed in (m)g/Dfl (1990).

	CO_2, g/Dfl	SO_2, mg/Dfl
Machine industry	354	284
Automobile industry	411	306
Manufacture of transport equipment (other enterprises)	336	260
Construction projects	322	259

Emission data with regard to the production of materials are scarce. Therefore, the GEm values of the materials relevant for this study are derived from a limited number of sources. These sources are a data bank which contains emissions from all industrial and non-industrial activities in The Netherlands in 1992 (Hoofdinspectie Milieuhygiëne, d1992) and some studies which focus on the emissions related to the production of materials or parts of the materials production processes (Frischknegt, 1994, Fraanje, 1992, Habensatter, 1991, Hoefnagels, 1991).

The emission data bank including all industrial and non-industrial activities in The Netherlands is maintained by TNO emission registration. Industrial emissions originate from all types of industry. Non-industrial emissions concern emissions derived from, for instance, heating, transport and agriculture. A large share of the industrial emissions (90 to 95 percent of the total emissions) are emissions from companies of which the individual emissions are known. These emissions are registered by the companies themselves. It is important to realise that, in case a company for instance produces passenger cars, only the emissions produced in The Netherlands are included in their emission figures. Not included are emissions which result from the manufacturing of semi fabricates which are imported by the car company. Estimates for the total emissions in The Netherlands as well as the emissions specified per industrial activity are available in the public domain. For the separate industrial activities, published in the so-called individual emission registration, these emissions are specified in physical units i.e. for instance in kg per kg output or in kg per product unit.

Examples of the activities considered in the TNO data bank are the production of SBR, the production of raw iron, and the casting of cast iron products. The emissions in The Netherlands related to these activities make up part of the GEm value of e.g. steel plates. Emissions produced in foreign countries in favour of the final product produced in The Netherlands can be derived from other sources.

Such sources which discuss the emissions related to the production of materials or parts of the materials production processes are also used to derive the GEm values directly. The GEm values of materials such as sand are available as such (Fraanje, 1992). However, the GEm values of many other materials have to be calculated by combining the emission data of several materials and processes. E.g., the emissions resulting from the production of raw iron is calculated by combining the emissions resulting from sinters, pellets, limestone, cokes, oxygen, etc. Next, the emissions resulting from the production of sinters and pellets are calculated by combining emissions from the production of iron concentrate and other components (Fraanje, 1992).

The calculation of GEm values is time consuming. Table 2.11 shows the reference data set for process emission analysis as derived from the sources above. An estimate of the indirect emissions of capital goods stocks is made by means of this data set and by means of the material balances of vehicles and of infrastructure which belong to the capital goods stocks.

Remarkable in table 2.11 are the differences among the materials with respect to the CO_2 emissions. Since a strong relation exists between energy requirements and CO_2 emissions, the differences among the materials with respect to CO_2 emissions should be comparable with the differences with respect to the GER values (cf. table 2.8). From this point of view, the emissions resulting from the production of aluminium are far too low. CO_2 emission resulting from the production of concrete are higher than they would be merely due to the relation between energy use and CO_2 emissions because in the case of concrete production, CO_2 emissions do also include process emissions resulting from the production of lime(stone).

One can easily estimate lower bounds for the CO_2 emissions of the materials by assuming that the cumulative energy input for the production of the materials is all gas. For aluminium, the lower bound is 11088 g CO_2 per kg of aluminium (11088 = 198 MJ/kg times 56 g/kg). For steel, it is 1690 g/ kg steel. Therefore, one can conclude that CO_2 emissions of steel are somewhat underestimated while those of aluminium are far underestimated.

Unfortunately, in general, for both CO_2 emissions and other emissions the data available are inconsistent and incomplete. Therefore, the data set specified in table 2.11 has to be considered being indicative.

Input-Output Energy product Process Emission Analysis (IOEpPEmA)

For 1990, the CBS published the cumulative energy requirements, divided over several primary as well as secondary energy carriers, and the total production value of 316 economic activities (CBS, d1990). For 1993, the CBS published emission data of secondary energy carriers specified per economic sector (CBS,

Table 2.11 The reference data set for process emission analysis, emissions factors in g/kg.

Material	CO_2	SO_2	CO	NO_x	VOC	Aer
Steel/iron:						
Steel	1233	8.82	38.9	8.29	0.73	16.9
Aluminium	1290	75	17.0	27.9	4.07	37
PVC	2596	7.61	0.690	6.31	2.55	0.561
SBR	50.7	-	-	35.6	3.96	-
Asphalt	140	0.386	0.155	0.441	0.093	0.004
Concrete	480	0.883	1.307	1.609	0.584	0.022
Sand	2.68	0.038	0.044	0.084	0.011	-

Explanation:
The following materials are derived from the sources 1) Hoofdinspectie Milieuhygiëne (d1992), 2) Frischknegt (1994), 3) Fraanje (1992) and 4) Habensatter (1991):
Steel: 3; Aluminium: 2,4; PVC: 3; SBR :1; asphalt: 3; concrete: 3; sand: 3.

d1993). These emissions are *direct* emissions, i.e. emissions related to economic activities of the sectors only. The two CBS databases form the basis for the application of the methodology described in this subsection.

As shown by figure 2.7, IOEpPEmA consists of the two main steps (cf. section 2.4). Step 1 combines energy and process-related emission figures and the energy requirements of economic activities to calculate activity-related emission figures expressed in (m)g/Dfl. Step 2 combines these emissions per Dfl and total investments in transport capital goods stocks in order to calculate the indirect emissions of a transport system. The methodology applied in step 2 is similar to the methodology applied to calculate the embodied energy of transport capital goods stocks. It will not be detailed in this section.

The elaboration of step 1 consists of two parts. First, it deals with the calculation of *cumulative* (secondary) energy-carrier related emission figures for several economic sectors relevant for this study. The calculation is performed by combining sector and (secondary) energy-carrier related *direct* emissions figures, published by the CBS (d1993), on the one hand and *cumulative* mutual deliveries of economic sectors, made available by Wilting (1996b), on the other hand. Second, the indirect emission figures, expressed in (k)g/GJ, and the energy requirements of the activities based on secondary energy carriers are combined in order to calculate the indirect emissions of the activities concerned, expressed in (m)g/Dfl.

Cumulative sector- and energy-carrier related emission figures

For 1993, the CBS published emission data of secondary energy carriers specified per economic sector (CBS, d1993). Such CBS tables are available for CO_2 SO_2, CO, NO_x, VOC and aerosols emissions. For each of these compounds, the CBS tables distinguish thirteen different energy carriers and nineteen different economic sectors. The emissions figures published, expressed in (k)g/GJ, are *direct* emissions, i.e. emissions related to economic activities of the sectors only. These are supposed to be equal for the year 1990.

The *cumulative* emission figures of each of the economic sectors relevant for this study, i.e. sector 34, 35 and 40 (cf. table 2.12), are calculated as shown schematically in figure 2.14. The cumulative energy input of an economic sector S consists of the direct energy inputs and the indirect energy inputs. The direct energy inputs of sector S are calculated by multiplying the direct energy inputs of sector S, expressed in MJ per Dfl product of sector S (Wilting, 1996b), by the production value of sector S (cf. step Idir). The indirect energy inputs of sector X in sector S are calculated by multiplying the cumulative deliveries of sector X to sector S by the direct energy input of sector X in sector S, expressed in MJ/Dfl of sector X (cf. step Ib,ind). The cumulative deliveries of sector X to sector S are the product of the cumulative deliveries of sector X to sector S, expressed in Dfl per Dfl of sector S, and the production value of the sector S (cf. step Ia,ind). The cumulative energy inputs of an economic sector by all other economic sectors including the sector itself are divided over the secondary energy carriers coal, oil, gas and electricity.

The emissions resulting from the use of these secondary energy carriers are derived from the CBS tables containing the *direct* emissions of the economic sectors. These tables distinguish several types of coal, oil and gas products. The direct emissions from the use of coal are represented by the emissions resulting from the use of ordinary coal, those of oil by the emissions resulting from the use of HBO[13] and those of gas products by the emissions resulting from the use of natural gas. The choice for these representative energy carriers is based on the fact that these energy carriers are the most frequently used energy carriers in their category in The Netherlands (CBS-NEH, 1992). Direct emissions from electricity correspond with the emissions from the electricity sector in the CBS emission tables (d1993)[14].

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[13] HBO (HuisBrandOlie) is a group of several light oil products.

[14] The direct emissions from the use of electricity in The Netherlands can also be calculated by combining the total national emissions (N.V.SEP, 1996) and the total national central electricity production (N.V.SEP, 1993). Emission data calculated this way correspond to the emission data of the electricity sector in the CBS tables (CBS, d1993).

For each of the sectors 34, 35 and 40, the combination of its cumulative energy requirements per energy carrier and the direct emissions of the delivering sectors per energy carrier leads to the cumulative emissions of the sectors specified per energy carrier (cf. steps II,ind and II,dir in figure 2.14).

Table 2.12 shows emission data per unit of energy input of the economic sectors 34, 35 and 40, i.e. the sectors to which the 'transport related activities' belong (for explanation cf. table 2.12). The figures shown in the table are weighted averages of the figures specified per energy carrier which are actually used in the analysis. However, the weighted averages are more of general

Table 2.12 Cumulative emission factors of relevant economic sectors for IOEpPEmA, expressed in (k)g/GJ (1990).

Sector[*1]	CO_2	SO_2	CO	NO_x	VOC	Aer
	kg/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ
34	89.5	57.5	14.7	118	5.25	4.13
35	92.0	56.9	15.8	118	5.29	3.92
40	85.8	64.7	33.7	133	7.48	5.21

*1 Sector 34 concerns 'the automobile industry', sector 35 concerns 'the industry for manufacturing of transport equipment (other enterprises)', sector 40 concerns 'construction projects' such as infrastructure. For more information about of the sectors, cf. table 2.6 and appendix B.

Table 2.13 Direct (dir) and cumulative (cumul) emission factors of relevant economic sectors for IOEpPEmA, expressed in (m)g/Dfl (1990).

Emissions	sector 34[*1]		sector 35		sector 40	
	Cumul	Dir	Cumul	Dir	Cumul	Dir
CO_2 (g/Dfl)	351	33.7	284	18.9	279	32.2
SO_2 (mg/Dfl)	226	23.2	176	13.8	210	34.3
CO (mg/Dfl)	57.9	3.41	48.8	1.81	110	52.4
NO_x (mg/Dfl)	463	57.2	363	32.4	431	27.2
VOC (mg/Dfl)	20.6	1.60	16.3	0.83	24.3	7.56
Aerosols (mg/Dfl)	16.2	1.16	12.1	0.69	16.9	1.94

*1 For more information about of the sectors, cf. table 2.12, table 2.6, and appendix B.

interest and show similar differences as are present in the energy-carrier specific figures.

For the same economic sectors, table 2.13 shows emission data per monetary unit of product. These figures can be calculated based on the same data sets as are used to calculate the emission figures per energy unit. Data shown in table 2.13 are of interest for calculations described in chapter 7.

Activity-specific energy requirements
For 1990, the CBS published the total energy requirements, divided over several primary as well as secondary energy carriers, and the total production value of 316 economic activities (CBS, d1990). This analysis uses the secondary energy input data of transport related activities[15].

The energy input data of the activities are increased by 10% in order to incorporate the energy embodied in the capital goods required for the production of the final products. For industrial activities in the Netherlands, these energy requirements are estimated at about 10% of the total energy input (Wilting, 1996c). Table 2.14 shows the secondary energy requirements of the activities that are relevant for this study.

2.7 The applied methodologies for rail, road and water transport

Several data sets are available for the different freight transport systems and therefore, several input-output and process-based energy and emission methodologies can be used to calculate the indirect energy requirements.
Tables 2.15 and 2.16 show the energy and emission methodologies applied to calculate the embodied energy and emissions of road, rail and water freight transport. The water transport system considered is inland shipping. Most of the calculations deal with infrastructure and vehicles separately.

Data sets are insufficient for complete process analyses. The energy requirements and indirect emissions with regard some parts of the freight transport system can only be estimated by IOEA. In the analyses based on process-analyses, part of the embodied energy or indirect emissions is calculated based on IOEA.

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[15] The values published have been corrected for additional products from the activities which are used in other industrial activities, i.e. the energy input of the activities is decreased by the embodied energy value of these products.

However, since the focus in the process-based analyses is strongly aimed at processes and materials, the analyses are classified as being process analyses[16].

As indicated before, the basic structure of the energy and emission analysis methods in this freight transport study is the combination of the embodied energy or indirect emissions of the system, the depreciations of the system and the transport performance belonging to the system (cf. figure 2.15).

In IOEA and IOEEmA, the embodied energy and indirect emissions are derived from the value of the capital goods stocks and the energy/emission intensities of the economic sectors. The start values of these analyses are highly aggregated. In the calculations, parts of the transport system are studied and specified. The method follows a top down approach. In the process analysis based analyses, PEA and PEmA, the embodied energy of the system is based on the physical units, such as the number of vehicles, the mass balances of these vehicles and the GER and GEm values of the materials.

Table 2.14 Cumulative energy requirements for several transport-related economic activities, expressed in MJ/Dfl (1990).

	Car/ car parts	**Ships**	**Trains**	**Infra-structure**
Secondary energy carriers[*1]				
Coal products	0.81	2.93	1.42	0.68
Natural gas	1.05	0.32	1.65	0.68
Raw oil	2.63	2.28	3.23	6.14
Electricity	1.87	0.30	2.28	2.73
Cumulative energy intensity, MJ/Dfl	6.38	5.83	8.58	10.23

*1 The energy intensities in this table are derived from values published by the CBS (d1990). The raw oil energy intensities are the sum of the intensities of two categories of oil products. The other categories correspond one to one with categories published by the CBS tables. Combined heat and power, a separate category in the CBS tables, is omitted from table 2.14 since its contribution to the energy intensities of the transport-related activities is negligible. Finally, *all* energy intensities are adjusted in order to include the capital goods for production. The energy intensities are increased by 10 percent (for explanation, see subsection 2.6).

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[16] According to the definition (cf. subsection 2.3.4), these analyses could also be classified as being hybrid.

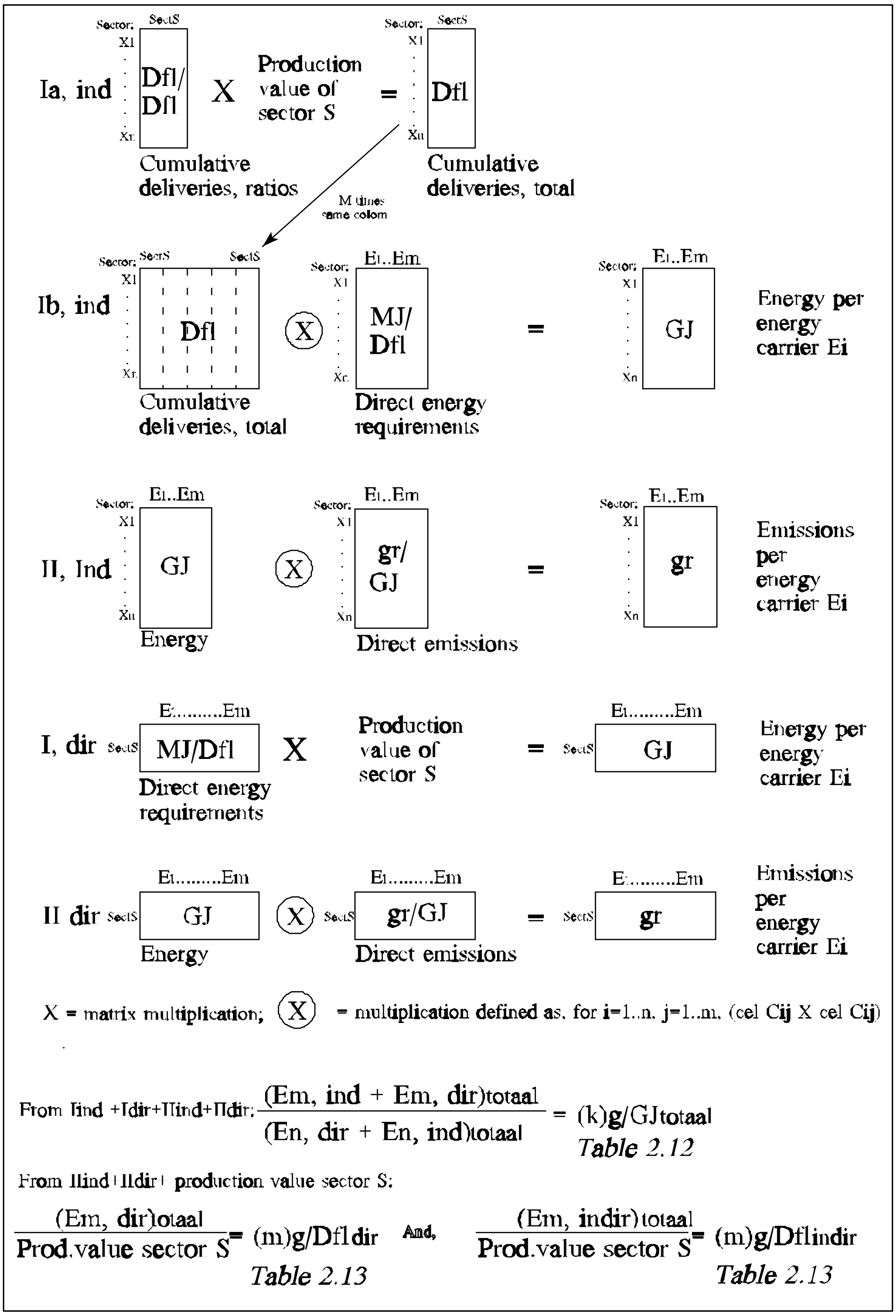

Figure 2.14 The calculation of the cumulative emission factors of sector S.

Table 2.15 The methodologies applied to calculate the indirect energy requirements of freight transport.

Transport mode	Subsystem	Methodology*1		
		IOEA hist	IOEA 1990	PEA
RAIL	Infrastructure	X	X	X
	Vehicles		X	X
ROAD	Infrastructure		X	X
	Vehicles	X	X	X
INLAND SHIPPING	Infrastructure		X	
	Vehicles			X

*1 IOEA-hist = Input-Output Energy Analysis, based on historical energy intensities;
IOEA-1990 = Input-Output Energy Analysis, based on energy intensities of 1990;
PEA = Process Energy Analysis.

Table 2.16 The methodologies applied to calculate the indirect emissions of freight transport.

Transport mode	Subsystem	Methodology*1		
		IOEEmA 1990	PEmA	IOEpPEmA
RAIL	Infrastructure	X	X	X
	Vehicles		X	X
ROAD	Infrastructure	X	X	X
	Vehicles	X	X	X
INLAND SHIPPING	Infrastructure	X		X
	Vehicles		X	

*1 IOEEmA 1990 = Input-Output Energy Emission Analysis, based on production technologies of 1990; PEmA = Process Emission Analysis; IOEpPEmA = Input-Output Energy *p*roduct Process Emission Analysis.

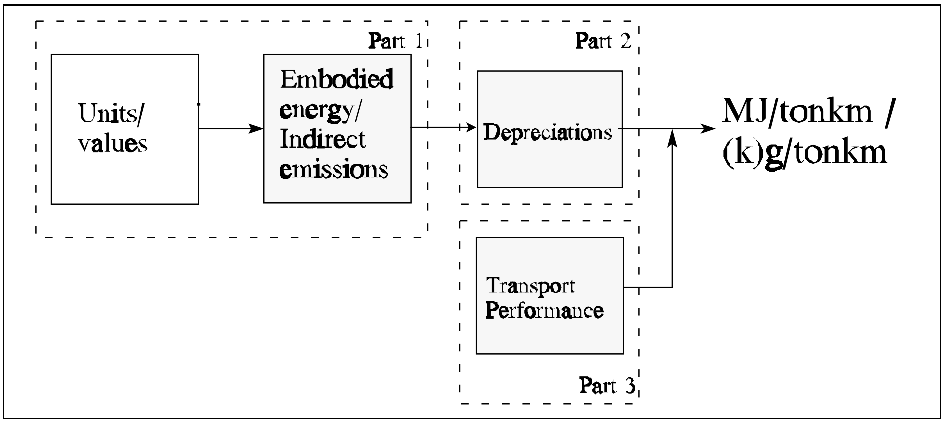

Figure 2.15 The common structure of the freight transport system analyses.

The starting values of a process analysis calculation are highly desegregated: even parts of vehicles are distinguished. In the calculations, a higher aggregation level is reached. The process analysis approach is bottom up. In IOEpPEmA, a combination of process and energy-specific emission data and product-specific energy and monetary data leads to the embodied energy and indirect emissions of the system. In the calculations, some parts are top down and others are bottom-up. The aggregation level of the method can be classified as intermediate.

The chapters 3 till 6 inclusive

Chapter 3 till 5 inclusive discuss the energy requirements of one transport mode in detail. These chapters start with an introduction describing the system, the subsystems and the system boundaries and contain a table which indicates the methods used in this analysis for the subsystems ’vehicles’ and ’infrastructure’. Next, in separate sections, the input-output analysis and the process analysis based estimates of the (sub)systems embodied energy are detailed.

Each section contains figures showing overviews of the calculations. These overviews present the basic structure of the analyses of the different transport modes and subsystems, i.e. the relations among the embodied energy, the depreciations and the transport performance of the transport system (cf. figure 2.15). In each analysis, the three parts of the basic structure are thoroughly discussed.

For each (sub)system, firstly, *the best available estimate* of the indirect energy requirements is calculated. Next, in a sensitivity analysis, the consequences of assumptions made to derive this best estimate are evaluated. An uncertainty analysis is not possible since the variance in most published and calculated data is not available. The following categories of variables are distinguished in order to structure the sensitivity analysis:

- * Strong and Time-Independent (STI).
  These variables are derived from a reliable source and are supposed to remain constant in the long term.
- * Strong and Time-Dependent (STD)
  These variables are derived from a reliable source and have a well-established variable value in the long term.
- * Weak (W).
  The weak variables are variables which are based on rather uncertain data. However, they are not inaccurate by definition. They may be based on expert opinions or literature. They can be both time independent and time independent.
- * Strong Methodological (SM)
  These variables result from choices with regard to methodological problems. The value of SM variables is firmly established.
- * Weak Methodological (WM)
  These variables result from choices with regard to methodological problems that can be topic of discussion.

In a sensitivity analysis, firstly, all variables and methodological choices which played a role in the calculation are summarised in a table. Next, various alternative values for the weak (W) and strong and time-dependent (STD) variables and other methodological choices for the weak methodological (WM) variables are discussed and evaluated.

For each transport mode, results with regard to the ’vehicle fleet’ and ’infrastructure’ based on the different methods are compared and discussed in a subsection at the end of the chapters. Results with regard to all transport modes are summarised, compared and discussed in *chapter 6*.

Extrapolation of the results to other countries or regions and to future systems should be made with due care. After all, the results comprise characteristics of the Dutch system up to 1990. The following features are of special importance:

a features typical for a specific transport mode

E.g., the composition of the fleet in small and big trucks influences the results since the relation between load capacity and embodied energy of the vehicles is different for both types of trucks,

b features typical for the structure and organisation of the total transport system

Characteristics which are related to the structure and organisation of the total transport system can be divided in good-specific features and features related to the logistic organisation of the transport system. Good specific features are, for instance, the mass and volume of the goods. These latter two parameter determine the total mass transported, the load factors, and thus, the embodied energy per ton kilometre. Characteristics of the logistic organisation of the transport system are logistic features of freight modal split choices as well as logistic features of freight transport in relation to passenger transport. Another division of the goods over the different transport modes or another share of freight transport in the total transport performance influences the results.

Such logistic characteristics play an important role in the assignment of values to the performance value of the system and the (freight) transport system depreciations. This concerns the arrow from part 1 to part 2 in figure 2.15.

c *features connected to the technologies applied in the production of vehicles and infrastructure*

The efficiencies of the technologies as applied in the production of vehicles and infrastructure are country and time specific. For instance, in IOEA, these efficiencies are incorporated in the energy intensities of the Dutch economic sectors for the years 1945-1990.

Results should be interpreted in the light of the three features mentioned above. The results of the rail, road and water-transport analyses include the characteristics of the categories discussed and thus describe *the state of the art of the transport modes in 1990 including the system characteristics as specified.*

The chapters 3 till 5 which deal with the transport modes rail, road and water transport respectively, discuss the characteristics which are typical for each transport mode (feature a). Chapter 6 discusses the characteristics pertaining to ’the transport system’ and ’production technology’, with a common influence on the results for rail, road and water transport (features b and c).

Chapter 7

Chapter 7 discusses the indirect emissions of all transport modes calculated by the methodologies Input-Output Energy product Emission Analysis (IOEEmA), Process Emission Analysis (PEmA) and Input-Output Energy product Process Emission Analysis (IOEpPEmA).

The main purposes of studying these emission analyses is to construct and study methodologies for emission analysis. Since parts of the recently existing data sets for these analyses, in particular that of PEmA, are incomplete and inconsistent, the corresponding results for the indirect emissions should be treated with due care. Nevertheless, results give a rough estimate of the importance of indirect emissions in relation to direct transport emissions.