Licentiate thesis for the degree of Licentiate of Engineering

Report 45

ENVIRONMENTAL PERFORMANCE CALCULATION IN TRANSPORT LCI

– Allocation Method Design Issues

by

Sebastian Bäckström

Submitted to the
School of Technology Management and Economics
Chalmers University of Technology
in partial fulfilment of the requirements for the
degree of Licentiate of Engineering

Department of Transportation and Logistics
Chalmers University of Technology
SE - 412 96 Göteborg, Sweden

Göteborg 1999

Report 45

ENVIRONMENTAL PERFORMANCE CALCULATION IN TRANSPORT LCI

- ALLOCATION METHOD DESIGN ISSUES

ISSN 0283-3611

Published by:
Department of Transportation and Logistics
Chalmers University of Technology
SE - 412 96 Göteborg, Sweden

Printed in Sweden
Bibliotekets Reproservice CTHB, Göteborg 1999

" … the theory of market competition, if followed consistently, will inevitably lead to all manner of cross-hauling and wasteful transportation for which the country must in the end pay."

Commissioner Eastman
Interstate Commerce Commission, 1926

caroline
tiden vi betraktar verk med leende våra r
är långt
tack!
sebastian

....

Errata

Licentiate thesis for the degree of Licentiate of Engineering, Report 45

ENVIRONMENTAL PERFORMANCE CALCULATION IN TRANSPORT LCI
- Allocation Method Design Issues

Sebastian Bäckström

The following errors are due to changes by the author introduced after the language checking was completed. The reader is asked to oversee the remaining minor language errors.

Errata with impact on the scientific presentation:

Page no:	**In print:**	**Replace with:**
VII	… functional units: kWh/tkm, g/kg …	…functional units: tkm, kg delivered …
4.	…when applying the *LCA* method…	…when applying the *LCI* method…
31.	…In *figure* one can *se* the difference…	…In *Table 2*, one can see the difference…
38.	…or with electrical *lorries* why the…	…or with electrical *forklifts* why the…
39.	…the result in section showed…	…the result in section *4.3* showed…
44.	…a net of 18 kilo bananas)…	…a net of 18 kilo bananas/*box*)…
45.	*Lorry is the dominating transport mode for transports to the harbour. However, some areas of Costa Rica are served by trains.*	*The assumed fuel consumption for the climate control represents a high estimation.*
62.	Table *9*	Table *9.a*
62.	Table *10 [in both places]*	Table *9.b*
67.	… activity in *LCIAs*, and…	… activity in *LC(I)As*, and…
81.	…analysis of the vehicle *EPD* presented.	…analysis of the vehicle *EP data* presented.
81 and 82	Figure *6*	*Figure 6.a*
88.	Figure *6 [in both places]*	*Figure 6.b*
91.	… is shown in Figure *8*.	… is shown in Figure *7*.
111.	… part in equation *1*.	… part in equation 2.
114.	… route, see Table .	… route, see Table *17*.

PREFACE

I would like to express my sincere gratitude to:

The initiators of this research project:

Antonia Ax:son Johnsson,
Chairman of the Board of Directors for the Axel Johnsson Group

Roland Matz,
former Managing Director of SABA Trading AB

and

Lars Sjöstedt,
Professor of Transportation and Logistics, Chalmers University of Technology, who has also been my patient head supervisor.

The parties generously providing financial support:
SABA Trading AB, Årsta,
KFB – The Swedish Transport and Communications Research Board, Stockholm,
TRB Miljö AB, Kungsbacka.

All supporting persons, especially:
Ph.D. Magnus Blinge, M.Sc. Anders Roth, my colleagues in the research group for Logistics and the Environment, Ph.D. Lars Hultén, TFK Göteborg, Ph.D. Johan Woxenius, Ph.D. Mats Johansson, Ph.D. Kenth Lumsden, Ph.D. Tore Hagman and Tore Sosklampi, colleagues at the Department of Transportation and Logistics, Fil. Kand. Lille-Mor Arnäs, LM Lingua for transferring the text into readable English, Christine Lavegård for guiding me

in my personal development and Ph.D. Tomas Kåberger for deterring me from extensive calculation tool development.

All the following persons supporting me with empirical material, knowledge and insights, especially:
Ola Peterson, SABA Frukt & Grönt AB, Helsingborg, Jan-Olof Arnäs, TRB Miljö AB, Kungsbacka, Per Björkman[1], SABA Frukt och Grönt AB, Årsta, Ole Siegerstedt, Lars Pettersson, Elisabeth Gustavsson Stena Line AB, Göteborg, Karl-Henrik Robért, The Natural Step, Stockholm, John Nilsson, Chief Engineer - Winter Wave, Malcolm Hobday, Chief Engineer - Chiquita Deutchland, Sune Lyhagen, Scandlines, Helsingborg, Rolf Persson, TT-Lines, Trelleborg, Kenth Rånson, ICA Väst, Kungälv, Martin Karlsson, Skandinaviska Bananimporten, Göteborg, Anders Graneskog, Skandinaviska Bananimporten, Helsingborg, Lars Göran Brunberg, AB Banan-Kompaniet, Göteborg, and James Johannesson, AB Banan-Kompaniet, Stockholm.

The thesis was made possible with the help of a great number of persons. To those not mentioned above, I would like to give my final gratitude.
Thank you!

Sebastian Bäckström
Göteborg, November 1999

---

[1] Presently with the D&D-Group.

ENVIRONMENTAL PERFORMANCE CALCULATION IN TRANSPORT LCI

- Allocation Method Design Issues

Sebastian Bäckström
Department of Transportation and Logistics
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
sb@mot.chalmers.se

ABSTRACT

The presented work focuses on method-related questions encountered when the life cycle inventory analysis (LCI) method is applied to transport systems. A systems-based analytical framework for environmental assessments of transport chains is presented. As an example of such studies, the case of bananas transport from Central America to Sweden is evaluated.

The assessment of the banana-transport chain revealed a large fossil fuel dependence (>99%), leading to an emission between 0.7-1.2 kg fossil CO_2 per kg banana, as brought to a private household in Sweden. The major contribution of the emissions originates from the propulsion of the refrigerated vessels, however, in relation to travelled distance, lorry distribution and use of personal car is by far the worst. These last stages of the chain make up 15% of the total emissions.

Based on examples from the case study a more detailed discussion concerning allocation of environmental performance data is presented. This section addresses allocations at different levels in transport LCI, and allocation methods relevant to environmental analysis of cargo transportation are presented.

In the case study, choice of allocation method when calculating the links where bananas are transported together with other goods introduced a variation in the order of 25% in relation to the end result.

Allocation methods for combined passenger-vehicle ferries are assessed and methods are suggested for consignments transported as air cargo or with a distribution lorry.

Keywords: Transport chain, Transportation, Logistics, Allocation, Environment, Environmental Performance, Energy, Emissions, Fossil CO_2, Life Cycle Inventory Analysis, LCI, Life Cycle Assessment, LCA, Distribution, Air cargo, Bananas, Reefers

CONTENTS

Page

Terminology, Acronyms and Abbreviations

Terminology

The following terms are introduced or used with the following meaning.

Allocation	*here:* assigning EP data to related activities (such as cargo or passenger transport)
Atmosphere control	Control of temperature, humidity and gas composition (i.e. oxygen concentration)
Environmental impact	The actual change in the state of, or prospects for, a natural-, social- or technical system
Environmental Performance Data	measurement data representing the size of the environmental performance parameter, i.e. kg emitted NO_x , litre diesel per functional unit
Environmental Performance Indicator	Magnitude yielding an indication of, or used for further studies of, actual impact upon the environment, for which no analysing- or measuring method exists, i.e. barrier effects due to forest roads.
Environmental Performance Parameter	Magnitude describing the environmental performance of the system under study, i.e., emitted NO_x , diesel consumption.
Functional unit	Smallest unit to which the environmental performance is related. Example of functional units: kWh/tkm, g/kg delivered.
Reefer	Cargo ship with controlled atmosphere (temperature, humidity, oxygen content etc) in the cargo rooms. Normally smaller ships (2-8000 DWT) with high speed capacity (often >20 knots)
Supply chain	A transport chain as viewed by the cargo owner (or the receiver)
tonne	1000 kg
Traffic	The physical movement of vessels / vehicles in order to realise transport
Traffic mode	A set of technical principles for supporting, guiding and propelling a vessel / vehicle in relation to its infrastructure.
Traffic system	The operations of vehicles in an infrastructure and the necessary control system/authority
Transport	Physical relocation of cargo or passenger by employing a well defined traffic system
Transport chain	The linking of consecutive transportation activities in order to carry out a specific transport
Transport system	A system encompassing the traffic systems needed for a well

	defined set of transports.
Transportation	Comprehensive denomination for the realisation of transport, including generation of the required traffic.
Transportation system	A system encompassing the (professional) transportation activities needed for a well defined set of transports. (e.g., an intermodal transport system, the container system)

Acronyms and Abbreviations

The following acronyms and abbreviations are introduced or used with the following meaning.

EP data	Environmental Performance Data
EP parameter	Environmental Performance Parameter
fu.	Functional unit
FC or fc	Fuel Consumption
ei	Environmental impact
kWh(eng.)	The energy delivered by an engine (excl. transmission) expressed in the unit [kWh].
kWh(fuel)	The (higher) heat value of a fuel expressed in the unit [kWh].
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LC(I)A	Used when the discussion applies to both LCA and LCI
ld	Load
MKB	Swe: Miljö Konsekvens Beskrivning; 'Environmental Impact Analysis' (note: to be separated from an LCA)
pac	(re-)Packaging process
rl	Relocation
Ro-Pax	Combined passenger and vehicle ferry.
RoRo	Roll on Roll off, the cargo is driven on board and ashore, either by means of own engine (cars/trailers), or by means of special tractors.
st	Storage
trm	Terminal handling
uld	Unload

1 INTRODUCTION

Environmental issues related to business operations are becoming an integrated part of modern company strategies. This process creates a need for common management- and business economics tools (e.g. accounting, life cycle cost analysis, logistics etc.) capable of treating strategic resource- and environmental issues. This has triggered the ongoing development of methods such as risk analysis, environmental consequence analysis (MKB), energy analysis and more recently Life Cycle Assessment, LCA.

The purpose of an LCA of a defined system is to generate information about the interactions (pollution, resource use etc.) with surrounding systems (natural, social and technical). The method tries to embrace the effects taking place as a result of the activities related to the different parts of the 'life' of a product or service. This information complements traditional economic information, e.g. price, cost and revenue, as these quantities often do not include relevant external costs and therefore only offer a limited understanding. Thus, the LCA method is useful in generating better understanding of present systems and future options.

In order to achieve this, both the method and the data put into it must be sound and reliable and what is to be considered reliable is determined by the question that is in need of an answer. The method will therefore be application-dependent, demanding careful attention of the analyst.

The LCA method can be divided into two separate stages. The Life Cycle Inventory Analysis, LCI, with the purpose to generate a set of environmental performance data related to the investigated system. This data can then be used in a Life Cycle Impact Assessment, LCIA[2] with the aim to describe the impact the system has upon the defined environment. This work will primarily deal with aspects of the LCI method and will only briefly comment upon the issues addressed by the LCIA method.

The LCI method is continuously applied to new areas in order to provide answers to even newer research questions, cf. eco-labelling, environmental product declaration, and ISO/EMAS certification. In this development process, questions are risen regarding how the method should be used and developed, thus providing the LCI method researchers with a multitude of interesting topics In LCI method research, method-dependent variations in the end result have been recognised as a difficult task to manage. One of the central issues related to this problem is the partition of environmental burden between simultaneous outputs from a process, e.g. the allocation problem.

When applying the LCI method to transportation processes, data quality issues are usually more carefully assessed than method variations. The aim of this work is therefore to penetrate questions related to allocation method when applying the LCA method to transportation systems, this in order to contribute to the body of knowledge related to environmental assessment of transports. The work provides information directed to those who perform LCIAs enclosing transportation as well as persons involved in logistics analysis and environmental co-ordination on a company level.

---

[2] For an introduction to the LCA and LCI methods, see Baumann et.al (1999).

2 SCOPE OF WORK

2.1 Formulation of research issues

The research perspective used in this work is a combination of the logistic perspective of cargo flow and the Life Cycle Inventory Analysis (LCI) method. The merge of these methods was presented in a resent Ph.D. thesis from this department (Blinge 1998). Blinge dealt extensively with the environmental issues related to energy supply to the traffic systems. The present work builds upon the framework presented by Blinge, i.e. the *Energy Logistic Model*, and combines environmental information of the energy supply chain with traffic systems performance in order to present a calculation method for entire goods transport chains. The underlying systems perspective upon transport, together with the definitions and terminology of sustainable transport research, is presented in Sjöstedt (1997).

The scientific space within which this work is to be found is the overlap between the theories of LCI and Logistics. The contribution is thus a framework available both to LCI- and logistics analysts and should not be seen as an attempt to enclose the two methods. The underlying emerging paradigm, yet not adequately developed, contains the idea that environmental information is not to be differentiated from traditional logistics parameters (e.g. time, money, quality measures and information flows). The LCI method is in this perspective to be compared to activity-based cost analysis or the Wilson formula for stock level management. The presented work could therefore be viewed as an attempt to shed light upon the applicability of LCI to the area of transportation systems analysis.

The research perspective applied in this work is therefore a systems perspective applied to goods transport systems when performing an environmental assessment. The scope of the environmental performance analysis covers all activities within the transport chain, including subsystems such as vehicle operations (i.e. traffic), terminal handling, storage, energy supply, vehicle supply and use of infrastructure. The focus upon the flow of resources (material, information, money) in a transport activity is borrowed from the business logistic perspective, whereas the LCI method is used in the analysis of the environmental dimensions.

Research issues

1. How should the LCI method be applied to transport systems?
2. How can the environmental performance of the present transport system for banana import to Sweden be assessed?
3. a) How can allocation be carried out when applying the LCA method to transportation systems?

   b) does allocation, to any significant degree, influence the final result of environmental assessments of transport systems.

The second question is answered by the application of LCI to the defined transport system. The assessments of the first and third questions have the LCI method itself as the research object. The construction and impact of methods to allocate environmental performance data to the transported cargo are specifically investigated.

2.2 Related work

2.2.1 Previous work

Transportation of cargo has been the object of investigation in several studies during the past ten years. Several sources regarding the subject are therefore available and each work has its given question and perspective of research (see below). When overlooking the publication list, there are works applied to both micro and macro level, i.e. which focus on selected parts of the traffic system as well as on complete transportation systems. Some studies are traffic mode specific, other cargo type specific. The area of alternative fuels and exhaust gas abatement has attracted several authors. There are authors whose work aims at data collection, others on method development. Several of them attempt to supply environmental analysts with as relevant data as possible. A set of background reading concerning environmental aspects of transport chain analysis are found in Henriques et al. (1999), Berglund (1999), NTM (1998), Flodström (1998), Maibach *et al.* (1995), Eriksson *et al.* (1995), Alvarsson *et al* (1995), Kolb et al. (1995), Demker *et al.* (1994) and Flodström et al. (1994).

2.2.2 Parallel work

In parallel to the pursuit of the work presented in this report, contributions have also been made to the

- construction of calculation methods and compilation of available EP data for the transport modes within the NTM network, see NTM (1999).
- generation of LCI data for fuel production, published in Blinge (1997).
- solution of the problems encountered when determining the environmental performance data connected to the use of electricity in transport chains published in Bäckström (1999).
- contributions to the production of an environmental handbook for transport purchasing agents (chapter 5,6 and 7 in TFK (1998))

The work within these areas, although related to the present study, is not presented in this report. However, data presented in NTM (1999) and Blinge (1997) are extensively used in the case study presented in chapter 4.

2.3 Work design

The research process leading to the generation of the knowledge presented in this thesis originates from the 'dinner table' question:

"What does the environmental performance of the transport system, bringing bananas to Swedish consumers, look like?"

In order to answer this question, the following tasks were identified:

- a definition of environmental performance relevant to the assessment of the transportation system
- a need to develop a calculation method capable of yield the desired information
- the collection of relevant site specific data.

The question, when first expressed, focused upon bananas imported from Central American countries. The calculation method, however, was to be applicable to any origin of the bananas, or other type of produce/cargo. The broad character of this approach to the question turned the focus to more general aspects of environmental performance calculations of transport system. Therefore, the following question was formulated:

How is the environmental performance of a transport chain assessed?

The work presented came to focus upon this question but as a start, the following sub-questions were identified;

1. How is the life cycle perspective/method applied to transport chain analysis?
2. Which steps in the transport chain are to be included into the analysis?
3. How is the environmental performance for the different transport modes assessed?
4. Do the different definitions of cargo in the different steps influence the calculations?
5. How is the environmental performance data for a transport link allocated between the activities in the link (i.e., between investigated cargo and other cargo or passengers transported)?

The existing literature covering environmental assessment of transport chains did not present any detailed treatment of the allocation problem in LCI. Question number 5 was therefore chosen for a further analysis.

A complementary question was also raised, namely: - to what extent does the choice of allocation method influence the result of an LCI of a transport chain?

The work was then carried out by making an inventory of available methods and by suggesting new designs where previous methods were lacking. Selected methods were then applied to allocation situations encountered in the case study of banana transport. The impact of allocation method design was thus demonstrated.

2.4 Composition of the report

The structure of the report follows the three issues questions formulated in section 2.1.

In chapter 3, a systems-oriented model for environmental performance calculations of transport chains is presented. The model is an attempt to view a transport system from a common logistics and LCI perspective. The purpose of constructing the model is to support the application of the LCI method to transport systems. This work therefore addresses question 1 above.

Chapter 4 contains an application of a limited LCI to the transport system bringing bananas from Central America to Sweden. The case study explores energy utilisation, emissions to air and lead time for a main case as well as for a number of alternative systems. The presented work provides the answer to the second question. This case study also serves the purpose of supplying the discussion in chapter 5 with illustrative calculation examples.

This discussion concerns the design of allocation methods in order to distribute environmental performance data to the relocated cargo. Chapter 5 discusses the recent progress of the general allocation method issue in LCI before exploring its application to studies of transport systems. An extensive discussion, drawn from examples in the case study, yields suggested methods for selected allocation situations. Traffic modes, not covered by the case study, are treated in constructed cases, e.g. air cargo. An allocation method impact analysis of the result of the case study finalises chapter 5. This chapter is thus devoted to the third question.

The report is then finalised by a stating a number of conclusions leading to a discussion aiming at future research topics.

3 ANALYTICAL FRAMEWORK

The awareness of the large contribution to the total amount of air pollution that originates from the transportation sector has raised the demands of further knowledge about the environmental performance. The object of interest spans over a broad spectrum, from separate vehicles, different transport systems to entire transport chain.

The scope of present studies addressing these issues varies considerably. Research questions are formulated at different levels with different perspectives: What are the total national emissions of substance x? How will the total amount of emissions change after reconstructing a road, for example due to selection of routes, time of travel, speed of vehicles and changes in number of trips? What are the emissions levels of a specific engine-/vehicle-/fuel type in congested city traffic? How much CO_2 was emitted during the transport of the milk served in the cafeteria? Or how large are the world-wide CO_2 emissions from the logistics system of Mc Donald's? Another relevant research issue[3], is how much emissions of, e.g., CO2 can be emitted by a transportation system in a sustainable future.

With such a broad perspective of the environmental dimension of transportation, there is a need to carefully address the real purpose of the research question at hand. One has to consider where the frontier of

---

[3] The issue is presently under attention at the Department of Transportation and Logistics, Chalmers.

knowledge is to be found, i.e. what methods to apply when solving the question and where to obtain relevant data.

This chapter introduces a perspective used when assessing the environmental performance of transportation chains. After this perspective of the analysis is established, relevant parameters are presented together with the methods needed in order to execute a calculation.

The purpose of this chapter is to supply a 'site map' for analysis of the environmental performance of goods transport chains. Since a transport chain can be assessed in many dimensions, the suggested model will be of an open character. Open in this sense refers to the flexibility of the model to answer questions put forward from different perspectives (transport purchaser, supplier, researcher, policy-maker etc.) by providing clear and easy access to the information.

3.1 Systems Perspective

An environmental assessment of goods transportation is by its nature a systems study. A number of subsystems is engaged before, during and after the physical transport is executed. This means that an analysis of a transport starts by a definition of the system, i.e., the system boundaries, its parts and their interactions within and across the system boundary. The investigations applied to the system then aims at understanding these interactions and/or the effect of the same. In the case of environmental studies of transportation systems, one has to extend the technical system to *enclose* parts of the surrounding (natural, social and technical) systems.

The complexity of identifying and describing concerned natural systems is probably only superseded by the task to describe and understand the *interaction* between them and the transport system. Nevertheless, an important purpose of the generation of such knowledge is to relate the transport to an environmental effect (or impact) due to relations between the transport system and the surrounding systems. In reality, this is usually expressed as a potential effect, as the required knowledge to make the connection is not yet compiled. However, work is in progress, and a recent publication from the national communication research board Thunberg et.al (1997) pointed at this as an important area to focus upon.

Instead, one has to give in to a number of approximations put in place by defining system boundaries in different dimensions. System boundaries are set up in relation to time, physical dimensions (i.e. geographical, natural systems) and other technical systems with the purpose of to define what parts of the system to include in the analysis. The definition is made in accordance with the present research question, thus excluding non-relevant or negligible parameters.

A system boundary could also be set up as a result of lack of method or data to describe a parameter/dimension. Such limitation will of course compromise the ability of the study to answer the research question.

3.2 Parameters

The parameters under study are describing the environmental performance of the transport of a specific goods item. As explained above, these parameters are to be viewed as indicators of a potential environmental impact.

The unit under study in the model is, at the most detailed level, any piece of goods transported between two addresses by any transport chain. At other levels, the model can supply the result of using a more aggregated unit of study, such as a transport link or an entire transport system.

The indicators of environmental impact investigated in most available studies of transport systems are *energy utilisation* and *regulated emissions to air*[4]. Fuel related emissions like CO_2 and sulphur oxides are also common. However, there are a large number of other relevant parameters with well-known possible potentials to introduce impacts. Examples of such dimensions are noise and vibration, unregulated substances (e.g. N_2O, aldehydes, and palladium) biological effects of radiation, land use and barrier effects, risks of reducing bio-diversity etc.

In contrast to regulated emissions, these issues are usually not quantified without knowledge about the recipient. This difference is caused by tradition and regulations, since well known environmental problems can be connected to these dimensions. One should note that there is no difference, as far as the LCI method is concerned, between reporting emissions to air and reporting noise levels, vibration energy, area of land use etc. These are all parameters that can be relevant for an LCI depending upon the research question. The questions how to connect these emissions to the effects in the surrounding systems is a task for the analyst performing an LCIA (or LCA). However, the present lack of methods and measurement data for many of these parameters forces most LCI analysts to leave them outside the system boundary. This argument is even more valid for the LCA analyst as compared to the LCI analyst, the task of the latter being only to collect the emission data.

The LCI analyst will in any case end up with a selection of parameters perceived to be relevant for the present research question. These dimensions of the environmental assessment is hereby denoted the *environmental performance parameters*, with the acronym *EP parameter*. Such a parameter can be connected with a measurement reading indicating its magnitude. This value of the parameter will be denoted *environmental performance data*, with

---

[4] Regulated engine emissions: Nitrogen Oxides, Particular matter, Carbon Monoxide, (non Methane-)Hydro Carbons/Volatile Organic Compounds (VOC).

the acronym *EP data*. Thus, the EP parameter NO_x emitted to air could be presented with the EP data. 6,7 g NO_x/kWh (eng.).

In the analysis one can differentiate the cause variables from the effect variables. Examples of cause variables would be energy utilisation or the size of CO_2 emissions, while typical effect-parameters would be resource depletion, increase of global average temperature or reduction of biological productivity from a farm field/forest. With this notation, we are usually not in the position where the connection between the emission and the effect can be assessed. Present knowledge limits us, with few exceptions (e.g., NO_x, SO_2), to discuss the size of selected cause parameters. One should note that, somewhat misleading, the size of energy utilisation and emissions of regulated substances to air are often denoted the environmental effect[5]. The results of such statements are of course of a more limited value.

3.3 Analytical dimensions

The dimensions of interest when assessing the environmental performance of a transport system are:

- the flow of goods through the different stages that build up the transport system,
- the supply of support (e.g., vehicles, energy and infrastructure) to the transport activities,
- the environmental performance of each sub-stage in the supply chain and
- the complex chain of processes leading to the impact upon the environment.

---

[5] One has to carefully distinguish between an "environmental effect" and an emission that (could) lead to an environmental effect.

These dimensions are indicated in Figure 1 below. The figure also shows how each dimension can be analysed as a chain of events separated from each other.

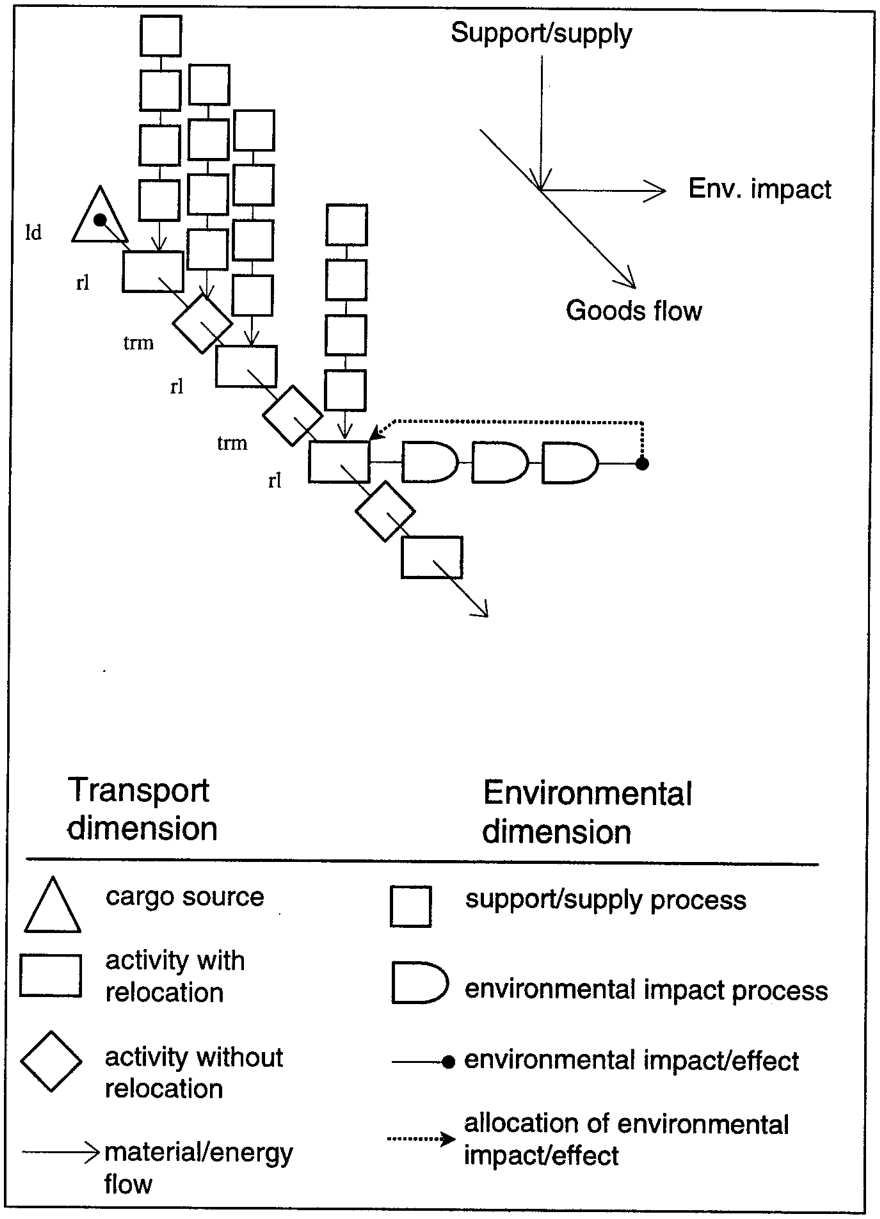


Figure 1 *Main dimensions in environmental assessment of transport.*

3.3.1 Material flow dimension

The base for the calculations is the flow of cargo from a defined source to a defined destination. This flow can be described by a number of sub-activities, "supply or transport activities", all contributing to the realisation of the relocation of the defined cargo. This chain of activities is in this work denoted a transport chain. The sub-division is made to a level of detail large enough to enable the investigation. This is the approach used in logistics, and examples of activities could be terminal handling, loading/unloading, relocation by vehicles, storage or changes to the consignment. Common quantities under investigation are transport cost, throughput time, delay risk, labour intensity, stock volumes etc.

In the suggested model, transport activities are shown as squares and rectangles along the diagonal (see Figure 1 above). The following abbreviations are used to denote the different processes:

Process	*Notation*
Relocation	rl
load/unload	ld/uld
Terminal handling	trm
(re-)packaging process	pac
Storage	st

Relocation is any movement of the cargo within a traffic system, as opposed to the motions of the cargo from a storage position to a loading ramp. In this work, such relocation is covered by the definition of the terminal handling process and when making these definitions, the work enters a grey-zone between transportation and material handling. The purpose of these definitions is not to contribute to the discussion of definitions within these (overlapping) disciplines (see p.15 in Öjmerts 1998). The ambition is to find a sub division level allowing analysis in varying detail.

The load/unload refers to the process of transferring the cargo between different vehicles or between the vehicle and a terminal. An illustrative example is the unloading of a container from a ship; this process of transferring the container from the ship to the quay is in this work denoted unloading. The transport of the container to another vehicle (train, lorry or ship) or a holding position would fall under the terminal handling. Energy use while in the holding position (cf. refrigerated containers) is booked as storage. The division of the transport chain can be developed into further detail. As an example, relocation by a ship could be divided into different steps with different environmental profile, manoeuvring in harbour and locks, steaming close to shore, cruising on open sea, approaching shore, cruising in channels etc. The same can be done for the other traffic modes.

Returning to the figure, the diagonal with its activities constitutes the 'spine' of the analysis. This is the process to which all other dimensions connect. Environmental performance[6] calculations are usually dominated by activities involving fossil fuel combustion. However, depending upon the nature of the transport chain, other parts could contribute substantially.

3.3.2 Supply/support dimension

Each activity in the transport chain is dependent upon supply of specific prerequisites such as energy, material and constructions (vessels, houses, pallets, containers etc.), infrastructure, personnel, information, community service etc. All these activities have their specific environmental performance, of which all, or a share, are to be allocated to the activity, see Figure 2. The size of the share has to be evaluated in accordance with an allocation procedure, an issue further discussed in Chapter 5.

---

[6] Environmental performance defined as energy utilisation and emissions of measurable substances to air.

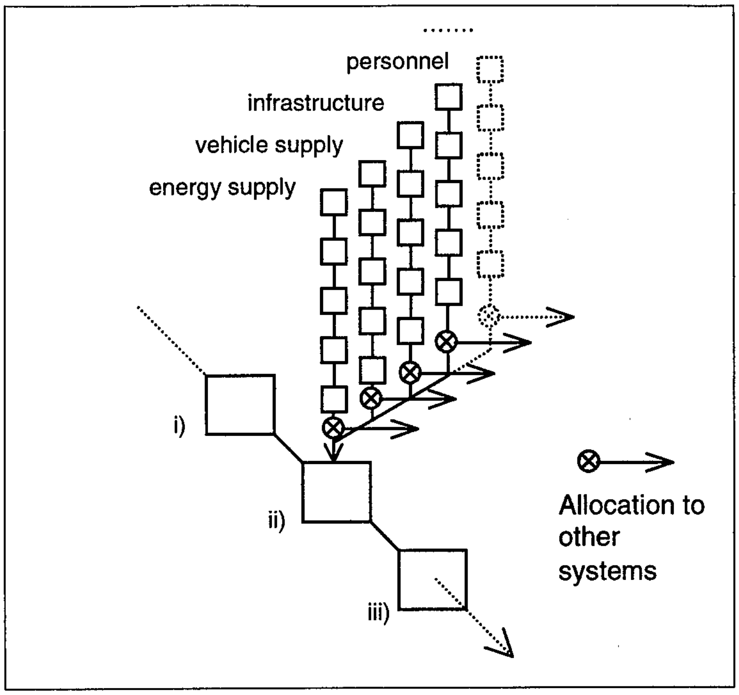


Figure 2 *Environmental performance from several support systems allocated to transport activity ii).*

The size of the environmental performance from all such support systems is, however, often not evaluated, often due to a perceived insignificance due to diminutive magnitude. The uncertainty introduced by such assumptions is believed to be small as the bulk of energy use and emissions is caused by the activity itself. Exception to this 'rule of thumb' is however not hard to find, e.g., the supply of energy carrier. The energy supply issue has, in contrast to other, been investigated in considerable depth (Blinge 1998, Brandberg *et al.* 1992, DeLuchi 1991, Frischknect *et al.* 1995, and Maibach *et al.* 1995).

Data regarding the other parameters are continuously becoming available, whereas, the nature of the data (usually situation-specific and non-generalisable) still makes it cumbersome to obtain a complete picture. Example of data is an LCA investigation of road use in Sweden (Stripple

1995), vehicle production (Kordi *et al.* 1979, Volvo 1997), electricity use for the different traffic modes Höjeberg (1995) and staff journeys to work[7] Magnusson (1999).

The relative contribution from these support activities will differ between the different parameters investigated. As many of them are related to energy, an indication of the contribution can be obtained by an energy analysis. The work of Kordi *et al.* (1979), Stripple (1995) and Blinge (1998) indicates that, on top of the energy that the vehicle uses, one must add an extra

- 7-15 % for fuel production,
- 4-8 % for vehicle construction and maintenance and
- 5-10 % for infrastructure construction and operations.

That these parts should be included is today not disputed although their significance to the final result is often unknown. Several other factors introduce uncertainties well above the effects of these contributions. As for road traffic, climate effects, traffic situation and driving style can introduce fuel consumption variations of 50-100 %.

---

[7] An LCI investigation regarding the environmental performance of the production of one seat*kilometer in a city bus showed a significant contribution to the HC and CO emission from the cold starts in relation to the driver's journeys to and from work.

3.3.3 Environmental impact-effect dimension

A common purpose of LCIs is to obtain a representation of the environmental performance of the system under study. What is understood by environmental performance varies, why the analyst must state how the term is defined (see section 3.2). In its simplest form, one could be referring to a number such as the fuel consumption (e.g. l/10km) or number of vehicles operated on alternative fuels. Sometimes, the lack of well-known environmentally hazardous substances or activities (e.g. asbethos, freon as a coolant and oil tank cleaning at sea) is presented as an indication of environmental performance.

Although, e.g., fuel consumption often leads to an environmental impact in preceding and proceeding steps, it cannot in itself be called an environmental impact. The real environmental *impact* can be defined as a change in the state or prospects for a natural, social or technical system. This impact will then contribute to a change in an observable variable, such as the number of species present in a habitat or the yearly increase of growing stock or cancer mortality per 1000 inhabitants. These changes can be denoted environmental *effects*. It must be stated that the relation between these effects and the contribution from different emissions can only be established on an aggregated level. Establishment of the cause-effect relation for individual cases demands an information stock presently not achievable.

Returning to the definition of the impact, the definition above contains the unresolved problem of different values in defining what is to be understand as 'negative' or 'positive' impacts, i.e. what impacts should be considered? This issue, although crucial to the value of the results, is usually not dealt with in the inventory analysis. Instead, in LCA, this discussion is focused upon the valuation and assessment steps. However, values of the analysts, or the commissioner, are reflected in the LCI-analysis, e.g. in research question formulation, in scope definition, system boundary selection and data source/quality selection. A selection of what impacts to consider, i.e. an indirect definition of relevancy, is a necessary step in all investigations with limited resources. A safe policy regarding this would be to clarify the opinion of controversial issues (such as the global warming, risks of nuclear accidents and preferences of future generations). Although it is important for the applicability of the results, this work will not discuss this issue further.

Another important issue related to the definition of the term environmental performance is how to connect an event in the transport system with the actual impact upon the concerned system, i.e., nature, humans or other technical systems. In theory, it is possible to assess the actual environmental impact. One could study the composition, amount, position and time for all emissions from the transport system, including underlying support systems. For air pollution, one would thereafter apply the science of atmospheric chemistry, physics and metrology in order to find out how the pollution is transformed, diluted, dispersed and deposited. At that point, disciplines such as chemistry, biology, geology and medicine will assess the type and size of the actual impact. These sub-processes are shown as half ellipsoids (see Figure 3). The different steps in the chain is named A, B, C, ... etc. making up an environmental impact path, or cause-effect chain.

The same procedure can then be carried out with all the other environmental parameters, such as emissions to soil and water, resource depletion, noise, barrier effects etc. These aspects will not be explored further in this work. For more information on this matter see Steen (1996).

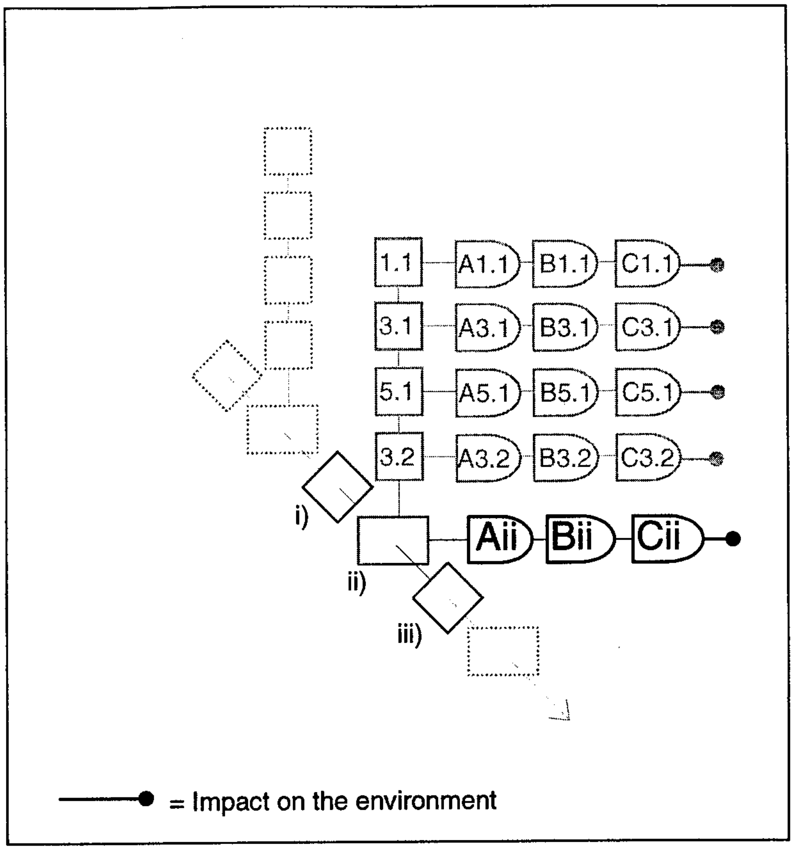


Figure 3 *Environmental impact path from transport chain stages.*

As shown in the figure, the impact paths form each support activity can also be investigated. Along this path, several processes, some of complex and yet not fully understood character, will interact with the emissions under study, making it difficult to point back and hold the emission alone responsible for the subsequent impact. However, in situations where this is possible, and the nature and the size of the impact is established, the impact can be connected back to the activity in the transport process causing the emission (see Figure 4).

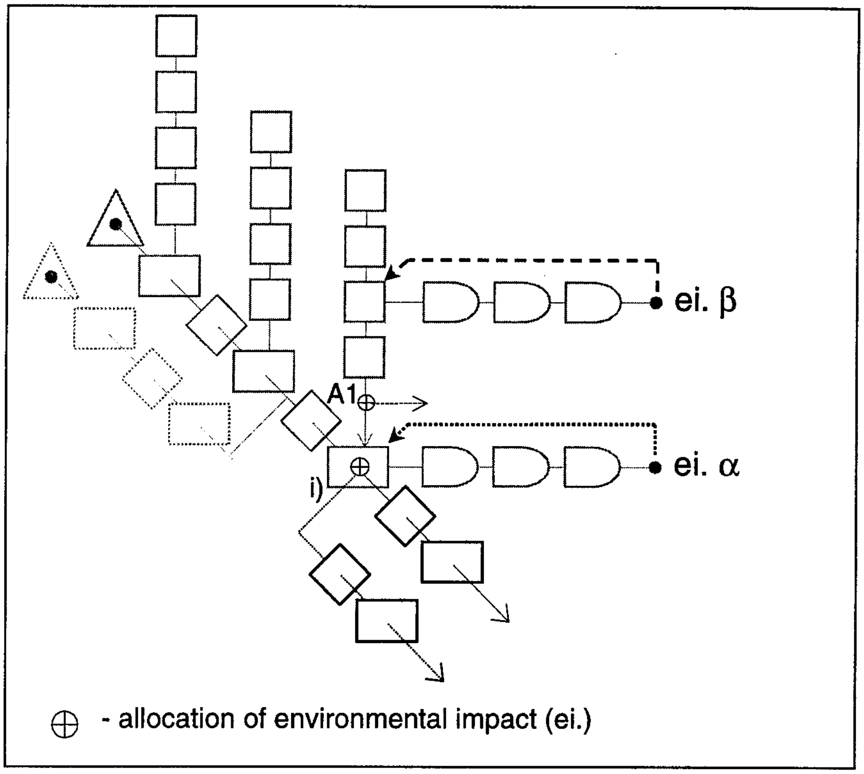


Figure 4 *Allocation of the actual environmental impact to the transport activity.*

To relate all the impacts from all relevant activities, including supporting activities is of course a task rapidly growing in scope as the complexity of the transport chain increases. In Figure 4, it is shown how the impact, β, from a supporting activity, is first connected to the support activity, and then via A1 related to the supported activity (**i)**)[8], which in addition causes the impact α.

In Figure 4, the need to split the environmental impact between several activities is also indicated. In the supporting activity the environmental impact (i.e. ei.β) is split between all its successive activities. In the case of the

---

[8] The impact could be the acidification caused by the engine exhaust from the oil tanker bringing the crude oil to the refinery that produces the diesel used by a distribution lorry in activity **i)**.

oil tanker, the crude oil carried by the tanker will yield several other products (e.g., petrol, propane gas, grease) as well as the diesel used in activity **i)**. Thus, only a portion of the total impact will be added to the environmental impact of activity **i)**. This allocation (at A1) procedure can be constructed in several ways, leading to variation in the result Blinge (1998). This is also the case with the allocation indicated within transport activity **i)** in Figure 4. In the figure are two separate transport chains that overlap in activity **i)** indicated. If the consignments in the two chains are not identical (in nature and dimensions), the same question arises, i.e. how to divide the environmental impact between the consignments. The question of how these allocations could be carried out, and what impact that may have on the result is the topic of Chapter 5.

3.4 Summary of the analytical framework

The environmental performance of a transport is defined as an assessment of the actual impact and effects on all natural, social and technical systems effected. A common method when attempting to assess this performance is the Life Cycle Inventory Analysis (LCI)[9].

When applying LCI to a transport, the first step is to divide the transportation into its sub-operations in detail, allowing the environmental performance per functional unit to be calculated. This is done by first identifying all relevant EP parameters which then are operationalised and represented by EP data. Examples of common units for EP data would be *gram NOx per vehicle kilometre* or *kg* CO_2 *per litre of diesel fuel produced/delivered*[10]. Thus, EP data

---

[9] Readers unfamiliar with LCI (and LCA) are directed to introductory literature such as TFK (1998) and Baumann et.al (1999).

[10] This kind of information is sometimes, somewhat misleading, named the environmental effect. The real impact upon the environment can however only be assessed after combining this with information regarding the role of the emitted substance in a subsequent influence upon the natural system.

represents entities such as the amount of used primary fossil energy, the amount of emitted polluting substances or an estimation of the related actual impact upon the natural systems from such emissions. An inventory of the EP data from relevant underlying sub-operations[11] is compiled and allocated to the operations concerned, (see Figure 4).

More complex environmental impacts such as land use, barrier effects, reduced bio diversity and resource depletion could also be considered. However, methods and data for such parameters are still not available. In this way, part of EP parameters from, e.g., the production of the energy carrier is allocated to the use of that energy carrier in a transport process[12]. The parameters allocated from underlying processes are combined with EP parameters for the process itself, yielding a sum, which is subsequently allocated to the processed cargo. This last step is done in order to obtain the environmental data expressed per functional unit. At this point, the information reflects the environmental performance of the combination of the systems, enabling the transportation of the defined cargo.

3.5 Applying the LCI method to transportation

An environmental assessment of a transport chain as outlined above contains several calculations of the size of cause parameters. This section contains a general description of the calculation methods used when assessing the transport activities with relocation. This is the same as the emissions from the traffic process (road, rail, air or sea) or the operation of pipelines and cableways.

Applying the LCI method to a transportation system is done in a number of steps. As a guide to the reader, not familiar with LCI, is an overview of the different steps is presented below:

---

[11] The relevant sub-operations are obtained during the screening of the technical system.

[12] A transport process could be, e.g., a vehicle/vessel operation or a cargo handling operation.

	Activity	*Description*
1.	Defining the object of study.	The object of study could be - the output of one functional unit (tkm, lane meter×km) from a transport chain - a specific shipment - a defined amount of cargo or - a specific transport chain (or system).
	Identifying the boundaries for the calculation in space and time.	Parts of the systems should be included? What affected systems should be included? Over what time scale should the work extend? How far back in supporting systems should data be obtained.
2.	Identifying relevant subsystems utilised in the different steps.	Inventory of vehicles and transport systems, including (all) steps such as relocation, storage, terminal handling, empty return trips etc.
3.	Acquiring situation specific-data.	Mapping of each step in order to generate the input data necessary to calculate the environmental performance related to the cargo under study. Relevant data could be: -distances, -vehicle characteristics (size, age, technique level, exhaust after treatment, fuel consumption), -energy carrier/source, -degree of utilisation, nature of other cargo, -cargo handling equipment, etc.

	Activity	*Description*
4.	A systematic selection of data and methodology for calculation reflecting system boundaries and the question at hand.	The analyst is often faced with a complex data assembly, i.e. aggregated data, old data, and lack of key-data. Choices are made regarding missing data replacement, allocation method, and marginal/average/specific data selection. Different strategies can be applied (average, worst case) in accordance with the question/purpose of the study. Choices, regarding methods, influencing the results are common, e.g., consider allocation methods, real measurement data vs. laboratory test data.
5.	Calculations yielding the result in relation to the selected unit (per tonne*km, per kg delivered, per year, etc.)	The volume of calculations rapidly escalates in response to dimensions such as, - number of activities in the transport chain, - degree of accuracy, - number of integrated transport relations.
6.	Sorting results	The results of the calculations are sorted in a manner determined by further analysis. In the case of an LCA, data could be grouped by time and location of emissions (direct/delayed, urban/suburban, and coastline/ocean) or by type of environmental impact (characterisation).
7.	Assessment of feasibility and limits of uncertainty	An important step since the lack of previous knowledge causes a lack of "gut-feeling". The limit of uncertainty yields a range that usually is more honest to communicate.

The selection of what parameters to be investigated reflects the purpose of the study. In Table 1, three other studies are compared with the present work. The first one, BRA MILJÖVAL cargo transport, selected a number of parameters from which all transport modes could be assessed. Systems performing below absolute limits are eligible to be labelled with the BRA MILJÖVAL-label. One important limitation governing this work is the demand for quality data. When constructing the labelling system, the cost of obtaining quality assured data was recognised, and by an intelligent selection of parameters, most of the negative environmental performance can be assessed.

The second example, Environmental Product Declaration, is a system for analysis and communication of environmental performance. The system is based on LCI, and thus delivers data to be further processed (e.g. an LCIA or compared to absolute limits in eco labelling). The results area sometimes sorted into environmental impact categories. For this purpose is the emission data further processed, e.g., CO_2 and N2O are multiplied by their GWP-factor[13] and presented as an single figure.

In the third example, the selection criterion was "all substances for which data is available for all traffic modes".

---

[13] GWP = Global Worming Potential. A number indicating a substance's relative contribution to the greenhouse effect as compared to the same amount of CO_2.

Table 1 *Examples of EP parameter selection.*

	EP parameter used in:			
EP parameter types	**This work**	**BRA MILJÖVAL-labelled cargo transports**	**Environmental Product Declaration,** (milk transport)[14]	**NTM**
Energy	Fossil	Non-renewable energy sources	Non-renewable resources (with energy content)	Fossil Energy
	Nuclear (thermal)			Nuclear (thermal)
	Renewable		Renewable resources (with energy content)	Renewable energy
Emissions to air	CO_2, total		Greenhouse gases (GWP 100 Years)	Total CO_2
	CO_2, fossil			Fossil CO_2
	NO_x total NO_x urban	$SO_x + NO_x$	Oxygen-consuming substances	NO_x
	NMHC	NMHC	Ground-level ozone creation	HC
	CH4			
	PM >2		Emissions of toxic substances	PM
	PM >0,5			
	CO			CO
	SO_x		Acidifying gases (SO_2-equivalents)	SO_x
			Ozone depleting gases (ODP 20 Years)	
Resources		Plan for deconstruction	Renewable resources (without energy content)	
			Non-renewable resources (without energy content)	
			Generation of waste	

---

[14] Environmental Management Council 1998

The selection of parameters in the present work is, with modifications described below, based upon the work of NTM.

A further division of the emission data in regard to the geographical position is made. As discussed in section 3.3.3, the environmental performance in terms of actual impact and effect is dependent upon both position and the time of the emission. This information is required if a further analysis is to be carried out, attempting to connect the emission to air with an impact. In the case of health effects, one has to establish a connection between the emission to air and a dose to humans. The parameters influencing this connection are (among others):

- position of emission (geographical and height above ground/sea level),
- trajectory of emitted substances in the atmosphere,
- presence of other substances or factors (e.g. sunlight) inducing chemical transformation of the substance while airborne,
- population density,
- time of day (are people indoors or outdoors, working/sleeping etc.) and
- ability of pollutant to deposit.

Since it was determined that these types of cause-effect chains were out of the scope of this work, data in this detail was not collected. Instead, it was (as a first approximation) decided that since emissions in densely populated areas, i.e. urban areas, are likely to have a larger impact than in rural areas, urban emissions were to be presented separately. A position index was first suggested with the following divisions, Ocean, Coastal, Rural and Urban. The purpose is to avoid comparison of emissions that are likely to have significant differences in effect upon natural, social or technical systems. This information could then be used in a further impact assessment. The application of this method in the case study in chapter 4 leads to a simplification. Presenting data at the suggested specification level proved impractical why the selection was narrowed down to a specification of urban and total (= Ocean + Coastal + Rural) emissions.

3.5.1 Definition of cargo

In the LCI method, a functional unit, fu., is defined in order to execute all calculations in relation to the same object. In transportation, the definition of the fu. will be expressed in terms of an amount of cargo in relation to a specific distance or position. Examples of functional units are, *one car delivered to customer in north-eastern US, one litre of milk relocated 1 (road) km*, or *1 kg bananas relocated from Costa Rica to a private household in Nybro.*

In the calculations, one has to consider that cargo is often surrounded by both packaging material (bags, boxes, crates etc) as well as cargo handling equipment (pallets, containers, swap bodies, trailers or wagons). The EP data for the traffic modes are usually given in relation to what the traffic operator actually relocates, i.e. usually not only the useful cargo itself. Envisage the transport of one container filled with 20 pallets, each carrying 48 boxes of bananas. In the case of a lorry or train operator, emissions could be given as g/container position (or TEU[15]) or per tonne put on the trailer/wagon.

However, when the lorry or the wagon is brought onto a RoRo ferry, the ship operator will provide an EP data related to the trailer/wagon together with the container upon it. The data should only concern the container and its contents, since this data will be distributed among the pallets inside. The EP data assigned to each pallet is then further divided among the boxes and finally to the bananas in the boxes, see Table 2.

---

[15] TEU = Twenty foot equivalent unit.

Table 2 *Example of block specific data for a 40 feet container loaded with 960 banana boxes on 20 pallets.*

Entity	Weight total	 per functional unit
	[kg]	[kg/kg bananas]
Bananas	17 414	1
Box	1 440	0.083
Pallets	600	0.034
40-foot container	4 800	0.28
Total:	*24 254*	*1.4*

In figure one can se the difference between the weight of the bananas (17 414 kg) and the loaded container (24 254 kg). In this way, the functional unit is the bearer of all the EP data. This example can be made more complex by introducing different types of cargo within the container, a situation calling for a more sophisticated allocation method (see Chapter 5). When the container is transported empty, i.e. when it itself could be considered as the f.u., one could allocate the EP data to the latest or the next transport. A framework for this allocation is also presented in Chapter 5.

3.5.2 Data issues

The data acquisition in transport studies is usually cumbersome. Data has to be obtained in two dimensions, regarding the *transport chain composition* and regarding the *utilised transport systems/vehicles*, each presenting difficulties in obtaining relevant data input.

The mapping of an transportation system requires data about the different addresses, the nature of the shipments, what type of terminal handling, storage, packaging and cargo handling equipment is applied, which transport system is used, when how and along which route. The result is a map of all the activities taking place in the transport chain, i.e. the diagonal in Figure 1.

The other dimension deals with the data describing each transport activity. This is the description of the activities inside each rectangle in Figure 1. What kind of vehicle or vessel is used? What energy utilisation and emissions are related to its operations? Will there be return cargo? Which ferry route is used? Which specific ferry is used? What is the degree of utilisation of the ferry? Is it a designated or integrated cargo transport? The answers to this kind of questions will yield the information needed for the mapping of the system in a detail allowing the environmental calculation.

Data sources

What combination of data sources to use is dependent upon the purpose of the study. A detailed situation specific investigation (e.g., Berglund 1999) would turn towards the companies executing each sub-operation in the transport system, e.g., a lorry operator, a train operator or a ferry company. An investigation trying to reveal a national average or a screening of the operations in a company is more likely to apply aggregated data such as statistical data or average data (cf. NTM 1998).

Data can be obtained from a number of different sources. Environmental information related to traffic and transport is collected for a large number of purposes: national statistics, research projects, for certification purposes, for marketing and political lobbying, for alternative fuels demonstrations, in public purchase negotiations etc. The applicability of the data therefore varies substantially. The use of aggregated units (g/tkm, g/year) makes it hard to assess and use the data when underlying data and assumptions are unclear or not known. The age of data is another common problem. New engine technology, improved fuel quality and installation of exhaust gas cleaning are examples of changes altering the relevance of data. Continuous turnover in the vehicle fleet introduces a alternation of average values.

Data management

Data management is an important issue in LCI analysis. An analysis is typically numerous in terms of activities for which data are to be obtained. A given resource can therefore be used either to obtain an overview of a larger system yielding data for several systems or a detailed knowledge of a few sub systems. Choices have to be made between data quantity and data quality.

Assessing the relevance, reliability and validity of the data is usually difficult, nevertheless crucial to the quality of an LCI. Systems for keeping track of quality information for the data has therefore been developed, e.g. see Pålsson (1999).

With data quality issues under control, the analyst needs a calculation and data management support tool. Several such have been developed in various projects and are available as calculation software together with databases. Normal office calculation tools such as Excel or equivalent can usually handle calculations of limited complexity. The calculation tool used in the case study is presented in section 4.2.2.

4 CASE STUDY
– TRANSPORTATION OF BANANAS TO SWEDEN

The analytical approach presented in the previous chapter was applied to the transport chain bringing bananas from Central America to Sweden. The study is a simplified variant of an LCI since many of the requirements for data management and documentation are not fulfilled. These steps were not considered valuable for the main purposes of the work:

- Screening the transport chain in order to learn about the relative contribution to the total EP data from the different stages.
- Supply data for the discussion regarding the impact of choice of allocation methods. This discussion is presented in the succeding chapter

4.1 Description of the transport system

Bananas are imported to Sweden mainly from Central American countries. The transport chain starts at the banana plant where the banana stem is harvested. The stem is transported by a cable way to a packaging plant, where the bananas are sorted and packed in plastic bags inside cardboard boxes. Lorry or train then brings the boxes to the harbour where they are refrigerated and stored while waiting for the reefer. The ship is filled to its max capacity and brings the bananas to one or more ports in Europe, where the bananas are processed for further transport. Up to this point, no other cargo is involved in the transport. From the harbour, the bananas are transported, by rail or lorry, to the different ripening units in Sweden. In this study, Helsingborg is selected as a representative case, since that unit sometimes obtain bananas landed at different European ports (Antwerp, Zeebrugge, Bremenshaven and Hamburg). At the ripening units, the bananas are stored and ripened in special climate controlled rooms[16]. Up to this point the bananas are not mixed with other goods except for the railcar or trailer who can be integrated in a transport system executing simultaneous transportation service (e.g. a train with mixed rail cars or a lorry on a RoPax[17] ferry). In such a system it is important to determine the share of e.g. energy use to be carried by the vehicle transporting the bananas. From the wholesaler, the bananas are transported in integrated shipments of produce direct to either

1. supermarket or
2. via another wholesale terminal, thereby further integrated with other utilities, to smaller shops or
3. other large customers[18]. In these parts of the transport chain the environmental performance must be allocated to different goods categories.

The last part of the transport chain including food stores consists of the private consumer bringing the bananas home by different transport modes, by foot, car, bike or a delivery service. These transports are also subject for allocations as bananas contribute to < 5% of the weight of a shopping bag and other errands can be tended to during the shopping trip.

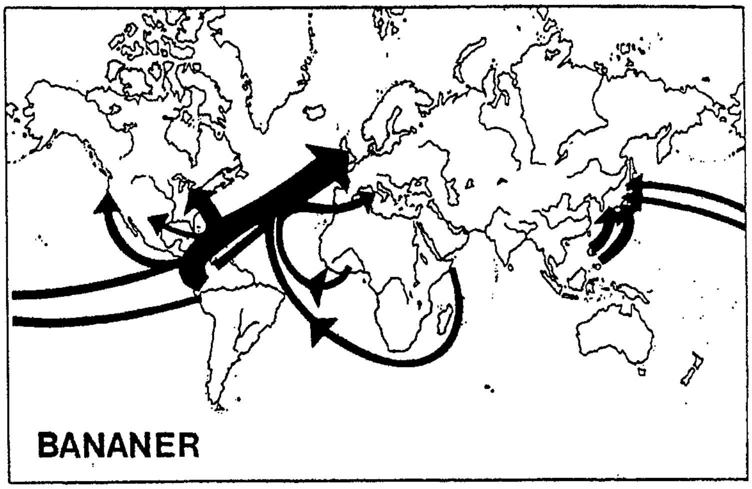
An illustration of the world-wide movement of bananas is given in the picture below.

---

[16] The green bananas are ripened in a process where the temperature is increased and ethene gas (2 ppm) is added to trigger the process.

[17] RoPax = combined passenger/RoRo ferry

[18] E.g. hospitals, canteens, and zoological parks.



Transport flows of bananas world-wide[i].

The analytical approach applied to the transport system is indicated in Figure 5. Information regarding the construction of this system was obtained by interviews and a case study by Castillo *et al.* (1999).

---

[i] Source: The Scandinavian Shipping Gazette, Nr. 50, p. 75, Dec. 1995.

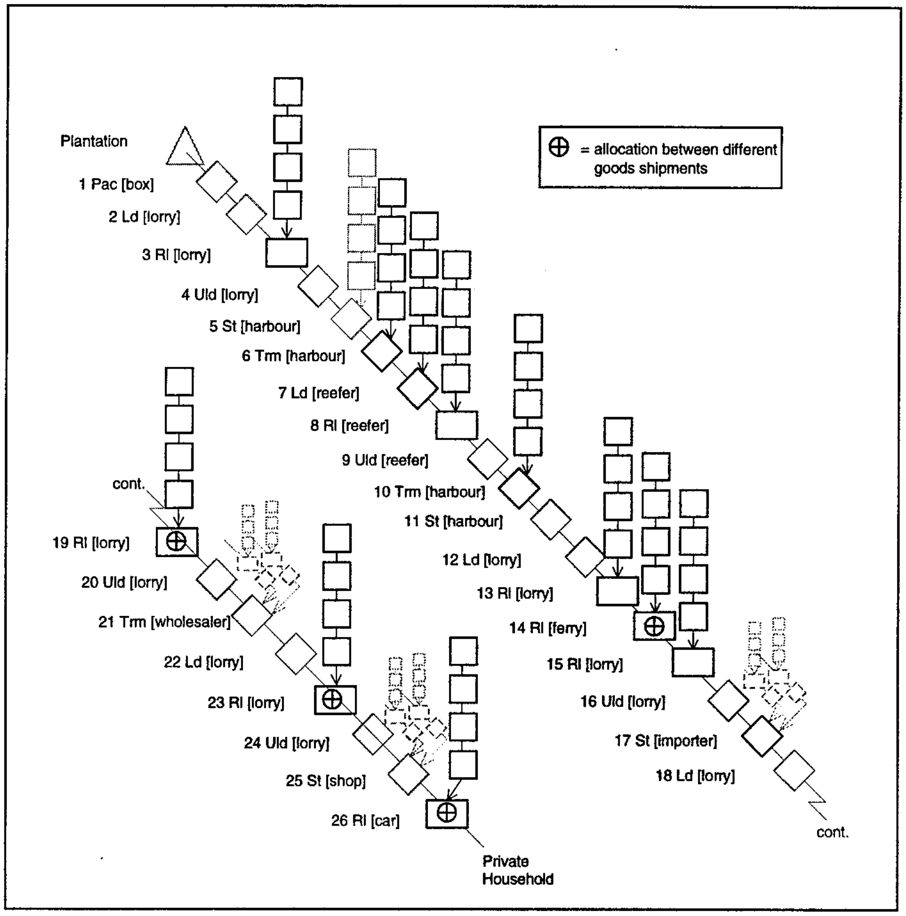


Figure 5 *The transport chain for bananas from Costa Rica to Sweden.*

The stages included in the calculations in this study are marked in black in the figure above. Life cycle EP data for the energy supply was included in all these stages. The stages excluded from the analysis are deemed small enough to not influence the analysis in a way compromising the results. Lack of data for loading and unloading operations together with storage at the wholesaler and shop excluded these from the calculation. However, several of the loading/unloading actions are done by hand or with electrical lorries why the contribution are small. Storage in the shipping harbour has not been assessed due to lack of data. The bananas are stored in containers operating on electricity. The contribution to the emissions to air are estimated small since the storage time is short (average 2-4 days) and >85 % of the electricity of Costa Rica is generated by hydropower. An analysis encompassing less limited spectra of EP parameters would of course have to include this stage. However, the result table in section showed very small contribution for similar activities to these mentioned above, supporting the assumption that these are negligible.

4.2 Calculations

4.2.1 Selection of variables

As stated above, this case study is a simplified version of a 'complete' LCI. The usefulness of a properly carried out LCI did not motivate the resource demand for such a project. The lack of data for several parameters and systems introduced further limitations. Attempts to obtain data for vehicle/vessel construction and service have been made. However, the result was sparse. The impact of this upon the result of the study was undesirable but not considered decisive for the ability to meet the purpose of the case study. The variations in the result due to lack of data related to vehicle construction and infrastructure operations are considered to be contained within the span between the high and low value. This analysis should therefore be complemented with data related to these aspects, as such information becomes available. As a result of this the number of parameters was limited to;

- <u>Energy</u> related to its primary source, fossil, renewable or nuclear.
  The specification of fossil and renewable origin is suggested as a first step in the direction of sound energy analysis. The common habit to compare energy from different sources and with different use in technical systems has been discussed for 30 years (cf. exergy analysis, see Kåberger (1999) or Blinge (1998)), without any change in sight. This suggested approach, of a less sophisticated, of dividing energy by its sources was introduced in

order to avoid the largest kind of misconceptions. A further step in this direction would be to recognise the differences between coal, oil, peat and natural gas, as well as the different nature of wood pellets, wind power and bio-gas. The values represent energy content in the primary energy source, except for wind power and hydropower, where the actual electricity generated are stated. Energy-*nuclear* is presented as the heat generated by the nuclear reactor.

- Emissions to air of the following substances: CO2, NOx, NMHC, CH4, PM >2, PM >0,5, CO, and SO2. The emissions presented originate from fuel combustion in engines and from the life cycles of electricity generation and fuel production.

  The argumentation for position-dependent environmental impact from emissions to air (see section 3.3.3) is recognised by the separation of the emissions taking place in urban areas. This is a first coarse division in order to recognise the different impact/effect potential for emissions at different locations. The difference between these numbers is thus emitted in rural areas or at sea. CO2 is presented as fossil and total. The difference between these values originates from renewable sources.

- Time is logged for the different transport stages. The purpose is to assess the impact of a more economic operation with slower speed for the reefers

4.2.2 The calculation tool

The calculations presented here are carried out using an Excel-based calculation tool. The calculations are carried out using a unified structure of the EP data presentation. This structure is reflected in the result tables in section 4.3. Using a unified structure allowed easy use of the possibilities for fast construction of calculation systems offered by the program (relative addressing, linked data and copy/paste functions). The calculations for a transport system is carried out in one workbook, containing three types of work sheets,

1. data support sheets,
2. transport link sheets and
3. the result sheet.

The result sheet contains the sum of the EP data from all the transportation link sheets. The result sheet also presents the EP data for each stage in the chain and its relative contribution to the total. The transport link sheet contain both the input data and the calculations of the EP data related to the activities in the specific link. The data support sheet contain underlying data used in several sheets (e.g. EP data for fuel production and electricity generation, information about cargo handling equipment and references to data sources) A calculation is then carried out by creating a set of transport link sheets altered in order to reflect the data for the real system. Although this is a primitive LCI calculation tool, knowledge about the total time spent with its development and operation would beset a sane time budgeting process.

4.2.3 Description of the stages in the banana transport system

The first step in the transportation of the bananas is done by a cableway bringing the stems into the packaging plant, where the bananas are inspected and prepared for transport. The bananas are packed in cardboard boxes, which are stacked upon pallets. The pallets are placed in 40 foot containers equipped with atmosphere control. The containers are brought to the harbour by lorries (at some locations by rail), where they are held pending further transport by a reefer vessel. No data was available for the processes preceding the lorry transport. Manual labour is assumed to provide most of the transport work in these stages why these are not considered.

1a Lorry transport

Activity: Transportation by lorry from packaging plant to nearby harbour – Port Limone

Vehicle/vessel description: Different lorries are used. The calculation assumes a Euro-sized trailer pulled by a tractor with a diesel engine equivalent to Euro 0 emission standard. No extra exhaust abatement systems. Diesel fuel in accordance with local standards (4 000 ppm sulphur)
No climate control.

Calculation base: This sub-calculation uses *one* container as base unit.

Calculation method: *Middle*: Based on typical fuel consumption for the lorry type (0.35 l/km)
High: Based on higher fuel consumption (0.4 l/km)
Low: Based on lower fuel consumption (0.3 l/km)

1b Lorry transport

Return trip of lorry. Identical to 1a, but with reduced fuel consumption (middle: 0.275 [l/km], high 0.3 [l/km], low 0.25 [l/km]) due to the lack of cargo.

2 Terminal handling

Activity: The bananas are stored in 40-foot containers stacked at a terminal 2.2 km from the quay.

Vehicle/vessel description: The containers are connected to grid electricity for temperature control. When the reefer arrives, the containers are moved to the quay by lorry. Forklifts (or reach-stackers) handle the containers.

Calculation base: This sub-calculation uses *one container* as base unit.

Calculation method: The emissions are calculated from the energy used in the diesel engines in the lorries and forklifts.
Middle: Calculated from operational data.
High: Assumed fuel consumption increase by 50 %
Low: Assumed fuel consumption decrease by 50 %

Comment: The accuracy of the data is low. Aggregated data is used, assuming a handling time of 10 minutes per container. The lorry and forklift uses diesel engines with an emission standard equivalent to pre-Euro conditions.

3a Sea Transport

Activity: 5 829 pallets are stowed in cargo rooms with atmosphere control aboard the ship. 150 containers are stored on deck, each with an electrical- and gas connection for atmosphere control. The ship does not call at any other ports on its voyage to Göteborg.

Vehicle/vessel description: A large reefer vessel operated by a main engine (15 000 kW) with 4 auxiliary engines (1 000-1 500 kW). The ship has a cruising speed of 20-22 knots, consuming some 2.5 tonnes of bunker per hour for propulsion, and 0.5 tonnes for refrigeration. Fuel, IFO 380, heavy bunker oil.

Calculation base: The calculation base is the entire ship.

Calculation method: The emissions are calculated from the energy used in the diesel engines for propulsion and electricity generation. Emission values originate from measurements of ship engines with various speeds.
Middle: Calculated from operational data.
High: Assumed fuel consumption increase by 10 %
Low: Assumed fuel consumption decrease by 10 %

Comment: The accuracy of the data is good.
The large size of the ship increases the efficiency.
The variations in fuel consumption cover differences in weather conditions and season fluctuations.

3b Sea transport

Return trip of reefer vessel. Identical to 3a, but with reduced fuel consumption due to reduced utilisation of auxiliary engines.

4 Terminal handling

Activity: Unloading of the vessel at quay, handling of pallets by cranes and fork lifts. The pallets are moved into storage houses for further transport. Specially designed unloading cranes, 'banana movers' are employed in Göteborg.

Vehicle/vessel description: Forklift and other cargo motion equipment. Fuel consumption assumed to 3 litres/operation hour. Each lorry handles 60 pallets per hour. The equipment is operated by diesel engines with Euro 0 emission standard.

Calculation base: 1 pallet (= 48 boxes, a net of 18 kilo bananas)

Calculation method: *Middle:* Calculated from assumed operational data. High variations in the fuel consumption are assumed due to lack of real measurements.
High: Assumed fuel consumption increase by 50 %.
Low: Assumed fuel consumption decrease by 50 %.

Comments: Several methods for unloading and terminal handling are available. Containers are moved into railcars or trailers. Special unloading equipment ('bananamover') is employed in Göteborg.
The EP data from this stage is a high estimate.

5a Lorry Transport – Göteborg - Helsingborg

Activity: The pallets are transported by a lorry with a trailer using temperature control.

Vehicle/vessel description: Large lorry and trailer with a total load capacity of 1632 boxes (= 34 pallets). Electrical climate control in the lorry and standalone diesel on the trailer. Total fuel consumption for climate control is season dependent. Assumed to 3 litres/hours.

Calculation base: 1 tractor with trailer carrying one 40-foot container

Calculation method: *Middle:* Average of higher and lower fuel consumption for this vehicle type, from NTM (1998).(0.49 l/km)
High: Fuel consumption (0.55 l/km).
Low: Fuel consumption (0.43 l/km).

Comments: Lorry is the dominating transport mode for transports to the harbour. However, some areas of Costa Rica are served by trains.

5b Lorry Transport - Helsingborg - Göteborg

Identical to 5a, but without atmosphere control in operation, and reduced fuel consumption (high 0.33, middle 0.305 and low 0.28 [l/km]) due to lack of cargo.

6 Ripening at ASK centralen in Helsingborg

Activity: The bananas are stored in ripening rooms for 5-10 days. Ripening process (temperature increase and ethylene injection) is started 5 days prior to delivery.

Vehicle/vessel description: Ripening rooms with atmosphere control units operated with electricity.

Calculation base: 1 box (=a net of 18 kilo bananas)

Calculation method: An electricity use of 1.5 kWh/box. Emissions from Swedish average electricity mix (from Blinge, 1997)

7a Lorry transport from ripening plant to a distribution centre.

Activity: Lorry transport, Regional distribution of bananas together with other fruit and vegetables.

Vehicle/vessel description: Medium-heavy lorry, regional traffic. The lorry loads 14 000 kg, of which 5 836 kg (6 pallets) are bananas (incl. package and pallets).

Calculation base: 1 lorry carrying a mixed load of produce.

Calculation method: Electrical climate control in the lorry. Increased fuel consumption for climate control is assumed to 2 litres/hours.

80 % utilisation of max weight capacity. 52 % of the utilised weight capacity bananas.

Middle: Average of higher and lower fuel consumption for this vehicle type, from NTM (1998) (0.35 l/km).

High: Fuel consumption (0.40 l/km).

Low: Fuel consumption (0.30 l/km).

7b Lorry transport, empty return trip.

Identical to 7a, but without climate control in operation, and reduced fuel consumption (high 0.3, middle 0.275 and low 0.25 [l/km]) due to lack of cargo.

8 Storage at distribution terminal in Växjö

Activity: The bananas are stored in cold rooms waiting for further transport to food stores.

Vehicle/vessel description: Cold rooms with atmosphere control units operated with electricity.

Calculation base: 1 pallet (= 48 boxes, a net 18 kilo bananas)

Calculation method: No measurement data available for the cold rooms. Contribution assumed negligible due to low emission electricity production in Sweden.

9 Lorry transport, distribution route (=no empty return)

Activity: Distribution of bananas together with other provisions to the food store.

Vehicle/vessel description:	Light lorry, distribution traffic.
Calculation base:	2 boxes delivered during an typical distribution route (total 300 km)
Calculation method:	The lorry is operated in a distribution route. The 2 boxes are delivered at an assumed distance of 25 km from the terminal. The calculation for allocation in the distribution is presented in section 5.4.2.
Comments:	*Middle:* Average of higher and lower fuel consumption for this vehicle type, as stated by vehicle manufacturer. *High:* Higher value of fuel consumption. *Low:* Lower value of fuel consumption.

10 Car transport by customer

Activity:	Home transportation of provision by customers' private car.
Vehicle/vessel description:	Modern car with petrol engine and best available exhaust treatment.
Calculation base:	1,5 kilos of bananas
Calculation method:	The bananas are transported together with 13,5 kg of provisions. The car trip serves two undertakings.
Comments:	*Middle:* Average fuel consumption for personal cars in Sweden. *High:* increase fuel consumption, assumed to 10%. *Low:* decrease fuel consumption, assumed to 10%.

Calculation utilities

Each calculation step is served by underlying data regarding fuel quality, engine emission standards, and abatement technologies. Some of the common components are gathered in separate worksheets.

a. Cargo handling

All calculations use the following data regarding packaging material and cargo handling equipment.

Table 3 *Banana box, pallet and container measures.*

Banana box		Unit
Carrying cap.	18.1	[kg bananas]
Weight	1.5	[kg]
Height	0.24	[m]
Width	0.39	[m]
Length	0.53	[m]
Area	0.21	[m2]
Volume	0.050	[m3]

Banana pallet		Unit
Carrying cap.		[kg]
Weight	30	[kg]
Height	0.13	[m]
Width	1.2	[m]
Length	1.0	[m]
Area	1.25	[m2]
Volume	0.17	[m3]
Boxes per pallet	48	Boxes
Weight		
Total, loaded	973	[kg]
Boxes and pallets	102	[kg]
Bananas and boxes	943	[kg]
Bananas	871	[kg]

Container		Unit
Carrying cap.	25 680	[kg]
Weight	4 800	[kg]
Height	2.6	[m]
Width	2.4	[m]
Length	12.2	[m]
Area (inner)	26	[m2]
Volume (inner)	58	[m3]
Pallets per container	20	Pallets
Boxes per container	960	Boxes
Weight		
Total, loaded	24 254	[kg]
Boxes and pallets	2 040	[kg]
Container, boxes and pallets	6 840	[kg]
Bananas, boxes and pallets	19 454	[kg]
Bananas	17 414	[kg]

b. Fuel production

Energy use and emissions from fuel production are included in all the processes. Fuel supply LCI data presented in Blinge (1997) were applied. These values represent the environmental performance of productions systems using *best available technology* for Swedish conditions, and are therefore a low estimate. The data quality is especially low for bunker oil production. No LCI-based EP data was found why the assumed value presented in NTM (1998) was used. This EP data is calculated as one third of the EP data for diesel production presented in Blinge (1997). No further analysis of this issue has been made. Electricity is used for climate control during storage and ripening.

4.3 Results

4.3.1 Main case: Costa Rica – Göteborg – Helsingborg – Växjö – Nybro.

The case study is carried out in two steps. First, as a starting point, a transport chain, representative for the large-scale import of bananas to Sweden, is evaluated. Next, variations to this main case are introduced and the differences in results are evaluated. The result from the calculation of the main case is presented in the table below.

Table 4 *Environmental Performance Data [per kg] for bananas transported from plantations in Costa Rica, via Göteborg and Helsingborg, to private households in Nybro, Sweden.*

EPP		**Unit**	**EP data**		
Energy		[MJ/kg bananas]	*High*	*Middle*	*Low*
Fossil			13.8	12.5	11.2
Nuclear (thermal)			0.137	0.119	0.101
Renewable			0.057	0.050	0.04
Emissions to air		[gram/kg bananas]			
CO2	total		999	907	814
	fossil		*999*	*907*	*814*
NOx	total		25	22	20
	urban		*0.06*	*0.05*	*0.04*
NMHC	total		1.3	1.2	1.1
	urban		*0.032*	*0.028*	*0.025*
CH4	total		0.016	0.014	0.013
	urban		*0.00001*	*0.00000*	*0.00000*
PM >2	total		0.00060	0.00052	0.00044
	urban				
PM >0,5	total		1.2	1.08	0.97
	urban		*0.0046*	*0.0040*	*0.0033*
CO	total		0.67	0.61	0.54
	urban		*0.19*	*0.17*	*0.15*
SO2	total		19	18	16
	urban		*0.010*	*0.009*	*0.008*
Other					
Time		[h]	638	638	638
		Days	27	27	27

These emissions distribute themselves among the different stages of the transport chain as shown in the following table.

Table 5 *Relative contribution from the different steps in the transport of bananas from Costa Rica to Nybro.*

	Stage in transport chain:	1	2	3	4	5	6	7	8	9	10		
EP parameters		Truck transport	Terminal Handling	Sea transport	Terminal Handling	Truck transport	Ripening in Helsingborg	Truck transport	Storage at distribution terminal in Växjö	Truck transport	Car transport	Total	
Energy	Fossil	0.75%	0.06%	**81%**	0.02%	1.95%	0.09%	3.57%	0.01%	4.25%	8.33%	100%	
	Nuclear (thermal)	0%	0%	0%	0%	0%	88%	0%	12%	0%	0%	100%	
	Renewable	0%	0%	0%	0%	0%	88%	0%	12%	0%	0%	100%	
Emissions	CO2 (fossil)	0.75%	0.055%	**81%**	0.017%	1.9%	0.23%	3.6%	0.031%	4.2%	**8%**	100%	
	NOx	0.50%	0.044%	**96%**	0.012%	0.70%	0.015%	**1.3%**	0.0021%	1.53%	0.29%	100%	
	NMHC	0.69%	0.11%	**87%**	0.016%	1.4%	0.16%	2.5%	0.022%	2.95%	**5.5%**	100%	
	CH4	1.2%	0.09%	**69%**	0%	3.2%	0%	5.9%	0.0%	7.0%	**13%**	100%	
	PM >2	0%	0%	0%	0%	0%	**88%**	0%	12%	0.00%	0.00%	100%	
	PM >0,5	0.24%	0.052%	**98%**	0.0055%	0.23%	0%	**0.43%**	0%	0.51%	0.40%	100%	
	CO	1.6%	0.25%	**56%**	0.036%	2.8%	0.20%	5.1%	0.028%	6.0%	**28%**	100%	
	SO2	0.010%	0.00070%	**99.7%**	0.00022%	0.025%	0.016%	0.045%	0.0023%	0.054%	**0.16%**	100%	
	Time	0.44%	9%	**46%**	3.8%	1.1%	**26%**	0.47%	11%	0.7%	0.026%	100%	

The result of the calculation yielded the desired picture of the environmental performance of the transport chain bringing bananas to a Swedish household. The actual value is to be found within the span of the high and low value presented in Table 4. The observations to be made are that:

- The transport chain is heavily dependent upon fossil energy, the reefer being the main cause. The road transports in the later stages contribute to the remaining fossil energy use. The exposure to possible future CO2 - related restrictions are therefore large.
- The contribution to the different parameters is somewhat different for the stages, reflecting the different energy (or engine) technologies. The ship emits almost all the SO2 (fuel-related) but only about half of the CO (diesel engine characteristics). This could be compared to the car that emits 30 % of the CO (Otto engine related –cold start) but only 0,3 % of the NOx.
- The transport chain has a lot of slack time. Half of the time is spent onboard the ship and an additional 20 % during the ripening process. The idea of operating slower (=less energy demanding) vessels would then be possible. A calculation for such a change is presented below. The ripening of the bananas could perhaps be started and controlled also during transport. The implication of this regarding technical system requirements and increased cargo sensitivity (to pressure and bumps) has not been investigated.

4.3.2 Alternative transport systems

A number of changes were introduced to the transport chain in order to investigate their impact upon the environmental performance. The EP data for the variations are presented in Table 10, page 61. The following variants of the transport chain were compared. The parameter(s) that were varied are shown in bold, everything else remained constant in relation to the main case, ceteris paribus.

1. Costa Rica - **Göteborg** – Helsingborg – Växjö; Large vessel, 21 kn.
   Costa Rica - **Antwerp** – Helsingborg – Växjö; Large vessel, 21 kn.

2. Costa Rica - Göteborg – Helsingborg – Växjö; **Large** vessel, 21 kn.
   Costa Rica - Göteborg – Helsingborg – Växjö; **Small** vessel, 18 kn.

3. Costa Rica - Göteborg – Helsingborg – Växjö; Large vessel, **21** kn.
   Costa Rica - Göteborg – Helsingborg – Växjö; Large vessel, **18** kn.

4. **Ecuador** - **Antwerp** – Helsingborg – Växjö; Small vessel, 18 kn.
   Costa Rica - **Göteborg** – Helsingborg – Växjö; Large vessel, **18** kn.

1. Port of discharge.

This calculation was performed in order to investigate the environmental performance of bananas landed in Belgian ports and brought to Sweden by lorry. The hypothesis was that the land-based transport would show higher EP data as compared to the reefer. The land based transport variant was constructed as a transport from Antwerp to Helsingborg by a tractor pulling a 40-foot container on a trailer. A parallel case was also constructed where the same container was put on a rail wagon pulled in a diesel engine-operated train. The diesel train was selected since this would represent the 'worst' case for a rail transport[19].

---

[19] The actual transport probably be executed by a combination of diesel and electric engines, however, the nature of that transport system was not investigated.

Table 6 *EP data for bananas landed in Antwerp, brought to Sweden by lorry or diesel train.*

EP parameter		Costa Rica - Gothenburg - Vaxjo	Costa Rica - **Antwerpen** - Vaxjo	Costa Rica - **Antwerpen** - Vaxjo
Energy	[MJ/kg bananas]	Large reefer, Fast, 21 kn.	Large reefer Lorry Antw- H-borg	Large reefer Diesel train Antw- H-borg
Fossil		10.5	10.6	10.0
Nuclear (thermal)		0.119	0.084	0.084
Renewable		0.050	0.035	0.04
Emissions	*[gram/kg bananas]*			
CO2	total	763	773	732
	fossil	*763*	*773*	*732*
NOx	total	18	18	17
	urban	*0.05*	*0.16*	*0.67*
NMHC	total	1.0	1.0	1.0
	urban	*0.028*	*0.033*	*0.055*
CH4	total	0.012	0.013	0.012
	urban	*0*	*0*	*0.00019*
PM >2	total	0.00052	0.00037	0.00037
	urban	*0*	*0*	*0*
PM >0.5	total	0.9	0.83	0.84
	urban	*0.0040*	*0.0093*	*0.0260*
CO	total	0.51	0.54	0.52
	urban	*0.17*	*0.17*	*0.22*
SO2	total	14	13	13
	urban	*0.009*	*0.087*	*0.172*
Other parameters				
Time	[h]	595	549	547
	[days]	25	23	23

The result of the calculations showed total values comparable in size. Differences in energy use and emissions were within the margin of error.

However, the emissions in urban areas increased, since the rail- and road transport passed through a densely populated area of Europe. The increase was especially noted for SO_2 (600%), PM>0,5 (100-350%) and NO_x (140-940%). The impact on natural, social and technical systems are therefore likely to be higher for the bananas landed in Antwerp as compared to the ones landed in Göteborg. Note that the increase of the actual impact will differ from the percentages presented above. The size of the relative impact can be assessed by performing an impact analysis, i.e., by extending the (limited) LCI into an (limited) LCA.

2. Size of reefer

The purpose with this calculation is to investigate the impact on the total EP data by choice of size of the vessels bringing the bananas to Europe. In this stage, a smaller reefer was substituted for the voyage whereas all other stages were kept constant (ceteris paribus).

3a/b Sea transport with small reefer.

Activity:	2365 pallets are stowed in cargo rooms with atmosphere control aboard the ship. 8 containers are stored on deck, each with an electrical- and gas connection for atmosphere control. The ship does not call at any other ports on its voyage to Göteborg.
Vehicle/vessel description:	A small reefer vessel operated by one main engine. The ship has a cruising speed of 18 knots, consuming 0.85 tonne of bunker per hour for propulsion, and 0.15 tonnes for refrigeration. Fuel: IFO 380, heavy bunker oil.
Calculation base:	The calculation base is the entire ship.

Calculation method:	The emissions are calculated from the energy used in the diesel engines for propulsion and electricity generation. Emission values originate from measurements of ship engines with various speeds. *Middle:* Calculated from operational data. *High:* Assumed fuel consumption increase by 10 % *Low:* Assumed fuel consumption decrease by 10 %
Comment:	The accuracy of the data is acceptable but not complete due to lack of direct measurement data. The variations in fuel consumption cover differences in weather conditions and season variations.

The reduced transport efficiency of the smaller reefer is reflected by a 25% increase of fuel consumption for the sea voyage along with the 2-day increase in cruising time. The time can of course vary. However, the decreased efficiency of the smaller vessel will yield an aggregated environmental performance.

3. Reefer speed

The energy demand for propelling a vessel increases rapidly with increasing speed[20]. The reason for this is the resistance to which an object is subjected when moving through a medium, together with the generation of the bow wave and a wake. Reefers are traditionally built for relatively fast operations (> 20 kn.) as compared to normal shipping (12-18 kn.). The reefers therefore show large fuel consumption in relation to the cargo relocated. This in addition to engines, not designed for low emissions, running on ('dirty') heavy fuel oils makes the reefer more polluting (per tonne×km) than other

---

[20] This is known as the 'cube rule': $\text{actual f.c.} = \text{design f.c.} \times \left(\frac{\text{speed}}{\text{design speed}} \right)^{a}$, $a \approx 3$

cargo vessels of a similar size. One way to improve the energy efficiency is to increase the cargo capacity by mounting containers on the deck. This has proven cost-effective and the reefers carrying bananas normally carry containers on deck. Another option would be to decrease the cruising speed of the vessel.

Depending on the design of the hull and the overall operating economics, this could be a feasible option. The gain is reduced fuel consumption at the cost of decreased productivity per unit time. The calculation presented does not encompass the overall feasibility of such a change in operation mode of the reefer. The calculation focuses on the change in environmental performance. The calculation assumed a decrease of 3 knots (-14%) which decreased the fuel consumption by 15%. This rather low response could be due to a deviation from the design speed of an advanced hull shape causing a deviation from the 'cube rule'.

A calculation of the fuel cost for the banana transport is presented below, together with the effect of an introduction of a CO_2 tax. The CO_2 tax would increase the transport cost by SEK 0.22 per kilo bananas with the present tax level. A suggested increase[21] of the CO_2 tax would increase the cost by SEK 0,88 per kilo bananas. In relation to the retail price this would be an increase by 4,5%. How this would propagate to the retail price will not be further investigated.

---

[21] The suggested tax is the level estimated to be necessary in order to maintain the Swedish CO_2 emissions at the 1990 level by 2010 (SIKA 1999). International shipping is among the hardest sectors to introduce CO_2 taxation, why this calculation should be considered as a very-worst case.

Table 7 *Reefer-related CO_2 tax cost increase in relation to banana retail price.*

Parameters	**Large Vessel, 21 knots**	**Large Vessel, 18 knots**	[Units]
Total fuel related cost:			
today, bunker	0.16	0.14	[SEK/kg bananas]
bunker + CO2 tax	0.39	0.33	[SEK/kg bananas]
bunker + suggested CO2 tax	1.0	0.88	[SEK/kg bananas]
Banana retail price		20	[SEK]
Increase du to present CO2 tax	1.1%	0.9%	
Increase due to suggested CO2 tax	4.4%	3.7%	
Transport data:			
Energy demand	8.1	6.9	[MJ/per kg bananas]
Bunker	0.20	0.17	[SEK/kg bananas]
Price of bunker (IFO 180)		100	$ US
Bunker cost	0.16	0.14	[SEK/kg bananas]
CO2 emission	0.59	0.50	[kg/kg banana]
CO2 tax levels:			
Present CO2 tax, sea bunker	0	0	[SEK/kg CO2]
Present CO2 tax, land transport	0.38	0.38	[SEK/kg CO2]
Suggested CO2 tax, sea bunker	1.5	1.5	[SEK/kg CO2]
Cost as if CO2 tax were introduced for bunker fuels:			
present tax level	0.22	0.19	[SEK/kg bananas]
after suggested increase	0.88	0.74	[SEK/kg bananas]

4. Origin of cargo

A majority of the bananas consumed in Europe are grown in Latin American countries. The distance and size of the vessels bringing the bananas to Europe vary. A calculation was made in order to find the extreme values for bananas from the Latin American countries. The best choice was the bananas from Costa Rica (9 900 km) brought to Göteborg by the large reefer cruising at low speed. The higher value is from a small reefer bringing bananas from Equador (12 000 km).

Table 8 *EP data for bananas of different origin, the highest and lowest values.*

EP Parameter		Ecuador - Göteborg - Växjö Small reefer	Costa Rica - Göteborg - Växjö Large reefer, slow 18 kn.
Energy	[MJ/kg bananas]		
Fossil		14.5	9.3
Nuclear (thermal)		0.084	0.084
Renewable		0.035	0.035
Emissions			
CO2	total	1053	668
	fossil	*1053*	*668*
NOx	total	27	15
	urban	*0.05*	*0.05*
NMHC	total	1.4	0.8
	urban	*0.028*	*0.028*
CH4	total	0.016	0.011
	urban	*0.00000*	*0.00000*
PM >2	total	0.00037	0.00037
	urban	*0*	*0*
PM >0.5	total	1.29	0.72
	urban	*0.0040*	*0.0040*
CO	total	0.67	0.53
	urban	*0.17*	*0.17*
SO2	total	21	12
	urban	*0.009*	*0.009*
Other parameters			
Time	*[h]*	649	590
	[days]	27	25

5. *Transport system efficiency*

As indicated in Table 5 does the distribution to the shop and the home transport by personal car contribute substantially to the total EP data. When the EP data is compared to the transported distance the car proves to be an inefficient transport system. The home transport by other means of transport was therefore investigated. Three alternatives to personal car were constructed.

- The system consists of a normal delivery van distributing 20 kg groceries to 30 households with a mean inter-distance of 0.5 km.
- The other two systems are based on distribution of individually packed groceries delivered to 6 pick-up points within walking distance from the home. The system could be suitable for an urban building structure.
- Trucks are used in the distribution and the cargo is packed either on pallets or wheeled pallets.

The relative energy efficiency for the systems is presented in table 9.

Table 9 *Energy demand for transporting 1 kg of groceries from shop to private household [MJ/kg].*

Vehicle type	**Cargo, total** [kg]	**Energy** [MJ/kg]	**Relation**	Nr. of households	Nr. of stops
Personal car:	20	1.1	27	1	1
Van	600	0.14	3.5	30	30
Diesel lorry - pallet:	3360	0.040	*1*	336	6
Diesel lorry - wheeled pallet:	3240	0.042	1.04	324	6

As seen from the table above, an improvement in energy efficiency in the order of 10-30 could be achieved by the suggested systems. This finding inspired to a comparison of the transport efficiency of all the transport systems involved in the transport chain. Table 10 shows the efficiency of the different transport systems as they are used in the case study, i.e. their performance when transporting bananas.

Table 10 *The environmental performance of the transport systems in the investigated transport chain (EP data per km*tonne bananas).*

EP parameter	**Reefer, Large**	**Reefer, Small**	**Lorry, Sweden**	**Lorry, Euro trailer**	**Train, Diesel (Danish)**	**Train, Electric (Danish)**	**Train, Electric (SJ-Sweden)**	**Car, as used (30 kg groc.)**
Max Capacity [# of banana boxes]	423 360	2 199	1 632	1 152	36 706	23 040	36 706	0.083
Energy [MJ/km*tonne bananas]								
Fossil	0.42	0.54	0.66	0.69	0.34	0.25	0	104
Emissions [g/km*tonne bananas]								
CO2	31	39	48	50	26	21	0.0030	7 565
NOx	0.90	1.1	0.43	0.45	0.36	0.060	0.000010	3.3
NMHC	0.044	0.053	0.044	0.045	0.017	0.00081	0.000010	2.7
CH4	0.00041	0.00052	0.0013	0.0013	N/A	N/A	N/A	N/A
PM >2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PM >0,5	0.045	0.055	0.0068	0.0071	0.01	0.0019	0.000001	0.33
CO	0.013	0.020	0.046	0.048	0.04	0.0029	0.000080	17
SO2	0.73	0.93	0.012	0.012	0.01	0.067	0.000005	0.88

The relative inefficiency of the car is apparent from this comparison. Noteworthy is the good performance shown for the emission parameters reduced by the catalyst (NO_x, CO). Also indicated is the similar performance for the diesel train and the reefer as discussed above. The advantage of electrical trains is illustrated by the Swedish state railways (SJ). The almost zero emission performance is due to the supply of BRA MILJÖVAL labelled Hydropower electricity (see Bäckström, 1999). The advantage of flexibility in the selection of energy supply is then executed in order to obtain low EP data for the operations.

Table 10 *Summary of the calculations for the different transport chains.*

EP Parameter		Costa Rica - Göteborg - Växjö	Costa Rica - Göteborg - Växjö	Ecuador - Göteborg - Växjö	Costa Rica - Antwerp - Växjö
Energy	[MJ/kg bananas]	Large reefer, Fast, 21 kn.	Small reefer	Small reefer	Large reefer, Lorry Antw- H-borg
Fossil		10.5	12	14.5	10.6
Nuclear (thermal)		0.119	0.119	0.084	0.084
Renewable		0.050	0.050	0.035	0.035
Emissions	[gram/kg bananas]				
CO2	total	763	907	1053	773
	fossil	*763*	*907*	*1053*	773
NOx	total	18	22	27	18
	urban	*0.05*	*0.05*	*0.05*	0.16
NMHC	total	1.0	1.2	1.39	1.00
	urban	*0.028*	*0.028*	*0.028*	0.033
CH4	total	0.012	0.014	0.016	0.013
	urban	*0.00000*	*0.00000*	*0.00000*	0.00000
PM >2	total	0.00052	0.00052	0.00037	0.00037
	urban	*0*	*0*	*0*	0
PM >0.5	total	0.89	1.08	1.29	0.83
	urban	*0.0040*	*0.0040*	*0.0040*	0.0093
CO	total	0.51	0.61	0.67	0.54
	urban	*0.17*	*0.17*	*0.17*	0.17
SO2	total	14	18	21.1	13
	urban	*0.009*	*0.009*	*0.009*	0.087
Other parameters					
Time	[h]	595	638	649	549
	[days]	25	27	27	23

EP Parameter		Costa Rica - Antwerp - Växjö	Ecuador - Antwerp - Växjö	Costa Rica - Antwerp - Nybro	Costa Rica - Antwerp - Nybro	Costa Rica - Göteborg - Växjö
Energy	[MJ/kg bananas]	Large reefer, Diesel train Antw- H-borg	Small reefer	Allocation, High (see ch. 5)	Allocation, Low (see ch. 5)	Large reefer, slow 18 kn.
Fossil		10.0	14.47	15	9.9	9.3
Nuclear (thermal)		0.084	0.084	0.084	0.084	0.084
Renewable		0.035	0.035	0.035	0.035	0.035
Emissions	[gram/kg bananas]					
CO2	total	732	1049	1086	719	668
	fossil	732	1049	1086	719	*668*
NOx	total	17	25	20	17	15
	urban	0.67	0.12	0.17	0.04	*0.05*
NMHC	total	0.95	1.33	1.3	0.95	0.8
	urban	0.055	0.031	0.048	0.015	*0.028*
CH4	total	0.012	0.006	0.021	0.012	0.011
	urban	0.00019	0.00000	0.00000	0.00000	*0.00000*
PM >2	total	0.00037	0.00037	0.00037	0.00037	0.00037
	urban	0	0	0	0	*0*
PM >0.5	total	0.84	1.18	0.90	0.83	0.72
	urban	0.0260	0.0078	0.0090	0.0026	*0.0040*
CO	total	0.52	0.74	0.90	0.44	0.53
	urban	0.22	0.17	0.29	0.09	*0.17*
SO2	total	13	19.7	14	13	12
	urban	0.172	0.064	0.015	0.005	*0.009*
Other parameters						
Time	[h]	547	584	549	549	590
	[days]	23	24	23	23	25

5 TRANSPORT-SPECIFIC ALLOCATION ISSUES IN LCI

5.1 Introduction

When a process in the life cycle of a product generates more than one output, allocation of the environmental performance of the process has to be made to the different outputs (if the system boundaries are not to be redefined). The methods applied when making this division vary with the nature of the product and process, but with one feature in common: the impacts upon the final result vary greatly with the choice of method.

Transportation is a common activity in LCIAs, and co-production is encountered when several consignments are transported simultaneously. Environmental performance data such as fuel consumption and emissions to air must in these cases be partitioned between the concerned consignments. The methods governing how this partitioning is to be carried out have previously only been sporadically assessed, in detail only in few cases (e.g., Flodström et al., 1994). This situation, along with the presumption that the allocation method could have a decisive impact on the end result, turned the focus of this work towards the allocation issue. Thus, in this chapter the question of transport-specific issues relating to allocation of EP data is addressed.

The work presented in this chapter concerns:

- An attempt to relate the allocation issues, encountered in transport studies, to the LC(I)A method as stated in the ISO standard and ongoing development.
- Allocations when the operation of the vehicle is assessed.
- Allocation between the investigated cargo and other transport services produced by the vehicle (i.e. passenger transport).
- Allocation between goods in a distribution route.
- Allocation between different consignments or types of cargo.

Method design issues related to these situations are investigated. Two detailed case studies are presented, 1) allocation between cargo and passengers on a Ro-Pax ferry, and 2) allocation between different cargo consignments in a distribution route to food stores. Both of these situations are encountered in variants of the transport chain for bananas to Sweden. The case study for banana transports was presented in chapter 4.

The presentation will start with the general allocation issues related to LCI (section 5.2), and proceed with the process of finding the EP data associated with the operation of the vehicle (section 5.3). The allocation of this EP data to the transported cargo is then treated in chapter 5.4. Section 5.5 presents a sensitivity analysis for the case study, and section 5.6 contains some concluding remarks.

The work presented is not an attempt to cover all the cases or aspects of allocation in LCI of a transport chain. It will therefore not fill the need for a handbook on the subject.

5.2 General aspects of allocation methodology

5.2.1 Allocation in LCA theory

"A general experience when carrying out an LCA study is that the selection of methods usually has a strong influence on the final results and can even overshadow product modifications made to improve the environmental performance. It is therefore necessary that all assumptions and prerequisites for the LCA study be carefully specified..." (Env. Mngm. Council, 1998).

The method of Life Cycle Inventory Analysis, LCI, (being a part of the LCA method) will be in a state of development for some time to be. Early attempts to harmonise the different LCA approaches (SETAC, 1993) have been followed by an ISO standardisation (ISO 14040-43, 1998). The discussion about how to apply this standard, and how the methodology should be further developed, continues to address issues at a broad as well as a detailed level, cf. Frischknecht (1998), Baumann (1998), Ekvall (1999) and Heijuns *et al.* (1998).

The ISO standard on the allocation problem

One of the central questions in the inventory analysis is how to allocate the environmental parameters from co-production processes to the unit process under study, i.e. how to partition *the input or output flows of a process to the product system under study*[22]. The problem arises when the system boundaries are defined so that all in- and outflows of the physical system are not included. This occurs in the case of joint co-production of a unit process, extraction and deposition of recycled materials and when dividing common inputs and outputs not directly related to the unit process[23]. The allocation problem is sometimes complex and may cause a substantial amount of work in order to consolidate the result of the LCI.

---

[22] ISO 14 040:1997(E), section 3.1, page 1.

[23] E.g. the production of a vehicle, machine or a building, or the operation of common utilities – administration, space heating, warehouses, sales etc.

The ISO standard recognises this and provides the following solutions:

1. *Wherever possible, allocation should be avoided or minimised. ...*

2. *Where allocation cannot be avoided, the system inputs and outputs should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; ...*

3. *Where physical relationship cannot be established or used as the basis for allocation the inputs should be allocated between the products and functions in a way which reflects economic relationships between them. For example, burdens might be allocated between co-products in proportion to the economic value of the products.*[24]

Neither of these options provides an unambiguous solution to the problem. This is also recognised by the standard, which requires that *the allocation procedure used for each unit process of which the inputs and outputs are allocated shall be documented and justified.*[25]

A solution in accordance with 1) above would be to expand the system boundaries. However, this creates a more complex system demanding increasing amounts of data. This can make the analysis impossible to carry out with respect to available time and resources. The allocation method 2) and 3) could be more successful if one constructs appropriate methods and investigates the effects of choosing one of them. What is to be considered as *appropriate* relates to the purpose of the LCI, i.e. one has to investigate whether or not the method provides a solution to the specific research question formulated in the goal and scope definition. This is expressed in the ISO standard as: *whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.*[26]

---

[24] ISO/DIS 14 041, section 6.4.2, page 16-17.

[25] ISO/DIS 14 041, section 6.4.1, page 16.

[26] ISO/DIS 14 041, section 6.4.1, page 16.

The lack of well-defined rules makes the LCI method more flexible on the account of its rigidity, and this at the same time as the communications of the findings from an analysis becomes extensive when a large part of the method becomes situation specific. With this presentation as a basis for a discussion of different allocation procedures, this work pursues the issues of allocation method design in the field of transportation.

Transport, a service without material balances

Transport is a service and a transport system is, only in a few relations and rare at least for the entire life span of the system, designated for the transport of a single type of goods. Such systems, e.g. pipelines, aerial ropeways, oil tankers, conveyor belts or shuttle ore train systems, will usually not require any advanced allocation method due to simultaneous production. These systems are therefore not further considered. Usually, transportation is a process that in one or more sub-parts yields more than one output, i.e. simultaneous relocation of different consignments. As opposed to the production of artefacts, the production of a successful transport does not alter the structure and composition of the cargo; it only changes its 'state'[27]. In LCA allocation methodology, the use of material balances for structure and composition changes as a base for allocations is preferred, as indicated in the ISO standard:

> *The inventory is based on material balances between inputs and outputs. Allocation procedures should therefore approximate as much as possible such fundamental input-output relationships and characteristics.*[28] ...

This guideline, when applied to transportation, is crippled by the lack of clear direct physical relation between 'material' input (and related environmental

---

[27] Here 'state' denotes position and temperature etc. An exception is the sorting of mail in special railcars and imaginary attributes such as the equatorial passage of *Line Akvavit*.

[28] ISO/DIS 14 041, section 6.4.1, page 16.

performance) and the output of the relocation[29]. This makes this suggestion less useful. However, in a few cases, there will be an accessible direct (marginal) relation between a change in the load put on a vehicle and the related change in EP data for that vehicle. Such relations are found in the case of airfreight where the impact of an extra unit of weight can be calculated accurately (Larson *et al.*, 1996). On the other hand, if the same cargo would be put on a ship, no such clear relation would exist[30]. These relations would only be able to deal with the marginal EP data, leaving the discussion about allocating of the 'empty vehicle'-related EP data unattended. Therefore, in most cases a material balance of the transportation process will not yield sufficient information for allocation.

LCI research the allocation problem

Further guidance is to be found in contemporary LCI method research. The allocation problem is treated in Frischknecht (1998). In this work, Frischknecht cites Tomas (1969) who stated

"minimum requirements necessary for a theoretical justification of a non-arbitrary allocation method as

1. The method should be unambiguous.

2. It should be possible to defend the method. (...)

3. The method should divide up what is available to be allocated, not more and no less. The method should be additive."[31]

---

[29] Compere the combined production of different plastics from oil with the transport of different types of plastics by a lorry running on diesel oil. The oil used in the production process can be allocated to the products by a physical relationship (e.g. by the number of carbon atoms). No such direct relationship exists when the service 'relocation of the different products' is produced.

[30] E.g., due to the fact that an under loaded ship will compensate by filling ballast tanks in order to maintain stability.

[31] Thomas (1969), page 537.

The last point puts an focus on the demand of congruity between the allocated amounts of e.g. emissions and the real emission taking place in the system. This is also expressed in the ISO 14041standard as: *the inputs and outputs of the unallocated system shall equal the sum of the corresponding inputs and outputs of the allocated system. Any deviation from mass and energy balance shall be reported and explained.*[32]

Frischknecht also suggests an adaptation to the proposal by Horngren *et al.* (1991), i.e. a classification of the underlying objectives into following types:

i Cause and effect
ii Benefits received
iii Fairness or equity
iv Ability to bear

In transportation and logistics, these issues have attracted attention when tariffs have been negotiated. A tariff reflecting all relevant environmental external costs caused by the transport system would allow allocation by that portion of the price. The analyst will here run into an closed loop since the internalisation would demand information on how to allocate to different customers. Although a solution to this intriguing problem has been suggested in Heijungs *et al.* (1998), further difficulties with economic information is encountered. Besides, the transportation is very far from a system accounting for relevant environmental costs, e.g., several of the external costs of vehicles utilisation, use of infrastructure and supply of energy to the transport sector are inadequately internalised (see Hansson, 1998).

In dealing with the accounting of ecological commodities the guidelines above by Tomas (1969) reoccur in many LCA methods being suggested.

---

[32] ISO/DIS 14 041:1997(E), section 6.4.1, page 16.

Several of the general allocation approaches are pragmatic, as indicated by the principles for allocation suggested in Lindfors *et al.* (1995).

- natural causality or an adequate approximation
- economic/social causality e.g. expected gain or gross sales value
- physical parameters as allocation parameter, e.g. mass of outputs, energy *content of the output, exergy content of output, area of output, volume of output, molar content of output or arbitrary numbers (100/0 % or 50/50 %)*

Again, a focus upon processes producing commodities is recognised rather than service delivery processes. Lindfors suggests that 50/50% allocation method could be used for a simplified LCI, since this method ensures that information on "key issues" is not lost. Other guiding principles can be found, and more situation-specific methods (of quite disparate character) are continuously being developed as the LC(I)A method is adopted by new sectors and practitioners (see e.g., Heijungs *et al.* (1998), and Kim *et al.* (1998)).

The accountant's answer

The allocation problem has earlier extensively been dealt with in accounting theory in the search for methods to divide common/joint costs. Several methods presented in this discipline are[33] based on economic parameters connected to the different products (i.e. cost, value of products, revenue, profit, cost of substitution etc.). Another approach presented is game theory applied to the concerned actors in constructing allocation methods. The arbitrary nature of their construction and dependence upon, e.g., variable and imperfect market situations makes them more 'volatile' than methods based on physical dimensions.

Although these methods are considered in the LCI method development, their demand for economic information makes them difficult to manage for

---

[33] See Frischknecht (1998), p. 227, for a synopsis of "Allocation Methods for Joint Allocation"

external LCI practitioners. The willingness to communicate the results might also be limited as economic information is revealed.

Other transportation-specific conditions complicating the use of allocation methods based on economic relations are – large indirect costs, – irreversible and fixed investments, -uneven utilisation of resources in time and space. Analysis of the cost structure[34] also shows a digressive scale (decreasing price with e.g. increasing distance, size and frequency of shipment) due to better choice of vehicle size, degree of utilisation, rational terminal handling and lower relative fixed costs. Although these changes influence environmental performance, several posts show no or small relation to environmental effects (e.g. administration cost per trip/route etc.).

Although not supported by data in this work, economic based allocation methods are likely to be successful in transportation systems where EP data related costs (i.e., fuel cost, emission taxes/fees etc.) are relatively large.

As stated above can the market situation alter the result of allocation without any physical change taking place. The tariff system is in many transport systems substituted by contract based pricing, making the price information a sensitive business information difficult to obtain for the LCI practitioner. Further, the tariff system is complicated by different rebate systems making an allocation based upon economic bases hard to justify in accordance with the ISO standard.

Another problematic issue related to allocation methods based upon prices and costs is the Long-and-Short-Haul Discrimination problem. As presented by Locklin (1972) 'Long-and-Short-Haul Discrimination consists in charging a larger aggregate amount for the transportation of persons or property for a shorter than a longer distance when both hauls are over the same line, in the

---

[34] See e.g. Tarkowski (1977), p. 144.

same direction, and the shorter is included in the longer distance'. A graphic illustration of the problem is shown in fig below.

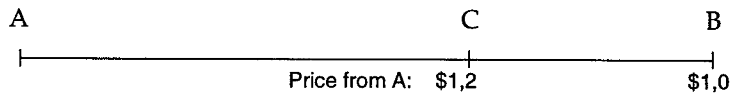


Figure 5 *Long-and-Short-Haul Discrimination. B is served by competing transport systems between A-B, C is not.*

The reason for the lower price to destination B could be a competing transport system available at this destination (e.g. a harbour, airport etc.) while C is only served by the transport system illustrated by the line. Allocation in accordance with price paid by the shipper will obviously deviate from any physical dimension describing the environmental impact by transporting the goods.

The economic base for allocation is thus hampered by three major drawbacks,

1. economic information such as prices, profits, revenues and costs are sensitive information hard to obtained from operators
2. prices are settled in negotiations on a market, thus yielding different prices for different customers, and changing with weak connection to the generation of EP data (cf. Tax Free on ferries) and
3. prices usually do not reflect internal, or external, costs related to the EP data.

In Berglund (1999) is the third argument used in order to support the abandoning a transport cost based allocation approach. The example referred to is an case from the environmental assessment of the transport system of the StoraEnso.

With these general LCI allocation methodology concerns as a starting point, this work will relate the methodology to the case of allocation in LCI of transportation, based on the examples found in the transport chain of banana import. As pointed out above, it is impossible to point out one method as *the best*. It is therefore not the ambition of this work to do so, instead the following sections investigate the impact of available and suggested methods, when applied to a transport chain.

5.2.2 Allocation issues in transport studies

A transport generally consists of several sub-activities, each with a number of supporting systems, and each with a separate environmental performance, (see Figure 2). In this model, sub-activities, with their respective environmental performance, is pictured as links in the transportation chain. The sub-activities often deal with a number of services simultaneously and hence, the co-production allocation problem is frequently encountered as the environmental performance of a transport is assessed.

A commonly complex nature of transportation systems makes LCI of transportation systems intriguing. The large numbers of combinations of transport vehicles, vessels, handling equipment, addresses, cargo types, transport modes, etc. call for an extensive description of the method used when carrying out allocation in an LCI of a transport. Despite this, a common understanding of calculation methods is especially important when different systems and results from different studies are to be compared. This issue becomes evident when e.g. transport companies are presenting information about their environmental performance to customers and other parties concerned.

The allocation question encountered in environmental assessment of transport chains has been treated in Flodström *et al.* (1994). The discussion in this work was focused upon the allocation of traffic-related emissions to the services provided. The work presented in this chapter focuses on a micro-perspective, trying to find a model capable of assessing the share of the total

EP data related to the relocation of a specific cargo consignment. Thus, this work does not consider the statistical approach needed in order to address questions like

- which transportation system will have the smallest share of the CO_2 emissions from Europe in 2005 or
- what would be the effect upon the national energy use by shifting x% of the national road transport work to rail?

One approach for such studies are found in Demker *et al.* (1994) and Flodström *et al.* (1994).

The aim of the allocation calculation is to burden the relocated cargo with the share of all environmental performance data (EP data) related to the realisation of the transport.

Relevant EP data originates from:

- making the vehicles accessible for the transport
- making the cargo handling equipment accessible for the transport
- the use of infrastructure
- the operation of the vehicles
- energy supplies to these systems.

When carrying out the EP calculations for a transport one allocates, in a first step, relevant EP data from the sub-processes to the vehicle (section 5.3), combines this with the operations-related EP data, and in the final step allocates this sum to the cargo carried by the vehicle (section 5.4).

5.2.3 Calculation examples

The discussion presented in this chapter uses examples of allocation from the investigation of the transportation chain employed in banana imports to Sweden, (see Chapter 4). The examples are presented in order to demonstrate the influences upon the result caused by the choice of allocation method. The investigation of the environmental performance of the transport chain explored variations in EP data in the different stages introduced by - uncertainties in vehicle type/data, - fuel source (electricity generation, fuel LCI, vehicle operations). The purpose of section 5.5 is to explore the impact on the final results of the case study caused by allocation method design.

Bananas are brought to Europe by reefers equipped with atmosphere control. The bananas designated for Sweden are landed in Göteborg (the Skandia- and the Free harbour) and to some extent in European mainland ports (Antwerp, Zeebrugge, Hamburg and Bremerhaven). The transport then proceeds by either train or lorry to an importer/wholesaler with ripening rooms. In the case of a train transport, the railcars with bananas are assumed to be integrated with other cars into a longer train set. A lorry from mainland Europe to Sweden will have to be transported by a Ro-Pax ferry or on a trailer RoRo ship. These three transport modes are examples of situations where EP data must be allocated between the different railcars, trailers or services provided by the vessel.

From the importer/wholesaler the bananas are transported together with other goods, either to a wholesaler, a shop or a large customer. These together with the final transport to a household will present examples of allocation situations.

This transportation chain thus contains several situations where allocation of environmental performance data has to be made to transportation services produced simultaneously. The impacts of allocation method choice are calculated and related to the case study. Hypothetical examples from rail and air complement the discussion in areas not covered by the case of the banana transport. The case specific data obtained by interviewing the operators are, where so is stated, complemented with data from literature and assumptions made by the author. This is done in order to expand and clarify the discussion.

5.3 Allocation to vehicle operations

The first step in the calculation is to identify all the EP data related to the transport and the size of the contribution from respective source will be calculated by applying an allocation method (where needed). The underlying idea is that the total EP data from all activities for providing the transport should be partitioned between the provided services. Contributions are collected from:

	EP data source	*Allocation*
1.	Vehicle production, reconstruction and scrapping	Per operating time, per distance, per transport work. Actual, average or planned performance
2	Service and maintenance, spare parts, consumption materials	See model below
3	Vehicle operation and energy supply	Data from positioning and empty trips has to be allocated to the transports. Covered by the model below.
4	Infrastructure construction and operation (e.g., road, rail and sailing channel construction and road lighting and snow ploughing)	Allocation to actual, average or planned traffic volumes. Time of integration for calculation of average values. Per vehicle type, per axle, per tyre, per weight. Does the road serve other purposes? Does road illumination serve other purposes?
5	Other service covered by the system boundaries (e.g., head office operations and personnel travel to work)	Per assignment, per vehicle, per transport work or other unit.

The first, second and third issues are covered by a model presented in the following section. The issue of allocation of infrastructure EP data is discussed in Stripple (1995) and Maibach *et al.* (1995). Although the last issue is left without further attention, contributions from such support processes can prove significant, (see Env. Mngm. Council, 1999b).

The EP data related to the vehicle provision and operations was chosen for a deeper study. In Figure 6 is a conceptual model for the analysis of the vehicle EPD presented. The model is based on a time analysis model presented in Manheim (1979). The presentation of the allocation model will be using the example of a distribution lorry engaged in a rail-road intermodal transportation system.

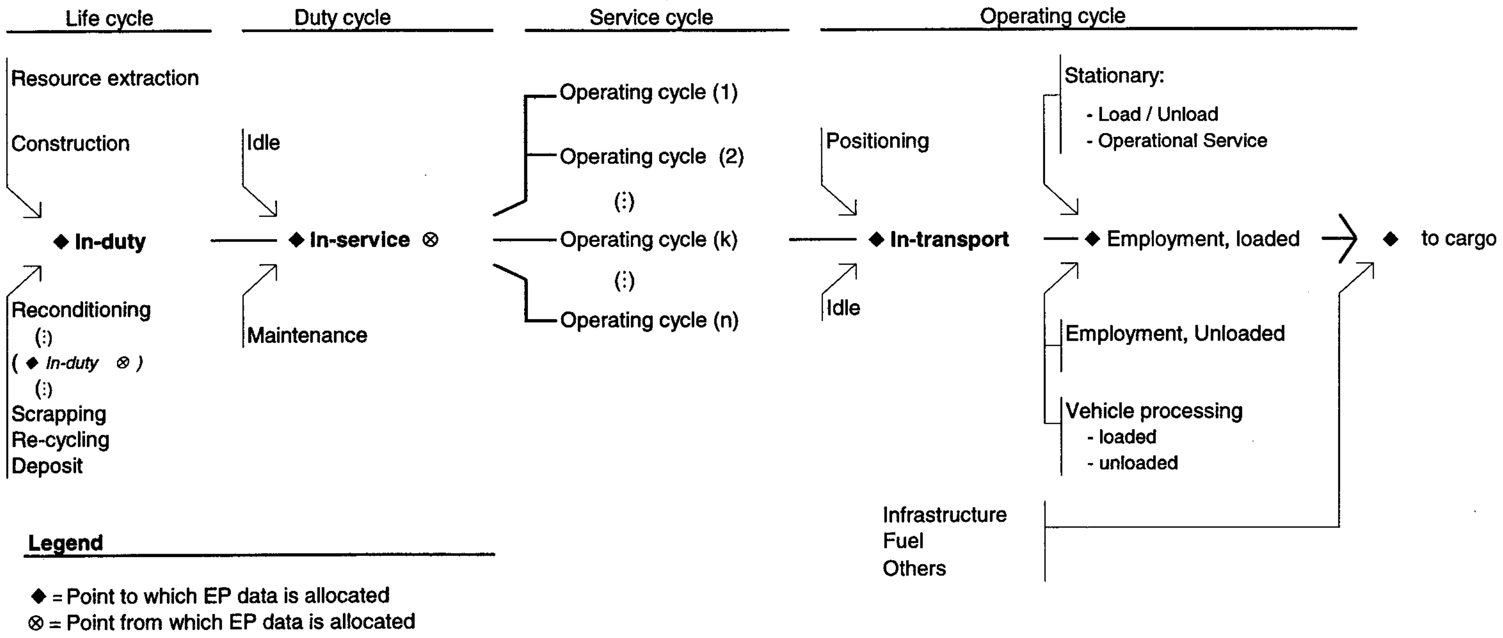


Figure 6 *A schematic map of allocation of EP data during a vehicle's life span (Developed from Manheim, 1979, p.222).*

The figure covers activities generating EP data to be allocated. The model does not claim to be exhaustive due to the different nature of the transport modes. The model could be used as a start in the mapping of case-specific EP data.

An illustrative example

Consider a privately owned lorry engaged in the haulage of containers in an intermodal transport system. The *life cycle* of the lorry is composed of construction phase, duty phase and the scrapping phase. The introduction of a recondition/reconstruction phase (i.e. changing engine or other large parts of the vehicle) yields several in-duty periods. In this case, a division of construction and scrapping EP data is made between the different in-duty periods. During the *in-duty cycle*, the lorry is in service, idle (e.g. periods of de-registration) and maintained (changing tyres, lubrication and engine oils, washing etc.). EP data for these activities are combined with the EP data from the life cycle and further allocated between the different *operating cycles* within the *in-service cycle*. A service cycle could be one day of operations, a longer trip or any other natural partition of the vehicle use. The allocation is ruled by the definition of the operating cycle, time, operating time, driven kilometres or could be made equal to each cycle. The latter method could be a *data-efficient* approach for a vehicle in routine operations. Allocation for a lorry engaged in operations with large differences in cycle time and travelled distance could be based on these dimensions instead.

Within the *operating cycle*, *positioning* is the trip between the driver's home and the first loading address. If the lorry is stationed at a garage between the operating cycles (e.g. at night), EP data for the driver's travel to work should be added to the figure. EP data from idle periods could origin from garage operations, electrical engine heater etc. During the *in transport* period, the vehicle is engaged in several activities. The lorry is stationary both during the loading/unloading processes and operational service as, e.g., refuelling[35]. The lorry is then employed with and without cargo. The vehicle-processing phase applies to vehicles without own propulsion capacity (rail wagons and trailers). The *employment, unloaded, vehicle processing* and *operational service* are activities that might have to be allocated between successive transports. The EP data for these activities are allocated to the *employment, loaded* phase, to which data for energy supply and infrastructure use is added. Finally, this sum is to be allocated to the different transportation services (cargo consignments, passengers or other).

Life cycle → Duty cycle

As stated above, the nature of the 'duty cycle' varies between the transport modes. The reefer used for the transport of bananas to Europe are typically docked for service reconditioning together with classification with a period of 5 years[36] while the lorries recondition engines after some 500 000 km[37]. The EP data from the non-operational and reconditioning parts of the life span (i.e. resource extraction, material and vehicle production, scrapping, material recycling and depositing) are allocated to the duty cycles by the parameter defining the cycle, i.e. operating hours, driven kilometres, number of starts and stops etc. EP data related to parts and systems replaced at reconditioning is either allocated entirely to the succeeding duty cycle or added to the construction and scrapping parts and divided equally to duty cycles.

The latter method is suggested when the reconditioning is planned in the design. In the other case, the life cycle of the construction of the reefer, its scrapping and material recycling has to be attributed to the different duty cycles. This can be done by using several methods based upon LCA recycling

---

[35] With EP data for evaporative emissions, if not included in LCA data for fuel supply.

[36] Hull inspection are made with charter interval, 2,5 years. (Hyttsten 1999)

[37] Personal communication, Arnäs (1999)

methodology[38] (ISO 14 041 1997). The number of duty cycles (with subsequent service cycles and amount of vkm or operating hours) can be determined by forecasts or by measurements of actual performance.

An estimate will show that the size of this contribution to the final relevant EP data justifies the previous discussion. Assume that a reefer of the size 8 000 DWT has a light ship weight of 4000 tonnes and is mainly made out of steel produced in Sweden. The total steel production-related CO_2 emission for ship production and reconditioning would be[39] 4×10^6 [kg] * 1,21 [kg CO_2/kg] (SPINE 1999) = $4{,}9 \times 10^6$ kg CO_2. This is the same amount that is emitted by burning 2 200 tonnes Heavy Fuel Oil (HFO), i.e. 1 500 operating hours at cruising speed. Thus, the CO_2 emitted during material production would amount to some 0,7%[40] of the total CO_2 emissions during lifetime operations. The emissions from other materials, transport activities and the ship construction are not included in this figure. A screening inventory, used to identify processes contributing significantly to the life cycle, would thus probably qualify the material and ship production to be investigated further. A rule of thumb in LCI is to include all contributions >1 % of the total. The result thus indicates that processes this far back could contribute significantly, especially for substances of large quantity or with high impact valuation.

An estimation, although not up to date, for the life cycle energy demand for lorry construction yielded the following data, see Table 11. The figures are likely to be high, and no credit was given for heat recovery etc. in material recycling or disposal.

---

[38] This is done, e.g., by adding the resource and construction data and then consider the ship as an artefact being re-cycled by the reconditioning processes. The in-duty cycles would obtain a lower EP data which might be wrong if the reconditioning is planned when designing the ship.

[39] Assuming two re-conditionings during the life cycle, each replacing 1% of the weight.

[40] Assuming a 30-year life span and 7000 hours of operation per year.

Table 11 *Energy demand for the manufacturing of a lorry with trailer (from Kordi et al. 1979, pp. A-30).*

	Energy Demand						
Type of vehicle	Material and Construction		Maintenance and incidental material		Total		Expected life time
	Electricity [kWh]	Fossil fuel [kWh]	Electricity [kWh]	Fossil fuel [kWh]	Electricity [kWh/10 km]	Fossil fuel [kWh/10 km]	[km]
Large lorry	26 200	68 620	8 200	74 500	*0.69*	*2.9*	500 000
Trailer	19 100	61 200	9 500	64 100	*0.29*	*1.3*	1 000 000
Large lorry with trailer	45 300	129 820	17 700	138 600	***0.97***	***4.1***	
Large tanker lorry	64 900	100 700	10 750	73 440	*1.6*	*3.6*	480 000
Trailer	85 500	74 800	9 500	64 100	*0.95*	*1.4*	1 000 000
Large tanker lorry with trailer	150 400	175 500	20 250	137 540	***2.5***	***5.0***	

These data are likely to have changed[41] due to more energy efficient operations and substitution of fossil fuels with electricity after the large-scale introduction of nuclear power[42]. Although somewhat old, these figures can be compared to the energy use for the operations of the tucks, i.e. the heat value of the fuel. Typical fuel consumption for these lorries, 4.5 dm^3/10km equals some 45 kWh(fuel)/10km. For the tanker lorry with trailer, the fossil fuel consumed during all the stages of the production would amount to 4.5 % of the energy in the fuel used per km. When the maintenance and incidental materials (oils, tyres and spare parts) are included, an equivalent of 8.5 % of the fuel energy is consumed in order to provide the vehicle. The EP data contribution from the electricity use is dependent upon location of production, or method when assessing environmental performance of electricity generation. Large variations in the end result are to be expected by

---

[41] Scania (Scania 1999) reports an figure of 13 000 kWh per vehicle from their own operations (i.e., excl. material extraction etc.)

[42] Weather or not the latter change is an improvement for the environment is an issue for the LCA-analyst to address.

such differences[43]. The discussion now turn to the question how the EP data connected to these parts of the vehicle life cycle can be allocated to the goods under study.

Duty cycle → Service cycle

The calculation above made the allocation of the CO_2 emission by distributing them evenly over all engine-operation hours. Other methods, in line with the suggested model, might yield different results.

When allocating by time, assuming two duty cycles of equal length, half the CO_2 emissions from the production of the steel would be combined with the emissions from regular service and maintenance. For the ship, this would be painting, changing oil, replacing cold media, providing supplies etc. The sum of emissions from all such 'pre-operational' activities is allocated to the different operating cycles. The definition of the operating cycles will determine the suitable allocation parameter. For a reefer with a constant level of activity, cycle time or travelled distance between calling at a base port could be used. In the case of uneven distribution of idle periods in the operating cycles, actual operating time, or distance travelled, could be considered instead of the total time. An operating cycle for the reefer, e.g. a round trip between Europe and Central America, takes about 4-5 weeks, allowing the ship to carry out some 20 operating cycles between a 24[44]-month maintenance interval. Each operating cycle will thus bear 15 tonnes of CO_2 emissions from steel production plus recondition and maintenance.

The EP data from maintenance during the duty cycle is combined with EP data from idle periods and allocated to the different operating cycles taking

---

[43] This issue, of large importance when assessing electrically propelled traffic, is tot addressed in this work. See Bäckström (1999) for further information.

[44] An assumed time interval.

place during the service cycle. This allocation is, again, performed by the parameter defining an operating cycle.

Service cycle → Operating cycle

The 'operating cycle' will be understood as the movements the vehicle makes between two approaches to a defined originating address a 'home'-depot, harbour, base airport, marshalling yard etc. (cf. the lorry example above). The definition of the cycle will be different for vehicles operating in scheduled traffic, such as distribution lorries, ferries, and cargo 'shuttle' trains, than for vehicles utilised in a more flexible manner. In such operations, repositioning and empty return trips are more frequent (e.g. normal railcars, trailers, tramp vessels). The definition of the operating cycle, as well as what parts of it that relate to the transport of the goods, governs how the allocation is carried out.

For a cargo vessel, the engagement could start by a positioning to the loading harbour. This is followed by an "in-transport" period lasting until the vessel is disengaged. The ship will then engage in a further mission, or become idle, sometimes after repositioning to a harbour likely to offer cargo in the near future. If the new load is available in another harbour, a new positioning occurs. We are thus faced with the question of defining what part of the pre- and post-positioning that are to be allocated to the transport under study, (see Figure 6)

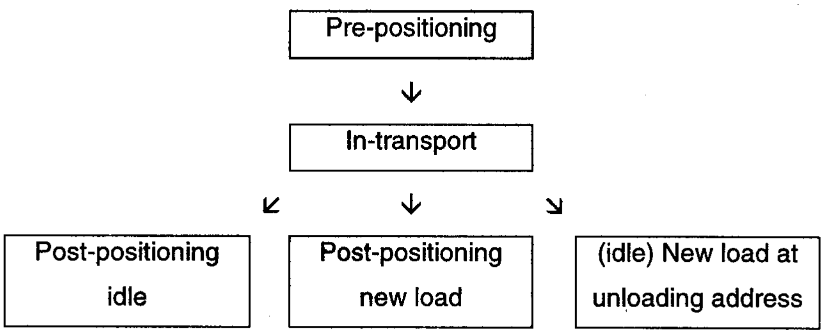


Figure 6 *Post-transport situations*

The two extreme cases are to either include both or none of the positioning journeys taking place in relation to the transport. A more cautious approach would be to include half of each of the positioning (compare sect. 5.2.1 above). When the ship unloads at an unusually distant port, one could allocate a larger portion of a post-positioning to the cargo bringing the vessel there. Another approach would be to, based on historical data, calculate an average positioning distance for the vessel under study. In the case study of the bananas, the entire return trip was allocated to the bananas brought to Europe. The presented situations could also be assessed by allocation in accordance with economic data. It is likely that the price will reflect both time and distance, although not necessarily in the same manner for different customers.

The distribution vehicle bringing the bananas from the wholesaler to the supermarket/grocery store can illustrate the other parts of the operating cycle. An operating cycle can be defined as the activities between the start at the parking in the morning until the vehicle returns there at night. The vehicle is driven to the wholesaler's terminal/unloading ramp – *positioning,* where the vehicle becomes stationary and the *loading* takes place. The vehicle is then *employed* in distribution to a number of addresses. At the delivery address the vehicle becomes *stationary,* and unloading (and loading) takes place. After the last 'station' the vehicle is called back to the terminal for further assignments and this return trip represents an example of *employment unloaded.* If the vehicle were to be returned directly to the parking, this would be a *post positioning.* Stops for refuelling, lunch break or other service is classified as a *station* with *operational service.* The EP data for loading and unloading is perhaps not crucial for the distribution vehicle. However, transport systems and vehicles with their own cargo handling equipment (ships, timber lorries and the 'light combi' system[45]) would yield data for this activity.

---

[45] This is train-road intermodal system where the train carries its own fork lift. (See Woxenius, 1998, pp. 181)

The first step in the calculation is summarised in the statement:

The part of the non-operation EP data from the life cycle, duty cycle and operating cycle of the vehicle is allocated to the part of the operating cycle where the vehicle is employed with the cargo under study. This EP data is combined with the EP data from the vehicle operation, infrastructure and fuel supply. The sum of this EP data is then to be allocated to the services provided, e.g. passenger and or cargo transport.

This allocation step is sometimes not considered due to

- lack of data for the different processes during resource extraction, vehicle production – service-maintenance and scrapping etc (see Env. Mngm. Council, 1999b, pp. 9).
- a perceived relatively small contribution from these parts of the LCA as compared to the operation of the vehicle. As shown above, and in other studies (Volvo, 1997, Maibach et al., 1995), this assumption should be verified.
- limited time window as defined in the system boundary definition, thus not covering these processes.

An inventory must recognise the need to distinguish the difference in time and location of the emission during resource extraction and the operation of the vehicle. This aspect is further complicated by any time lag between emission and environmental effect. The strategy for dealing with these issues is found in the definitions of the system boundaries, and is important for the characterisation and evaluation procedure in the full LCA.

The calculation above shows that, as more LCI data becomes available, this first step should be addressed in order to assess the relevance of the contribution. This is also the case as new data and impact categories are introduced into the analysis.

The discussion above could be continued with EP data for infrastructure, cargo handling equipment (e.g. Blix *et al.*, 1998) and fuel production. These areas have not been explored in this work, which instead turns to the question of how the allocation to the transported cargo is to be carried out.

5.4 Allocation to cargo within the operating cycle

Given the total environmental performance (direct and indirect) of the operation of the vehicle, we are left with the task of allotting this to the services performed by this operation, i.e. the relocation of cargo shipments and persons. This allocation step has to be further subdivided by transport systems categorised in three types, namely shipments with a transportation system designated:

1. for cargo transport combined with other services,
2. for simultaneous transport of goods with different destinations and/or of different nature and
3. exclusively for the transport of the cargo under study.

The first and the second types are the systems where allocation must be carried out at multiple stages in order to clarify the share of the EP data to associate with the transportation of specific goods. In the first case, simultaneous transport of passengers is the dominant issue. Other services that could be considered is societal support to maintaining public access to mobility, supplying transport service in contingency planning etc. Such side services, of importance for traffic to remote destinations, are not further considered in this work.

A decision-tree for the process is shown in Figure 8.

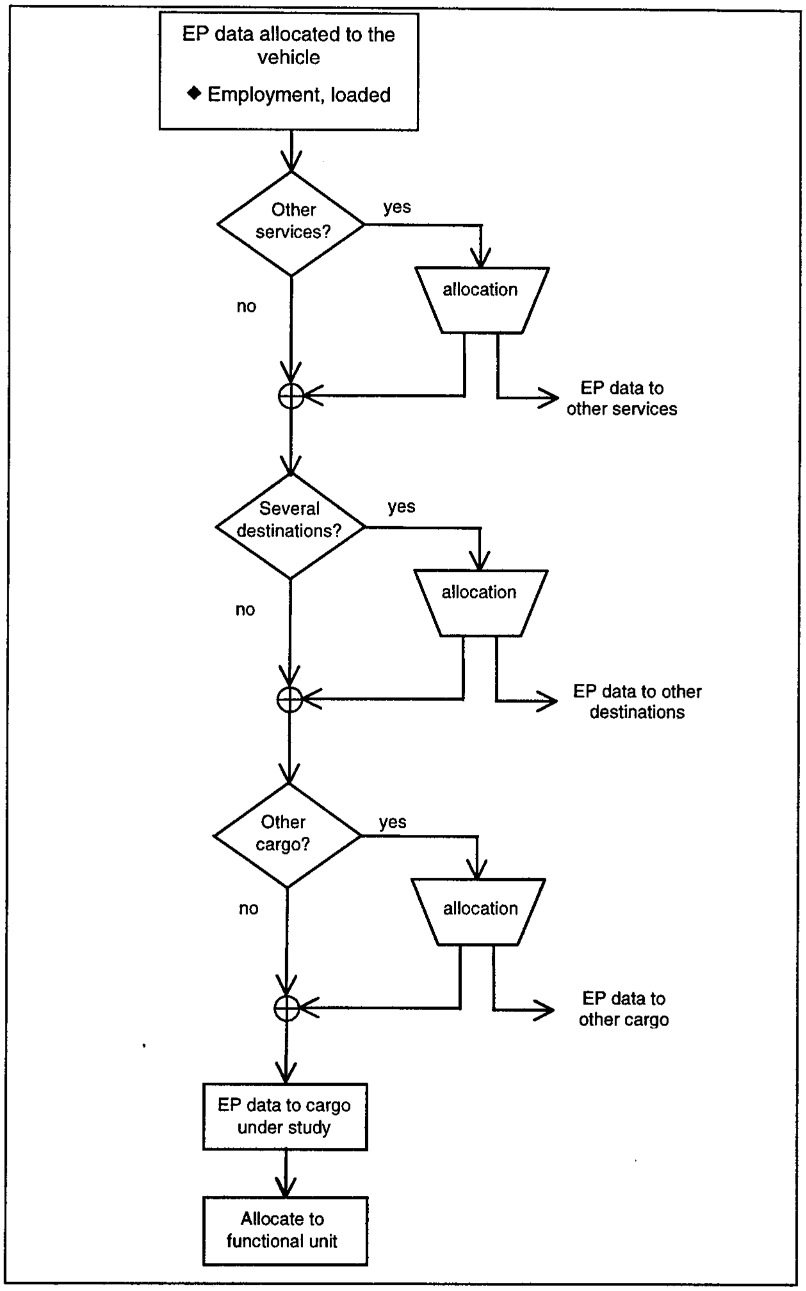
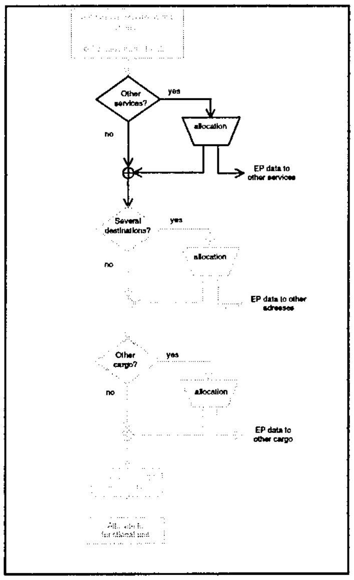


Figure 7 *Decision tree for allocation of vehicle-related EP data to cargo transportation.*

The three questions to address are

- how to separate the share of EP data related to the passenger- and cargo services respectively,
- how to allocate the cargo-related EP data in distribution traffic, and
- how to allocate the cargo-related EP data to the specific cargo under investigation.

5.4.1 Allocation between cargo transport and other services



This situation arises when studying a shipment transported in a system designated for cargo transport combined with other activities, e.g. RoRo passenger ferries, regular passenger flights, scheduled long distance bus traffic and passenger trains with goods wagon. The different nature of passengers and cargo, and related demands put upon the vehicle speed, safety, interior environment, service and supply, departure times etc. makes allocation an intriguing task.

The dominant transport mode, in terms of transportation work, where this occurs is the Ro-Pax ferry traffic between Sweden and Denmark, Germany, and Finland.

The RoRo ferry allocation problem has previously been treated in Flodström *et al.* (1994) where an exposé of methods are presented together with a suggested combination method using both the physical (volume) and the substitution method.

The presented allocation methods are based on physical relations (area, volume, weight and energy utilisation), theoretical substitutions to designated vessels, economic relations or combinations of these, see Table 12.

Table 12 *Suggested methods for allocation between cargo and other services.*

Denotation	*Description*
Equal- or "50/50"-method	All services share the burden equally
Estimated share	Any defendable estimation
Marginal method	The services are ranked. Main service bears the same amount of EP data as if transported by a designated vehicle. The remainder is allocated to the secondary service. Multiple services are treated accordingly in the ranking order.
Physical method	Allocation in proportion to a physical dimension used to assess the utilisation: volume, weight, area, length etc.
Cargo handling units	Container (TEU), semi-trailer, personal car equivalent, swap body, cassette, pallet place, wheeled container, etc.
Density method	The volume is combined with a "density" of the different services into a weight measure.
Unity method	Assigning each passenger a 'cargo equivalent' weight of 1000 kg and allocate according to weight.
Energy method	The total energy utilisation is reduced by the specific energy use for separate services (Climate control etc.). The difference is allocated in accordance with the energy use, caused by the different services.
Substitution method	Allocation proportionally to the performance of a designated vehicle related to the sum of all such designated vehicles that would substitute the combined transport.
Economic method	Allocation according to the price, revenue, profits, cost per service, value of cargo or other factors

In order to demonstrate the effect of different approaches, selected methods are applied to the ferries in traffic between Germany/Denmark and Sweden. The connections to the case study in chapter 4 are found when the bananas, landed in Antwerp, are transported to Sweden. This transport is done with a refrigerated semi-trailer pulled by a tractor, which makes the crossing to Sweden, by such ferries. An investigation of the allocation-induced variations in the end result on an LCI is presented in section 5.5.

The carrier usually presents information of the environmental performance of the ferry in relation to what the customer brings aboard the ship. EP data values given in the unit per tonne x kilometre and lane meter therefore relates to the whole vehicle. The EP data for the vehicle is then allocated to the cargo, see Figure 9.

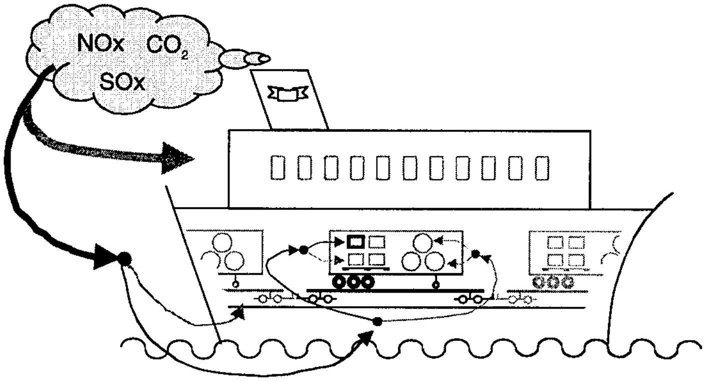


Figure 9. *Allocation between passengers and vehicles, between vehicles, between consignments and to a functional unit.*

Any level of aggregation of cargo handling equipment could be possible, i.e. actual cargo, per box, pallet, or trailer. The definition of the functional unit is of great importance and determines what is to be considered as cargo. This is important to state when aggregated units such as tonnexkilometre is presented.

In the banana case, the 4 000 kg semi-trailer carries 20 pallets, each loaded with 48 boxes, equal to 17 400 kg bananas, 1440 kg packaging material, 600 kg pallets, pulled by a tractor of 6 000 kg. Thus, the bananas amount to 65% of the 30 000 kg heavy vehicle entering the ferry. Since the functional unit in the present calculation is 1 kg of bananas, the EP data allocated to the vehicle will be divided by 17 400. In this way, no EP data is allocated to the packaging, cargo handling equipment or the vehicle.

Allocations for ferries between Sweden and Germany and Denmark

Nine different calculation methodologies were applied to five ferries in order to investigate the effect upon the size of allocated EP data due to different allocation procedures. The ferries were chosen by the following criteria: in traffic today, different configuration regarding number of passengers/number of trailers, speed, distance of route and availability of data. Data was obtained by public information available on the internet (see Ferries, 1999), by blueprints of the vessels (general arrangement plans) and by interviews with ship management departments at the companies.

A new fast ferry introduced in the Mediterranean was included for comparison with the higher EP data from increased machinery[46].

The calculations of EP data from ferries in this example result in a percentage of the EP data from the ferry operation to be allocated to the trailer + tractor (30 tonnes and 17 meters length).

---

[46] Superfast, MCR: 41 470 kW at 28 knots. DWT: 5600.

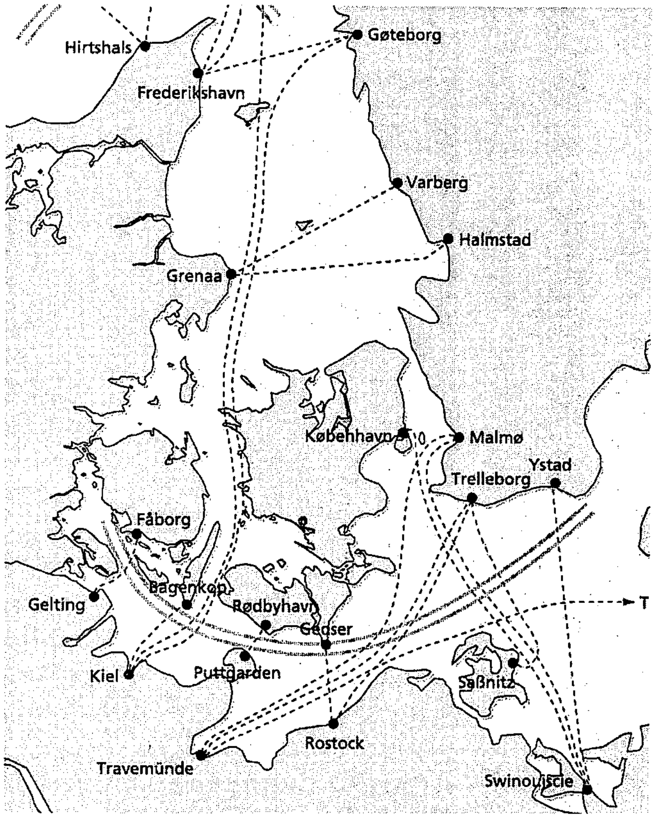


Figure 10. *Ferry routes between Sweden – Denmark/Germany. Helsingborg – Helsingör not marked (from Scandinavian Link 1999).*

The ferry routes investigated are presented in Table 13.

Table 13 *Investigated ferry routes. Vessel data and description.*

Route Crossing time	Vessel Company	LOA [m]	Beam [m]	Speed [kn.]	Pass. max	RoRo capacity [lm], max	Comment
Trelleborg – Travemünde 6 h.	M/S Robin Hood TT-Line	179	27	19.5	317	2400	Ferry with substantial lane meter capacity
Helsingborg – Helsingør 15 min.	M/S Aurora af Helsingborg Scandlines	111	28	15	1250	1700	Shuttle ferry, rail capacity, platform deck for extra automobile capacity.
Göteborg – Fredrikshavn 3 h. 15 min.	Stena Jutlantica Stena AB Group	184	28	21.5	1500	2100	Ferry with large lane meter capacity and reduced passenger service, rail capacity.
Göteborg - Fredrikshavn 3 h. 15 min.	Stena Danica Stena AB Group	155	29	19.5	2300	1806	Ferry with substantial passenger service. Platform deck for extra automobile capacity
Göteborg - Kiel 14 h.	Stena Danica Stena AB Group	175	31	20	2400	1630	Ferry with substantial passenger service.
Greece – Italy	Superfast III	194	25	28.5	1400	2700	Fast ferry with substantial car capacity

Table 13 does not include all the information used in the calculations. Extensive information regarding sizes of vehicle decks, passenger areas, cargo capacity and designated RoRo and passenger vessels of similar capacity were assembled and processed within the calculation tool. The underlying graphic material is too extensive to fit within the report.

The applicability of the following methods were investigated:

Table 14 *Investigated methods; description and variants.*

Method	Description	Variants	
50/50	1. 50% to passenger 50% to all vehicles.	a. trailer optimised b. car optimised	- available capacity - utilised capacity
	2. 50% to passengers incl. cars 50% to heavy vehicles.		
Substitution	3. EP data split in relation to EP data for designated vessels for passengers and trailers respectively		
Physical Methods	4. 1 passenger = 1 tonne		
	5. Volume	per m^3	
	6. Area	per m2	
	7. 'B_T -Method', for heavy vehicles, equivalent volume of a RoRo vessel with the same capacity.		
Marginal method	8. Trailer transport is considered as main activity and carries EP data equivalent to designated RoRo ship with the same characteristics.		
Economic methods	9. Revenue and profit	a. with duty-free b. no duty-free	

1. Allocation between passenger and vehicles

50/50

The 50/50 method was used in two ways. The half of the EPD allocated to the vehicles is in the first variant divided between all vehicles, lorries, cars and buses. This is done by utilised volume, (see equation 1 below). In the second version half of the EP data is allocated to the lorries, and the other half to the passenger and their vehicles together. The latter method will therefore allocate a larger share to the lorries.

Substitution

This method is based on the argument that cargo traffic would prefer an designated RoRo vessel, and should therefore be burdened with the EP data for such a vessel. The remaining EP- data should be allocated to the passengers.

Objections could be raised against this argument. A RoRo vessel would probably cruise at a lower speed (= lower fuel consumption), with different fuel quality (Swedish ferries usually operate on less 'dirty' fuels[47]), different sailing frequency and offer lower service degree for the drivers. The Ro-Pax ferry could thus still be an attractive choice for a lorry operator.

Physical Methods

Two variants were used.

1. 1 passenger = 1 tonne: The advantage of this method is its simplicity. Data regarding number of passengers are easily available. The method could be developed in to present different 'passenger densities' for different ferries (day or night, long distance or short route etc.)

2. Volume and Area: The utilised volume/area for different services could be measured from general arrangement (GA) plans. This is a somewhat tedious work if the ship builder does not make the data available.

   The volumes and areas for passengers and cars were, after measurements in GA plans, calculated for the vessels in this investigation. Areas reserved for lorry drivers were separated from general passenger areas.

---

[47] E.g., lower sulphur level and less heavy hydrocarbon compounds compared to average ferry operations in the world.

'B_T -Method'

The 'B_T method' is presented in Flodström *et al.* (1994) and the reader is referred to this publication for a more extensive presentation. The method aims at combining the substitution and volume methods. The method finds a way to handle the fact that volume data for passenger and vehicle spaces usually is not available. A description factor, B_T, based on available data, the gross tonnage - GT (=total volume of the ship) and the dead weight - DWT (=the approximated cargo capacity) was suggested. The B_T factor is stated as the relation GT/DWT. The idea behind the B_T factor is its proportionality to the relation between the displacement and the cargo volume. It was then observed that RoRo and Ro-Pax vessels showed comparable size of the B_T. Thus, the cargo volume of the Ro-Pax vessel is obtained by dividing its DWT by the B_T factor. The description factor has been calculated for a large number (34) of vessels and an average number of 0.67 have been suggested for typical Ro-Ro vessels (Flodström, 1999). The cargo volume is then divided by the total volume (GT) of the ship in order to obtain the share of the EP data to divide among the vehicles (see page 103).

Marginal method

The marginal method ranks the different services in order of importance. This can be done in several ways, by revenue, by volume or other factors. The EP data for a dedicated vessel performing the main service is used for the main service. The difference between this and the EP data for the combination vessel is divided among the remaining services in the same manner. The method introduces difficulties both in ranking the services and when selecting the comparable ships. Both steps includes explicit valuation.

In the calculations the transport of lorries was selected as the main service and RoRo ships with performance equivalent to the RoPax ferries were identified. The EP data for a trailer onboard the RoRo vessel was then divided by the total EP data for the Ro-Pax vessel.

Economic methods

The allocation example based upon economic methods was calculated with the following assumed data. An attempt to obtain real data failed due to the unwillingness to disclose company sensitive data[48].

Assumed relative revenue from	*Without tax free*	*With tax free*
Passengers:	40%	33%
Tax-Free sales	0%	33%
Cargo, lorries and trailers	60%	33%

Calculations could of course be based upon other economic parameters (profit, percentage allowance to cover fixed costs, ability to bear cost, marginal cost etc.).

2. Allocation between cars and lorries

The methods above yielded the share of the EP data assigned to the vehicle, or RoRo deck of the vessel. The allocation lorries and passenger vehicles (buses and cars - with or without trailers) then remains to be carried out. Normal overhead clearance on a RoRo deck is around 4,5 meters (lorry lanes). Some ferries, however, have special car lanes with limited overhead clearance, <2.5 m, while others are equipped with hoistable platforms over some lorry lanes. These can be lowered in order to provide increased car capacity during vacation periods. Due to these differences in configuration will the allocation of the EP data to separate vehicles will differ between the ships. Two alternatives are possible for the vessel where the RoRo deck has 4.5 meter clearance over all the lanes. Allocations could be made by all the utilised lane

---

[48] Empirical data was collected during the spring of 1999, a few months before the limitation of the duty free sales system. The uncertain situation during the transition period might have influenced the companies.

meters. However, when recognising that passenger cars demand lanes of smaller width (2.4 m) than lorries (3.1 m) allocations could be done in accordance with area instead of lane meter.

Allocations by lane meters for vessels with hoistable car decks, without recognising the limited use of car lanes, will yield lower values for the lorries. An allocation method encompassing the higher clearance demand of the lorries is presented by equation 1. The first term makes the lorry lane, due to its double overhead clearance[49], bear twice as much EP data as the car lane when the compensating factor *k* is set to 2.

Equation 1

$$\text{EP data for one lorry} = \frac{k \times \mathrm{lm}_{\mathrm{lorry}}}{\left(k \times \mathrm{lm}_{\mathrm{lorry}} + \mathrm{lm}_{\mathrm{car}}\right)} \times \frac{\text{length of lorry}}{\mathrm{lm}_{\mathrm{lorry}}}$$

where

$\mathrm{lm}_{\mathrm{lorry}}$ = total lane meter for lorries, $\mathrm{lm}_{\mathrm{car}}$= total lane meter for cars and *k* the area/volume compensating factor.

The factor k is the factor yielding the relation between the different demands of physical space. The factor could be set as the relation between the height or width of the lanes, or the combination, i.e., the cross section area. With typical dimensions, the *k* factor would be $\frac{4.5 \times 3.1}{2.2 \times 2.4} = 2.6$.

The calculations for the selected ferries required detailed information related to the vessel and its operation. The availability of configuration data was good for all ferries. Results from allocation according to these 9 different methods are presented in Table 15.

---

[49] As compared to cars.

Table 15 *Allocation of EP data from a Ro-Pax ferry to one semi-trailer. (percentage of the total EP data to be allocated to a semi-trailer of 17 meter and 28 000 kg.)*

	Robin Hood	Stena Danica	Stena Jutlandica	Aurora	Superfast	Stena Scandinavica
50/50 Pass/vehicl.						
winter; avail	0.35%	0.33%	0.36%	1.51%	0.32%	0.36%
utilised	*0.53%*	*0.45%*	*0.48%*	*2.01%*	*0.42%*	*0.48%*
summer; avail	0.35%	0.31%	0.33%	1.37%	0.28%	0.38%
utilised	*0.53%*	*0.41%*	*0.43%*	*4.53%*	*0.36%*	*0.48%*
50/50 Pass+cars/heavy V.						
winter avail	0.35%	0.33%	0.36%	1.59%	0.32%	0.36%
utilised	*0.53%*	*0.45%*	*0.48%*	*2.12%*	*0.42%*	*0.48%*
summer; avail	0.35%	0.44%	0.48%	3.40%	0.63%	1.17%
utilised	*0.53%*	*0.59%*	*0.64%*	*4.53%*	*0.85%*	*1.56%*
Substitution						
by same service	0.69%	0.38%	0.39%	1.07%	0.38%	0.34%
by likely service	0.39%	0.20%	0.37%	4.24%	0.19%	0.31%
Physical Methods:						
1 pass.=1 tonne avail	0.65%	0.42%	0.50%	1.23%	0.47%	0.43%
utilised	*0.96%*	*0.54%*	*0.66%*	*3.25%*	*0.61%*	*0.55%*
volume winter/trailer	0.61%	0.39%	0.65%	1.94%	0.47%	0.30%
summer/car	1.06%	0.43%	0.67%	1.60%	0.47%	0.30%
area winter/trailer	1.06%	0.28%	0.52%	1.32%	0.37%	0.18%
Summer/car	1.06%	0.26%	0.33%	0.50%	0.20%	0.11%
BT-Method	0.26%	0.10%	0.24%	1.00%	0.18%	0.11%
Marginal method	1.20%	0.66%	0.70%	0.82%	0.68%	0.52%
Economic methods						
Revenue -Tax free	0.35%	0.30%	0.32%	1.41%	0.28%	0.32%
Revenue -no Tax free	0.64%	0.54%	0.57%	2.54%	0.51%	0.58%
Largest share	**1.20%**	**0.66%**	**0.70%**	**4.53%**	**0.85%**	**1.56%**
Smallest share	**0.26%**	**0.10%**	**0.24%**	**0.50%**	**0.18%**	**0.11%**
Approx. CO2 emission from the ferry [kg/km]	200	370	350	250	450	470

The results from these calculations indicate a difference of a factor 3 - 9 between the largest and the smallest share allocated to one trailer. The B_T method shows the smallest share for all but the smallest vessel. Different methods yield the highest score, reflecting the different nature of the vessels. The relatively high *substitution* values for the Aurora is due to the difficulties to find data for a RoRo ship providing the same service.

It is futile to point out one method as being better than any other. The point made here is that the choice of method has the potential to introduce large variations to the results of an LCI. Examples of this effect is illustrated by a calculation example presented below, as well as in section 5.5. Since all the methods above could pass the criteria set up by the ISO standard, the LCI practitioner will have to make a motivated choice.

A few comments

The amounts of work demanded by the different methods were not logged. In general, the provision of the kind of data presented in Table 15 would be a substantial service to customers and LCI practitioners. Most of the methods present the analyst with some kind of difficulties. Defining a proper substitution vessel with a performance equal to the ferry proved to be a complex task, as well as decisive for the result. It is hard to account for all the dimensions describing a ferry transport service, sailing frequency, speed/crossing time, size of vessel, fuel quality, price, loading time, passenger service, harbour position etc. The transport of a trailer on a Ro-Pax ferry is a service of different nature as compared to a normal RoRo ship. Selecting a ship likely to substitute the ferry, with maintained service level for the lorry, is a complicated task subjected to value choices. Methods based on substitutions trying to assess these nature of the service are therefore likely to show an analyst dependent uncertainty.

Other aspects of the methods are the ability to reflect changes in the volumes of the different services. Should the method be sensitive for all variations in e.g. passenger utilisation, or should only a larger alteration[50] influence the result? Should the actual or the designed use of the vessel be decisive? Should the result reflect changes in the economic dimension without any physical change taking place (cf. possible changes in price structure due to the rail/road connection across Öresund)? The recent change of the tax-free system will change both the fleet composition and the utilisation pattern towards more cargo service. This is reflected by the removal of hoistable car decks (Stena Danica), introduction of vessels with larger lane meter capacity (Stena Jutlantica, Robin Hood) as well as high speed passenger ships (Stena Carisma). This separation of passengers and cars to faster vessels (cf. HSS 900/1500) and trailers to more RoRo-like vessels will reduce the need for allocations, thus decreasing the uncertainties introduced. The RoRo deck-related EP data was allocated between the vehicles in proportion to their occupied deck area or volume. This choice can be motivated by the fact that all vehicles are rather similar by nature.

The calculations are based upon an assumed degree of utilisation of 75% (Magnusson, 1996), and did not allocate any EP data to the unused capacity. This choice seems logical, but is not the only feasible one. A sailing frequency or departure time making it hard to fill up the vessel could cause the unused capacity. If the departure is due to, e.g., demands of the passengers, EP data carried by unused lane capacity could be allocated to the passengers. One could also argue that a planned surplus capacity as a strategic resource for future expansions should not burden present customers[51]. EP data related to

---

[50] A change such as the expected decrease in travel due to ending the duty-free system.

[51] This is a common situation in larger transportation systems. Consider Tor Selandia, a new Ro-Ro vessel on the trade between Sweden and England, which from its start of operations introduces an over capacity of some 30%. The utilisation of each vessel is decreased until the foreseen increase of cargo volumes is realised.

such over-capacity could be allocated to future operation/service or duty cycles, or to the vehicle operator herself.

Again, the answer to the questions presented above is to be found in the definition of the research question. The method-dependent variations in Table 15 will be of different importance to the end result depending upon the size of the allocated EP data from the ferry in relation to the EP data for the whole transport chain. In the case of trailer transport between Antwerp and Helsingborg, these variations induce a difference of 130 kg (730 - 860 kg) of CO_2 for the Puttgarden - Helsingör route and 550 kg (700 - 1250 kg) for the Trelleborg route. Whether or not this is critical for the assessment is dependent upon the transportation chain. A lorry transport between Helsingborg and Lisbon will of course not be affected as much as the one to Hamburg. The effect of this upon the assessment of the banana transport chain is presented in section 5.5.

Cargo in passenger planes

A second illustrative example is that of air cargo. Although most air cargo is transported in designated freight aeroplanes, free capacity (volume and weight capacity) in passenger liners is used for cargo transports. The amount of goods accompanying a regular domestic flight in Sweden is however very small, <100 kg/flight (Larson *et al.* 1996). An international flight from Sweden carries around 1000 kg of cargo (Acharjee, 1999). The EP data from an aeroplane can be divided into two parts, a) the EP data for flying the plane empty and b) extra EP data due to the extra weight of payload (passengers, cargo) and the extra fuel. Thus, a passenger plane will increase its EP data. in direct relation to the extra weight of the goods, see Figure 11.

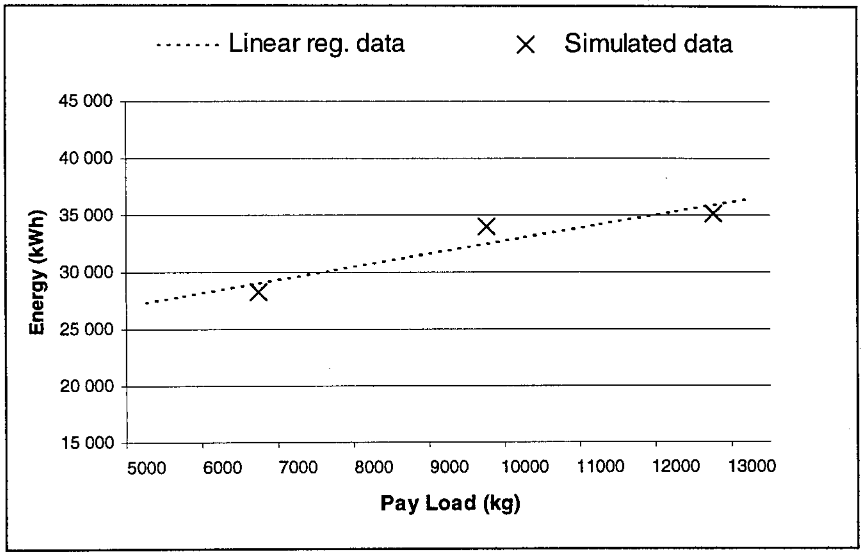


Figure 11 *Energy as a function of payload for a MD82 aircraft. Calculated values (with data from Larson et al., 1996 and NTM, 1999).*

The allocation of EP data to the goods can therefore be carried out in several ways:

1 Marginal method

When the airline is operated regardless of cargo availability, e.g. scheduled passenger traffic, only the extra weight dependent EP data is allocated to the goods. The cargo will then only carry the EP data related to carrying the goods and the extra fuel needed for the flight. The argument is based on the fact that passenger transport is the main activity and carries the EP data for the vessel itself.

2 By weight

The total EP data from the plane is allocated to both passengers and goods by weight. The argument for this method could be that the EP data for 'the plane itself' should be divided among the utilised weight capacity, regardless if it is cargo-or passenger-related. One can then further define chairs, restrooms, life saving equipment, provisions etc. as related to passengers and allocate EP data to this weight as well.

3 By weight and volume

Recognising that the EP data is produced both by overcoming air resistance and gravity forces, it is possible to allocate by both weight and volume. The EP data for operating the empty plane (below: $\text{epd}_{\text{empty}}$), caused by overcoming air resistance and carrying its own weight, is then in this method allocated to the payload by utilised volume. The EP data increase due to weight of payload, and related extra fuel (below: $\text{epd}_{\text{pay load}}$), of a plane with provisions, passengers and cargo could then be allocated to the weight capacity utilised by the different services. One has to consider the weight of installations related the to passenger service and cargo service separately. EP data related to the weight of chairs, catering, merchandise and restrooms should be added to the weight of passengers and their luggage.

Equation 2

$$\text{EP data}_{\text{cargo}} = \text{EP data}^{\text{plane}}_{\text{empty}} \times \frac{\text{volume}_{\text{cargo}}}{\text{utilised volume}_{\text{total}}} + \text{EP data}^{\text{plane}}_{\text{load}} \times \frac{\text{weight}_{\text{cargo}}}{\text{weight}_{\text{total}}}$$

4 Substitution, economic

One could also engage in various substitution calculations by identifying typical cargo planes operating on the same route. When doing so, one should be sure to compare data for the same flight distances and likely capacity; two parameters important for the calculations. Air cargo is an example of a transport mode where the physical relation between cargo weight and EP data is well articulated. The need for economic allocation methods should therefore be reduced. On the other hand, the cost structure for air cargo could be more advantageous if the fuel-related cost is relatively high (not supported in this analysis). This will most likely be the case when the energy- and CO_2 tax has been imposed on aeroplane fuel.

A calculation example for a transport of 100 banana boxes yields the following result;

Table 16 *Allocation-induced differences in energy demand for bananas transported as air cargo.*

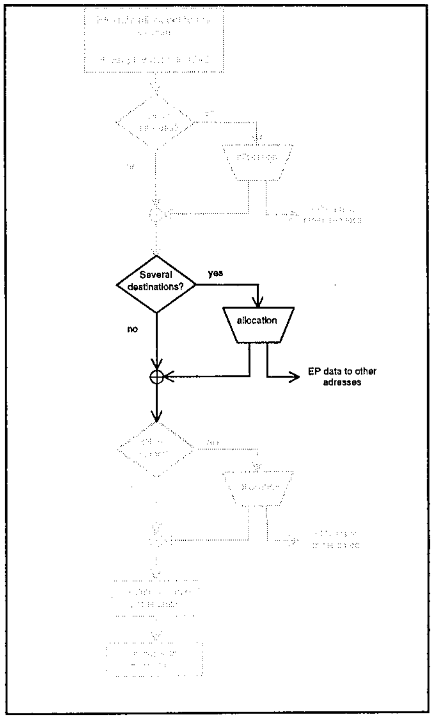
Allocation method	unit		kWh emitted for 100 boxes [kg]	kWh per kg/bananas
1) marginal	1.1	[kWh/kg]	2 245	**1.2**
2) weight	3.6	[kWh/kg]	7 070	**3.9**
2) volume	267	[kWh/m3]	1 326	**0.7**
3) equation 1	170	[kWh/m3]	3 089	**1.7**
	1.1	[kWh/kg]		
Cargo	100 banana boxes			
Weight	1964 [kg]			
Volume	5.0 [m3]			
Data for MD 82, 600 km with 9450 kg Pay-Load, tot. 34 000 kWh(fuel)				

Again, we find large differences in the result due to the method applied to the allocation. The volume method allocates a relatively small share to the cargo when assuming a 60% degree of utilisation of available volume. Since bananas are a cargo type with relatively high density (400 kg/m^3), we see in method 3 an influence of the volume-related part in equation 1. This is reflected by the difference in result between method 1 and 3.

It should be noted that the data above is only valid for the specific flight trajectory/envelope. The start and climb phase of a flight uses a substantial amount of the total energy. Especially, in case a plane makes an extra stop, it could be argued that the extra EP data is to be allocated to the service (-s) demanding the extra stop.

Two cases of allocation between passenger and cargo service is left unattended; firstly cargo with long distance buses and secondly cargo in high-speed cargo wagons operated in normal passenger train routes. Besides these, the case when passengers travel with a cargo vessel remains to be discussed. This work will now proceed with the next level of allocation, between different addresses served by one vehicle/vessel.

5.4.2 Allocation between consignments with different destinations.



When the EP data allocated to the cargo transport service has been established, allocation between consignments with different destinations/(origins) has to be sorted out.

Several destinations

The case of allocation to cargo shipments with different origins/destinations is illustrated by the distribution of bananas from the wholesaler to shops and larger customers. The simpler methods do not regard the distance parameter The EP data for the whole operating. cycle is divided between the cargo in relation to some physical dimension, or first by the number of stops, and then by physical dimension. The advantage is that the demand for information is reduced. When the distances and volumes are known, EP data can be divided between any physical dimensions in conjunction with the distance parameter. This allocation can result in 'unfair' results due to dependencies of the order in which the deliveries are carried out. Consider the simple example in Figure 12.

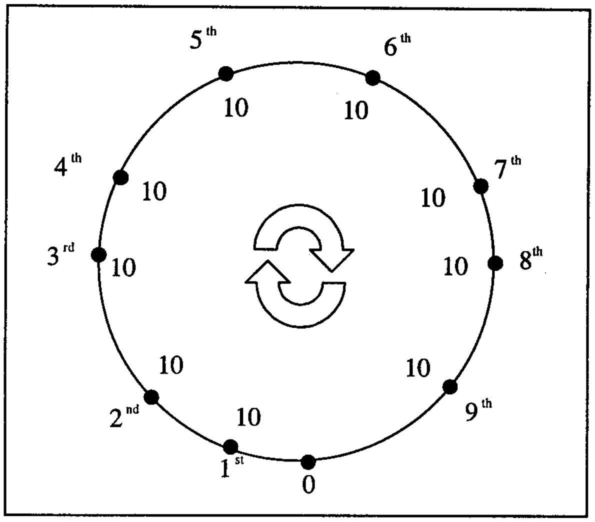


Figure 12 *A schematic distribution route with 9 stops, each receiving 10 units.*

The distribution route starts at position 0 with a load of 90 units. The route has 9 stops delivering 10 units at each stop and the vehicle returns to 0 after stop 9. Allocation with a method based on the distance will yield different results depending upon the direction of the route, see Table . The idea behind the distribution route is to lower the cost for each delivery as compared to making separate trips to each address. EP data from those trips will be lower for the closer addresses due to decreased distance. An allocation method accounting for this situation could be constructed as follows: The share of the EP data for the distribution route is calculated by dividing the EP data for an exclusive delivery at that address divided by the sum of all EP data from all such exclusive deliveries.

This method will not show any dependence upon direction, and could be further developed by accounting for the different EP data from optimal vehicle sizes for each delivery. Another option is to treat the cold-start related EP data separately from the EP data while in traffic. The cold start EP data could be divided equally between the stops, while the rest is divided according to the procedure above. The allocation equation would look like:

Equation 3

$$\text{EP data}\,[\text{stop i})] =$$

$$\frac{\text{Cold start emissions}}{\text{Number of stops}} + \left[\frac{\text{EP data for an exclusive trip to stop i)}}{\sum \text{EP data for exclusive trips to all stops}} \times \text{EP data for distribution trip} \right]$$

The advantage of this approach is demonstrated by an application to the distribution route presented above.

Table 17 *Different allocation strategies for distribution traffic.*

Stop nr.	**Unit size cargo, unit distance**				**Random size cargo and distance**							
	Allocation according to trp work		Min trp work allocation, unit size cargo, unit distance		Allocation according to trp work				Min trp work allocation, random size cargo, random distance			
	1 example				1 example		Average of 27 calculations		1 example		Average of 27 random samples	
	Clockwise	Anti-Clockwise	Clockwise	Anti-Clockwise	Clockwise	Anti-Clockwise	Clockwise	Anti-Clockwise	Clockwise	Anti-Clockwise	Clockwise	Anti-Clockwise
1	2%	18%	3%	3%	0%	14%	2%	17%	1%	2%	3%	4%
2	4%	16%	7%	7%	4%	16%	3%	15%	5%	7%	7%	6%
3	5%	15%	10%	10%	6%	11%	6%	16%	8%	7%	12%	12%
4	7%	13%	13%	13%	20%	27%	6%	13%	28%	30%	13%	12%
5	9%	11%	17%	17%	12%	10%	7%	10%	18%	15%	18%	18%
6	11%	9%	17%	17%	6%	3%	11%	10%	8%	6%	17%	18%
7	13%	7%	13%	13%	14%	7%	13%	8%	12%	13%	13%	13%
8	15%	5%	10%	10%	34%	10%	15%	6%	20%	18%	8%	7%
9	16%	4%	7%	7%	3%	1%	18%	4%	1%	1%	7%	6%
10	18%	2%	3%	3%	1%	0%	19%	2%	0%	0%	3%	3%

The method is calculated with both fixed and varied (random within a selected window) values for the distance and delivered weight. Statistics for a sample large enough to yield stable values are shown for the calculations with varying data. The tables show how the suggested method yields a distance-dependent but direction-independent allocation related to the weight of the delivered goods. The method is here based on the transport work defined as kg×distance. It could also be based on volume or area where these dimensions are more suitable.

Applied to the case of the bananas transported to Sweden, a distribution route to shops in Småland has been studied. The distances are actual while the delivered amounts of cargo is an example from a similar distribution in Halland (Månsson, 1999). The bananas are shipped from a wholesaler in Växjö, together with other provisions. The studied route has 9 stops at a total driving distance of 297 km, delivering a total of 7510 kg (32 m^3), of which 562,3 kg bananas (1,6 m^3). The amount of goods delivered and the distances between the stops vary, why a value for the largest and smallest share of EP data is calculated (se Table 18). These values are specific for the route, but serves as an illustration of the importance of the choice of allocation method. The constructed distribution route is shown in Table 18 below.

Table 18 *Distribution route to grocery stores in Småland.*

	Distance		Direct distance	Delivered amount of bananas	
	(km)	(km tot.)	(km)	(boxes)	(kg)
0 *Terminal*				*31*	*609*
1 Högsby	94	94	94	13	255
2 Berga	7	102	102	2	39
3 Oskarshamn	30	131	131	0	0
4 Mönsterås	26	158	133	4	79
5 Rockneby	29	187	125	0	0
6 Kalmar	16	202	111	6	118
7 Nybro	**29**	**231**	**85**	2	39
8 Broakulla	27	258	56	1	20
9 Lessebo	21	279	35	3	59
10 Terminal	**35**	314			
Total:	*314*		*1746*	*31*	*609*

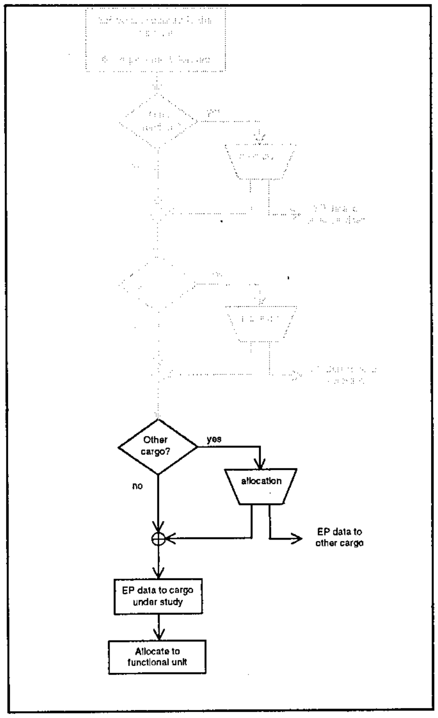
With the above the following allocation shares were calculated:

Table 19 *Allocation to the bananas delivered in Nybro calculated by different methods, % per tonne banana - of total EP data for the route.*

Disregarding distance		**For stop #7**
1 All cargo share evenly by weight		14%
2 All cargo share evenly by vol.		8.6%
3 all stops share evenly,		
then by weight		82%
then by volume		40%
Regarding distance		
4 by transport work,	weight	19%
	volume	14%
5 by min transport work	weight	11%
	volume	7.8%

Method 5a/b is calculated with allocation in relation to minimal distance to the address. Compared with method 4a/b, method 5 shows lower values due to the elimination of the direction related difference. These methods could also be further developed in order to be applicable to transport systems where cargo is delivered and picked up simultaneously.

5.4.3 Allocation between consignments to the same destination.



When the EP data allocated to the cargo transport service to a specific address has been established, allocation between cargo consignments of different nature remains to be sorted out.

Cargo, cargo handling equipment and packaging materials

Cargo handling equipment used for the transport should be included when the allocation takes place. The LCI method allocates the EP data to the functional unit, e.g., a kg of banana. If this allocation was to be made by weight, the bananas contained in the box, will have a share of 19.6/18.1 [kg/kg].

One can note that the inclusion of handling equipment contributes to an increase of the transport work. E.g., if one were to switch to a heavier type of container there would be a positive increase in transportation work, although the same amount of cargo would be relocated. The increased weight is likely to increase the energy use and emissions from the transport system. However, the change of cargo handling equipment might allow the selection of a more environmentally adapted transport system (cf. Containers on feeder ships or in an intermodal transport system).

Appropriate definitions of what is cargo can probably be found in the contract between the transport provider and the cargo owner. Any extra equipment utilised by the transport chain operator in order to handle the specific cargo is defined as handling equipment. For the LCI practitioner, one has to 'peel off' such extra allocations until the data in the end relates only to the functional unit.

Consider an example from the case study: Ferry emissions were allocated to (1) passengers and the rolling equipment. The emissions to rolling equipment are further allocated to e.g. (2) utilised lane meter. This part of the emissions is allocated to the goods on the lorry according to, e.g., (3) pallet positions and then further to the units carried on the pallet, e.g., (4) per box. The emissions thus carried by the box are subdivided down to (5) the units contained therein. Thus, depending upon the functional unit, one has to carry out the allocation in several stages (see Figure 9)

If the ferry operator would use some equipment, not used by another ferry, in order to move or secure the lorry and thus increase the share of the utilised lane meters, this will increase the burden upon the lorry without the customers control. This is no problem in an LCI but an important concern for transport operators when compering the environmental performance of their operations. The same definition of cargo must be applied when EP data is presented in aggregated units such as tonne × km.

Different cargo types

The first issue is encountered in shipment with a vessel/vehicle/system designated for simultaneous transport of different types of goods (e.g. the combined ore-tanker, the cargo train, a long distance lorry in line operation or a cargo aeroplane). Again the allocation of the EP data for a specific transport activity could be done with different methodologies, e.g. by weight, by volume, by floor area/length, proportional to fee, by possible substitution vehicles etc. This allocation was integrated in the example of the Ro-Pax ferry above. In that example, some methods yielded an amount of EP data to allocate to all the vehicles. The EP data was then allocated in accordance with the volume occupied by the trailer.

A different approach is needed when EP data are to be allocated to more heterogeneous cargo. Cargo with substantially different density, handling systems (cranes/ramps etc.) or demands such as energy supply, atmosphere control, and cargo comfort can introduce difficulties when choosing allocation method. Yet a similar issue to assess are the demands made on the transportation system by dangerous goods.

Relevant questions to address when choosing method are:
Does the cargo occupy capacity

- planned to be filled in order to carry out the transport
- left unused if the cargo is not transported
- engaged due to increased demand of capacity?

As for the latter question, are there new vehicles put into operation on an expanding market, or does the cargo help sustain traffic on a shrinking market?

A further question is if the cargo transported in line-traffic or on a charter basis? In the case of a charter, the vehicle-specific values could be used. In the line-based traffic, however, it can sometimes be relevant to consider an average EP data value based on data from the whole system. Consider the ferry operations between Helsingborg and Helsingør. An operator with 2 different vessels could either supply the customer with data for the specific ferry used for a crossing, or an average of the two. One will then have to specify the time of integration, which could be a section of a day, a week, a season, a year or any other time relevant for the ferry system.

A further consideration influencing the calculation is that of new technology put into operation due to an overall increase in demand or specific environmental demands made by certain customers. In the case of the ferry, an important customer, with vehicles making crossings with both ferries, can influence the ferry operator to switch to cleaner fuel on one of the ferries. Now, should the customer credit his calculations with the EP data from the 'clean' ferry for all his crossings, with the new lower average of both ferries, or with the lower EP data only for the trips with that ferry? One can successfully argue for all the three methods why the relevant method has to be determined in relation to the research question.

A Similar question arises when the shippers' demand of transport capacity is answered with new capacity. An argument for using the average value/average EP data is that the shipper cannot assess if new traffic will be generated or not, and should therefore not be burdened with more EP data than other customers. Again, the assessment of which method to use is governed by the purpose of the study.

Returning to the original allocation problem, i.e., finding a ground for allocation between different goods types or shipments. One can base the method upon

- dimensions limiting the cargo capacity (area, volume, weight or combinations of these. See air cargo above).
- the dimension causing the EP data, weight, air resistance etc. Specific EP data for cargo-related energy use (climate control, power connection etc.) is reduced from the common EP data.
- cargo-related priorities in choice of route, departure frequency, speed and subsequent EP data and degree of utilisation.
- availability of data
- in relation to EP data for transport with a designated vehicle able to carry out the transport

Most calculations will use combinations of methods in several steps.

Table 20 *Examples of dimensions and units.*

Mass	**Spatial**	**Cargo handling**	**Economic**
Actual weight Chargeable weight Weight for assessment of freight charge	Meter Square meter Projected surface Cubic meter/feet Lane meter Register ton	Pallet Wheeled container TEU/FEU Trailer position	Price Revenue Profit

Allocation in transport system exclusive for the transport of the investigated cargo

Environmental performance calculation for transports of this last type is the least complex since all the environmental impacts caused by the transport relate to the transport of the same, or very similar, type of cargo. The allocation is straightforward in the case of only one type of cargo (banana vessel or ore train). The analyst divides the total EP data with the amount of cargo relocated in order to get the magnitude of the EP parameters related to the functional unit.

Some physical dimensions such as weight, volume or TEU positions will, in most cases successfully allocate the transport of physically similar, but not identical, types of cargo (e.g. crude oil of different density or containers of different length and density). A dimension governing the amount of EP data could also be used. Consider a cargo train; the energy demand for starting the train is related to the weight of the train. Once in motion, energy is supplied in order to overcome aerodynamic- and rolling resistance together with energy used to overcome an uphill. An allocation method could therefore be based on wagon/cargo weight, per axle or in relation to the aerodynamic resistance[52]. If the details of the energy utilisation of the system is not known,

---

[52] The aerodynamic resistance is situation specific, depending upon the composition of the train and the position of the vehicle within the same.

allocation could be done in an approximated relation to a limiting factor (total train weight, total train length and weight per axle).

Remark

The discussion above has shown how the choice of method substantially governs the result of the study. The analyst is therefore faced with the task of a) choosing the method best fit to answer the research question at hand and b) to motivate why this is the case. Generating decision support and making an inventory of past events might demand different approaches. The effect of the allocation-induced differences will now be assessed for the case study presented in chapter 4.

5.5 Allocation-method-induced variations in the case of banana transport

Environmental performance calculations for the different stages in the banana transport chain were presented in chapter 4. The uncertainty in the results were recognised by calculating a high and a low value, based on variations in fuel consumption for the processes involved. The sensitivity due to allocation for the transport chain was assessed for bananas landed in Antwerp and transported to Helsingborg by lorry. The transport chain is the same as the one presented in chapter 4, with the exchange of the following stages for step nr. 5a/b:

5 Lorry transport
From: Belgium, Antwerp
To: Germany, Puttgarden, Ferry terminal

6 Lorry on RoPax- Ferry
From: Germany, Puttgarden, Ferry terminal
To: Denmark, Rödby, Ferry terminal

7a Lorry transport

From: Denmark, Rödby, Ferry terminal
  To: Denmark, Helsingör, Ferry terminal

8a Lorry on RoPax- Ferry
  From: Denmark, Helsingör
    To: Sweden, Helsingborg

Data for the empty vehicle going back was also calculated. This transport chain is subject of allocations in the four steps described below.

1. Transport by *lorry* from *Antwerp to Helsingborg*:
   The EP data for the two RoPax ferry crossings was allocated to the trailer choosing the largest and smallest percentage as presented in section 5.4.1.

	High	*Middle*	*Low*
Allocation method	50/50 passengers + cars /heavy vehicles	Volume, car optimised	Area car optimised
Share of EP data [%/trailer]	4.5%	1.6%	0.50%

The result in terms of difference in emission of CO_2 is shown below. The difference for the selected route was 18 % as compared to the lower value. The reason for this is the relatively limited distance travelled by ferry. If the same lorry was to choose the ferry between Travemünde and Trelleborg, differences in the order of 75 % between the allocation methods were demonstrated.

Table 21 *Allocation induced differences in CO_2 emissions for a lorry transport between Antwerp and Helsingborg using different ferry* routes *[kg CO_2 per trailer].*

Parameters	Unit	**Routes**											
		Antwerp-Puttgarden-Helsingör-Helsingborg						**Antwerp-Travemünde-Helsingborg**					
		Total		Road		Ferry		**Total**		Road		Ferry	
		High	**Low**	High	Low	High	Low	**High**	**Low**	High	Low	High	Low
CO_2	[kg/traile	**899**	**761**	880	749	19	12	**1313**	**752**	709	604	605	149
Difference (% of Low)		**138** (18%)						**561** (75%)					
Distance	[km]	895						721					
Crssing. time	[h]					1						6.5	

2. Transport by *lorry* from *importer to distribution central*:
   The EP data of the lorry was allocated to the different consignments by the physical allocation methods shown in Table 19.

	High	*Middle*	*Low*
Allocation method	Weight	Area	Volume
Share of EP data [%/kg bananas]	0.0101%	0.0097%	0.0091%

3. *Lorry distribution* from *distribution central to supermarket*:
   The EP data for the lorry was allocated to the delivered goods according to the methods presented in section 5.4.2.

	High	*Middle*	*Low*
Allocation method	All stops share evenly, then by weight	Minimum transportation work, [kg*km]	Minimum transportation work, [m3*km]
Share of EP data [%/kg bananas]	0.082%	0.011%	0.0078%

4. *Car* transport from *store to household*:
   The EP data for the car is allocated first between two errands, and then between the bananas and the other provisions

	High	*Middle*	*Low*
Allocation method	1 stop by volume	2 stops by volume	2 stops by weight
Share of EP data [%/kg bananas]	8.4%	4.2%	2.5%

These allocation keys were applied to the calculations for the bananas landed in Antwerp from a large reefer. All other steps in the transport chain were presented with only one value in order to investigate the allocation sensitivity. The resulting span between the higher and lower methods is presented in Table 22.

Table 22 ***Allocation method induced differences in EP data for the transport chain via Antwerp***

EP Parameter		**Costa Rica - Antwerp - Nybro**	**Costa Rica - Antwerp - Nybro**
Energy	**[MJ/kg bananas]**	Allocation, High (see ch. 5)	Allocation, Low (see ch. 5)
Fossil		15	9.9
Nuclear (thermal)		0.084	0.084
Renewable		0.035	0.035
Emissions	**[gram/kg bananas]**		
CO2	total	1086	719
	fossil	1086	719
NOx	total	20	17
	urban	0.17	0.04
NMHC	total	1.3	0.95
	urban	0.048	0.015
CH4	total	0.021	0.012
	urban	0.00000	0.00000
PM >2	total	0.00037	0.00037
	urban	0	0
PM >0.5	total	0.90	0.83
	urban	0.0090	0.0026
CO	total	0.90	0.44
	urban	0.29	0.09
SO2	total	14	13
	urban	0.015	0.005
Other parameters			
Time	[h]	549	549
	[days]	23	23

The large difference between some EP parameters, approx. +50-100% as compared to the lower value, confirms the assumption that allocation-induced differences can have large impact. In this calculation, the most inefficient transport steps, distribution and home transport by car, introduced the largest absolute variations. The ferry routes selected contributed less to the sum, and did therefore not govern the sensitivity. As indicated above, a longer ferry route would introduce larger variations.

Allocations related to the reefers

The sensitivity analysis did not assess the reefers. Since the reefer contributes with the majority of the EP data the differences induced by allocation method will be decisive for the end result.

A large reefer holds some 5000 tonnes of bananas in break bulk. The ship always leaves Latin America with 100% load factor and calls to different ports in Europe before returning empty. The EP data for the crossing is easily distributed to the bananas by a simple division. Some of the ships, however, carry containers on deck. These are today filled with bananas, indistinguishable from the others once unloaded from the ship. The calculations in the case study did not separate the bananas transported in the containers from those in the cargo rooms. EP data from the ship was divided by the total amount of bananas on the vessel. However, if the containers were to contain some other cargo, an allocation method would have to be constructed. This issue has not been treated in this work.

Another aspect of the reefer operation is the fact that the ship can (and often does) unload part of the load in two or more different harbours. The transport would then be subject to a distribution calculation as described in section 5.4.2. The same would apply if the reefer collects bananas in several ports in Latin America. The present work does not encompass these issues.

5.6 A few considerations

The methodology applied when carrying out an allocation calculation depends upon a number of situation-specific conditions. No single method is successful in solving all kinds of problems encountered when allocation is needed in LCI. The reason for this is the large number of combinations of cargo types, handling equipment, transportation vehicles, transportation systems, addresses and research questions.

This work points out the need to assess the impact of different methods before making a choice. In transportation LCA, allocations have to be made at different stages. The suggested model summarises the EP data related to the transport, and then allocates this to the different cargo consignments. The goal and scope definitions of the LCI will determine in what detail, with subsequent data demand, the calculation will be carried out in order to obtain an appropriate/acceptable quality of the answer. A trade-off has to be made between physical accuracy and data availability to process the calculation with finite resources.

The first parameter influencing the calculation methodology is the type and amount of cargo under study. The type will limit the number of transport systems that can be used in order to carry out the change of location while the amount will influence the choice of vehicle size and degree of integration with other transport chains. The functional unit will direct the analysis to the correct level of study, i.e. to what goods-carrying unit one should allocate – a railcar, a pallet in the railcar or a box on the pallet in the railcar, and so on.

It is also important to consider the size of the shipments and their distribution in time, when assessing the environmental performance of the transport. A study of the total flow of product X (during a time period) from a factory differs in this regard from the analysis of the transport of a batch of product X to a specific address. The former question demands a statistical knowledge about the transportation system during a time period, whereas the second question is answered by event specific information.

It is of equal importance that any conversion by re-calculation of transported weight, volume and distance, e.g. in order to show a larger transport work or obtain comparable dimensions for pricing, is clearly stated in order not to mislead the analyse. Such re-calculations are common in rate calculations in order to compensate for goods of extreme nature (such as low density, awkward dimensions etc.). These consideration are important when e.g. the result of an LCA is used as a base for (strategic) decisions regarding future systems or when the results of LCAs are used for compilation of statistical data for a branch of trade, nation or region.

6 SUMMARY AND CONCLUSIONS

6.1 Main Findings

Some of the major results from the study are summarised below:

- The design of allocation method in environmental performance calculation for transport influences the result of the analysis to such an extent that its contribution to the uncertainty of the result should be made visible.

  Calculations for one 17-meter trailer on a Ro-Pax ferry between Helsingborg-Helsingör showed a span of 0.4%-3.2% of the total emissions from the Ro-Pax ferry, corresponding to 4–34 kg fossil CO2.
  The choice of allocation method will therefore introduce substantial variations for transport chains containing long ferry crossings. Calculation for a lorry going from Antwerp to Helsingborg, via Travemünde-Trelleborg, showed a variation of 450 kg fossil CO_2 emission due to allocation method selection. The total fossil CO_2 emission for the transport, as calculated by different methods, did therefore vary between 750-1300 kg.

- The contribution to the total EP data from presumably negligible parts of the life cycle of a transport system cannot be neglected without support of a sensitivity analysis.

  The example of CO2 emissions from material supply to shipbuilding confirmed this. The allocation issues faced when identifying the share of this EP data to be assigned to specific transport tasks during the duty cycles of the vessel has previously not, in any detail, been analysed. A framework for such an analysis, complementing earlier work on fuel supply systems is presented.

- The transport-related environmental performance of bananas brought to a private household in Sweden was calculated. A typical case, representative for the main channel of banana import to Sweden, is presented in the units MJ- and gram emission to air per kg bananas, and amounts to the following figures:

Table 23 *EP data for the transport of bananas from Costa Rica to Sweden.*

Energy	**Emissions**						
[MJ/kg bananas]	[g/kg bananas]						
Fossil	CO2	NOx	NMHC	CH4	PM >0.5	CO	SO2
10	**763**	**18**	**1**	**0.012**	**0.89**	**0.51**	**14**

The EP data is dominated by the sea voyage (70-85% of CO_2, 90-95% for NO_x and >99% of SO_2). The contribution from operations between port and customer is dominated by road transport, especially for distribution with lorry (4-7% of CO_2 and 1-2% for NO_x) and when using private car for transport between the household and the super-market or grocery store (7-11% of CO_2 and 6-14% for NMHC).

The most inefficient part of the transport chain is the transport to the customer's home by car. The energy used for moving the 1 kg of banana 1 km by car moves the banana 250 kilometres with the reefer. Although reefers fail to substitute cars for shopping tours, saving in energy utilisation by a *factor 30* is demonstrated by a dedicated home delivery system with normal lorries.

- Allocation of EP data to cargo in the case of air cargo transported in passenger planes is examined, and a suggested method to carry out such an allocation is expressed as:

$$\text{EP data}_{\text{cargo}} = \text{EP data}_{\text{empty}}^{\text{plane}} \times \frac{\text{volume}_{\text{cargo}}}{\text{utilised volume}_{\text{total}}} + \text{EP data}_{\text{load}}^{\text{plane}} \times \frac{\text{weight}_{\text{cargo}}}{\text{weight}_{\text{total}}}$$

- Allocation of EP data to individual consignments in the case of co-distribution of cargo by lorry is examined, and a suggested method to carry out such an allocation is expressed as:

$$\text{EP data } [\text{stop i})] =$$

$$\frac{\text{Cold start emissions}}{\text{Number of stops}} + \left[\frac{\text{EP data for an exclusive trip to stop i)}}{\sum \text{EP data for exclusive trips to all stops}} \times \text{EP data for distribution trip} \right]$$

The method is invariant in relation to the direction of the distribution route and recognises differences in distance between the point of origin and the different delivery addresses.

6.2 Discussion

The ambition with this work is to contribute to the development of scientific methods assessing the environmental performance of transport chains. The work has its focus on the analysis of *the transport chain* and does not engage in issues related to calculation of the environmental performance of different vehicles in the *traffic systems* (or modes) concerned. The way in which this is done, and the selection of input data, is a source of uncertainty in the LCI calculations. The lack of EP data for the actual operations in the traffic system is, especially for road traffic, still a concern.

The aggregated EP data yielded by an LCI of a transport system must be supplemented by further information before it is used as a base for an environmental impact/effect assessment. In one case of emissions to air, actual environmental impact/effect depends upon the time and position of the emission. Dispersion pattern, transport and transformation of the substance, type of recipient are examples of situation-specific variables governed by atmospheric conditions, geographical position (i.e. in relation to population and effected natural systems) and height above ground of the emission source. The exposure to humans in populated areas, and photochemical atmospheric reactions are examples of effects dependent upon the actual time of day the emission occurs.

Presently, there is not enough knowledge and data available for an analysis encompassing all these issues related to emissions to air. However, an achievable first step in this process is a geographical specification. Urban and rural areas, defined in relation to population densities are suggested for road and rail. Ocean, coastal and urban is suggested for sea transport, while for air transport, the LTO[53] cycle emissions could be presented separately. EP data for support systems (i.e. energy supply, infrastructure and vehicle construction), if not already geographically specified, must be assessed on a site-specific basis.

The large potential impact of the choice of allocation method on the results of an LCI has been demonstrated in this work. The difference in result is a *method-induced variation* in contrast to the differences caused by *data uncertainty*. The differences between them are not always transparent to the various user groups. This validity issue is an example of why LCI calculation results are - or should be - used with caution. Presently, variations induced by selection - made intentionally or not - of different LCI methods, system boundaries and data sources are the cause of conflicting answers, provided by different analysts addressing the same research question. This stresses a major weakness of the LCI method.

---

[53] LTO = Land and Take off, includes all emissions under 1000 feet.

The elimination of differences related to *data uncertainty* can be achieved by the generation of more accurate data sources. An obvious solution to the *method choice*-related contribution to the problem would be to standardise the (allocation) method for LCI on transport chains. This would then, cutting both ways, force all analysts to make the '*same mistake*'.

An interdisciplinary body should undertake the task of developing and selecting these methods and data sources. The task should also contain an evaluation of whether or not a common method would fulfil the ambitions to increase the applicability of the LCI method. Manheim (1979) addresses this dilemma. His concluding chapter addresses the question of *value judgements* in transportation systems analysis:

"The value issues pervade all elements of transportation systems analysis; even issues that at first appear to be largely technical or managerial often contain significant value implications - even such decisions as what models to develop and what data to utilize ..."

"There is no rational, objective way of deciding what is the best model for a particular application. ... Technical expertise is a necessary precondition to make these judgements, but it is not sufficient. Technical expertise must be complemented by a thoughtful, perceptive appraisal of differences in perspectives among the interests who will be concerned ..."[54].

These insights are incorporated in the ambitions of the LCA method, however has proven hard to realise. The difficulties encountered, e.g. lack of exact and verified models and observational data, different values and interests together with limited knowledge about natural and social systems, seems overwhelming. This however, must not prevent the society from facing the

---

[54] Manheim (1979), page 583.

responsibility towards those, present and future generations, affected by our activities.

The following specific reflection on the results of the case study presented in chapter 4 is being made: Sweden has, in comparison with other countries located at the same latitude, high banana consumption per capita. An average of 17 kg/year and person yields a statistical personal intake of 2 bananas per week (150 g. each).

The LCI of the studied banana transport system showed a total fossil CO_2 emission of 135 g for *one* banana. At a first glance this emission looks surprisingly high – the fossil CO_2 emission related to a banana is almost equal to its own weight. Does this call for a change in the transportation system? Let us compare this with another activity that Swedes engage in on a large scale, and therefore are familiar with; car driving. A total of 57.3 billion kilometres were driven by Swedish cars during 1997 while emitting 12 billion kg of fossil CO_2[55]. In terms of CO_2 emission one banana is thus comparable to 650 meters of car driving.

An average car-related emission of 25 kg of fossil CO_2 per week can then be assigned to each inhabitant. The comparable transport-related emission for the weekly banana consumption was 0.3 kg[56]. The problem to determine which of the activities that returns the largest satisfaction per kg emitted CO_2 to a consumer refers to the classic issue of welfare theory; it can only be determined by the consumer him- or herself, and only so if the relevant information is available. The provision of environmental performance

---

[55] Assuming 1.5 person per car, a f.c. of 0.8 l/10 km generating the emission of 205 g fossil CO_2 per km (incl. 15 g. from fuel production)

[56] A person not driving a car would thus have to consume 24 bananas per day in order to keep up with the average car driver.

guidance is an example of information, necessary to furnish the informed consumer with in order to facilitate the desired value maximisation.

6.3 Suggestions for future work.

The relatively new field of LCI and LCA is of great interest to actors in the transportation service industry. The environmental issues related to transportation systems are coming under increased attention by all levels in the society. This implies the importance of the suggested future work. Referring to LCI and allocation, following issues is proposed:

- An extension of the presented work would be to analyse reefer transports serving several loading and unloading harbours. This could be done by development of the method for allocating EP data of a distribution route with the intention of also encompassing pick-ups.

- The hinterland transport of bananas from Göteborg is operated by rail to a number of Swedish cities where ripening plants are located. The EP data for the rail transport could be compared to that of an alternative transport by lorry.

- The development of allocation methods could be extended to the case of line-based part-load long-distance lorry transports (cf. Schenker-BTL, ASG, Fraktarna etc.).

- Allocation methods for different rail cars and train combinations should also be developed. The impact of different allocation methods for railcars on ferries are likely to show a variation of the same kind as for the lorry on a RoPax ferry (see section 5.4.1). The approaches to this allocation remain to be investigated.

- An investigation into the cost effectiveness of carrying out an LCI – or LCA – is suggested, when limited resources are to be used in order to reduce environmental impact.

Tasks for future work dealing with environmental performance calculations may be:

- The assessment of EP data for the traffic systems has already been pointed out as an area needing attention. The scarce availability of EP data for actual operation of vehicles and vessels is a key issue. It is especially urgent to look at combustion engines under non-steady state operations in lorry and diesel train operations. The implementation of advanced engine control technologies introduces an ability to continuously measure the emissions from individual lorries.

- The work of environmental performance analysis of fuel supply should be continued. LCI data for jet and bunker fuel is still lacking, and average data for diesel and petrol should be presented as a complement to present data representing the best available technology.

Several interesting tasks related to the case of banana (or produce) transport can be identified.

- Applying EP data to a transport system using alternative fuels and available abatement technologies.

- The EP data contributions from the infrastructure and the life cycles of the vehicles/vessels were only touched upon in this work. The contribution from these systems should be investigated more thoroughly.

- Analysing the impact upon EP data due to changes in the localisation of the banana ripening units and produce distribution units. One can also assess the impact related to changes in the transport systems between the units, as well as for the land-based import from European countries.

Investigate the transport related EP data for new concepts (apart from supermarkets) for distribution of groceries to customers.

References

Acharjee 1999	Acharjee, Prabal, Personal communication, Dept. of transportation and logistics, CTH, Göteborg, Sweden.
Alvarsson *et al.* 1995	Alvarsson E., Andersson T., *The Impact of Transport on the Environment - A Calculation Model for the Determination of the Environmental Effects Caused by Chains of Transport*, Thesis No. 5323/1995, Institutionen för teknisk logistik, Lund University, 1995
Andresen 1993	Andresen P., Reljanovic M., *Linjestruktur för Nordsjötrafik*, Thesis report, Dept of transportation, Chalmers Univ. of Techn. 11 February 1993.
Arnäs 1999	Arnäs J-O., Personal communication, TRB Miljö AB, Kungsbacka 1999
Baumann *et.al* 1999	Baumann K., Tillman A.M., A Handbook for LCA. To be published. Work in progress, Personal communication, November 1999.
Berglund 1999	Berglund A., *Incorporating Environmental Aspects in Transport Purchasing*, Thesis for the degree Licentiate in Engineering, Dept. of Design Sciences, Packaging Logistics, Lund University, 1999
Blinge 1998	Blinge M., ELM: *Environmental Assessment of Fuel Supply Systems for Vehicle Fleets*, Doctoral thesis, report 35, Dept. of Transportation and Logistics, Chalmers University of Technology, 1998.
Blinge *et al.* 1997	Blinge M. et al. *Livscykelanalys (LCA) av drivmedel*, KFB Meddelande 1997:5, ISSN/ISBN 1401-1271, KFB Stockholm, Juli 1997.
Blix *et al.* 1998	Blix L., Davelid M., Johansson B., *Lastpallar - en studie ur livscykelperspektiv*, SLU - Alnarp, Dept. of Economy, Student projec, 1998-05-20.
Branch 1996	Branch A.E., *Elements of Shipping*, /th ed. Chapman &Hall, London, 1996.
Brandberg *et al.* 1992	Brandberg Å., Ekelund M., Johansson A., Roth A., *Life of Fuels*, Ecotraffic AB, Stockholm, Sweden 1992.
Brown 1999	Brown D., *Increasing the sped in the Mediterranean*, Marine News, pp. 19, Iss. 1, 1999.

Bäckström 1999	Bäckström S., *Environmental Assessment of Energy Supply Chains for Electrically Propelled Road Traffic*, to be published, KFB Report 1999.
Castillo *et al.* 1999	Castillo V.H., Marias H., Peryre M., *Life Cycle Assessment on a Transport Chain of Bananas, Case* study within the course Energy & Environment, MOT 98, Chalmers University of Technology, Göteborg, February 25, 1999.
DeLuchi 1991	DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Centre for Transportation Research, Argonne National Laboratory, Argonne, Illinois, USA 1991.
Demker *et al.* 1994	Demker G. et al., *Miljöeffekter av transportmedelsval för godstransporter*, KFB rapport 1994:6, Stockholm 1994.
Ekvall 1999	Ekvall T., *System Expansion and Allocation in Life Cycle Assessment - With Implications for Wastepaper Management*, Doctoral thesis, AFR-report 245, Technical Environmental Planning, Chalmers University of Technology, 1999.
Env. Mngm. Council 1998	Environmental Management Council, *Requirements for CERTIFIED ENVIRONMENTAL PRODUCT DECLARATIONS, General principles and procedures*, MSR 1998:1, AB Svenska Miljöstyrningsrådet, 1998-05-15. (Available at: http://www.environmarket.com/document/epd/e_msr98_1.doc).
Env. Mngm. Council 1999a	Environmental Management Council, *Temperaturreglerad transport av mejerivaror*, (PSR 1999:2), AB Svenska Miljöstyrningsrådet, 1998-05-15. (Available at: http://www.sms-standard.se/pdf/epd/psr9902.pdf).
Env. Mngm. Council 1999b	Environmental Management Council, *Certifierad miljövarudeklaration Busstrafik, produktspecifika utgångspunkter*, PSR 1999:7, version 1.0, AB Svenska Miljöstyrningsrådet, 1999-09-02. (Available at: http://www.sms-standard.se/pdf/epd/psr9907.pdf)
Eriksson *et al.* 1995	Eriksson E. *et al.*, *Transporters miljöpåverkan i ett livscykelperspektiv*, Reforsk FoU report 126, ISSN 0284-9968, CIT/Chalmers, Göteborg , May 1995
Ferries 1999	The following internet addresses were used for obtaining

	data: www.ttline.se/fartyg/dackerobin.html; www.shipping-publ.no/prog/; www.stenaline.com/vessels; http://www.ferryguide.nu/. Transcripts of the information are kept in the empirical material.
Flodström *et al.* 1994	Flodström E., Sjöbris A., *Emissions- och Energivärderingsprinciper för transportsystem,* KFB rapport 1994:9, Stockholm 1994.
Flodström 1998	Flodström E., *Environmental Assessment of freight Transportation,* KFB rapport 1998:15, Stockholm 1998.
Frischknecht 1998	Frischknecht R., *Life Cycle Inventory Analysis For Decision-Making,* Doctoral thesis report, Swiss Federal Institute of Technology Zurich, 1998
Frischknect *et al.* 1995	Frischknect R. et al. (14 authors), *Ökoinventare für Energiesysteme, Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz,* Bundesamt für Energiewirtenschaft, 2. Edition, Zürich, March 1995.
Hansson 1998	Hansson l., *The Internalization of External Effects in Swedish Transport Policy - A Comparison Between Road and Rail Traffic,* Ph.D. Thesis, IIIEE, Lund 1997.
Heijungs *et al.* 1998	Heijungs R., Frischknecht R., *A Special View on the Nature of the Allocation Problem,* Int. J. of LCA 3 (5) p.321-332, 1998
Henriques *et al.* 1999	Henriques M., et al., *Godstransportkaeder - miljö og omkostningforhold,* TetraPlan A/S, Notat nr. 99.01, ISBN 87-90037-76-6, Copenhagen, July 1999.
Horngren *et al.* 1991	Horngren C.T., Foster G. *Cost Accounting, A Managerial Emphasis,* 7th ed., Prentice Hall International Inc. 1991
Hyttsten 1999	Hyttsten D., Personal communication, Ferm International Ship Management, Skärhamn, 1999
Höjeberg 1995	Höjeberg M., *Transportsystemens elförbrukning,* Elforsk rapport 95:19B, December 1995.
ISO 14 040 1997	ISO 14 040, *Environmental management – Life cycle assessment - Principles and framework,* ISO 14040:1997 (E),

	1st ed., Int. Org. for Standardization, Geneva, Switzerland 1998.
ISO 14 041 1997	ISO/DIS 14 041, *Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis,* ISO 14 041:1998 (E), 1st ed., Int. Org. for Standardization, Geneva, Switzerland 1997. (A standard is now established as ISO 14041:1998)
ISO 14 042 1998	ISO/DIS 14 042, *Environmental management – Life cycle assessment -Life cycle impact Assessment,* Draft International Standard 1998-09-17, Int. Org. for Standardization, Geneva, Switzerland 1998.
ISO 14 043 1998	ISO/DIS 14 043, *Environmental management – Life cycle assessment -Life cycle Interpretation,* Draft International Standard, Int. Org. for Standardization, Geneva, Switzerland 1998.
Jansson 1988	Jansson S-E., Samuelsson L., *Industriell kalkylering och redovisning –industriella ekonomisystem,* 7th ed., Nordstedts förlag, Stockholm 1988.
Kolb *et al.* 1995	Kolb A., Wacker M., *Calculation of energy consumption and pollutant emissions on freight transport routes,* The Science of the Total Environment 169 (1995) 283-288.
Kordi *et al.* 1979	Kordi, I. et al., *Energieffektiviteten för person- och godstransporter i Sverige, En jämförande analys,* Appendix, Transportforskningsdelegationen 1979:2, ISBN 91-85562-15-7, Stockholm, 1979.
Kåberger 1999	Kåberger T., *Aspects of Energy Resource Management,* report 34, Dept. of Physical Resource Theory, Chalmers University of Technology, 1999.
Larson *et al.* 1996	Larson L-G., Pålsson A., *Tekniska möjligheter att minska avgasutsläppen från flygtrafik i Sverige,* FFA TN 1996-33, Stockholm 1996.
Lindfors *et al* 1995	Lindfors L.-G. et al., *Nordic Guidelines on Life Cycle Assessment,* Nord 1995:20, Copenhagen 1995.
Lloyd's 1990	Lloyd's Register, *Marine Exhaust Emissions Research Programme,* Steady State Operation, London, 1990
Locklin, 1972	Locklin P.D., *Economics of Transportation,* Chapter 21, Richard D. Irwing, INC., 7the ed. Homewood, Ill. USA

	1972.
Magnusson 1996	Magnusson L., *The relation between service level and resource utilisation in the transportation industry,* Thesis work 96:03, Dept. of Transportation and Logistics, CTH, Göteborg 1996.
Maibach *et al.* 1995	Maibach M., Peter D., Seiler B., *Ökoinventar Transporte, Grundlagen für den ökologischen Vergleich von Transportsystemen und den Einbezug von Transportsystemen in Ökobilanzen,* SPP Umwelt, Modul 5, ISBN 3-9520824-5-7, Verlag INFRAS, 1. ed., Zürich, December 1995
Manheim 1979	Manheim M.L., *Fundamentals of transportation systems analysis,* Volume 1: Basic Concepts, MIT Press, Cambridge, ISBN 0-262-13129-3, Mass. December 1979.
Månsson 1999	Månsson K., Personal communication, ICA Handlarna Väst AB, Kungälv, Sweden 1999.
Nigbur 1997	Nigbur B., Personal communication, Operations Department, TT-Line GmbH, D-23570 Lübeck.
NTM 1999	Nätverket för Transporter och Miljön, *Environmental Performance Data for the transport systems,* presented at http://www.ntm.a.se, Stockholm 1999.
Pålsson 1999	Pålsson A-C, *Introduction and guide to LCA data documentation using the CPM data documentation criteria and the SPINE format,* CPM report 1:1999.
Scandinavian Link 1999	Scandinavian Link, Newsletter, Nr. 2, Scandinavian Link, Köbenhamn, June 1999.
Scania 1999	Scania, *Scania Environmental Report 1998,* Scania AB (publ), Södertälje, Sweden, 1999
SIKA 1999	SIKA, *Översyn av samhällsekonomiska kalkylprinciper och kalkylvärden på transportområdet - ASEK,* Sika rapport 1999:6, Stockholm, June 1999
Sjöstedt 1997	Sjöstedt L., *Managing sustainable mobility: A conceptual framework,* In *Information systems in logistics and transportation,* Tilanus (Ed.), Elsevier Science Ltd, Oxford,1997, pp 19-31.
SNF 1995	Svenska Naturskyddsföreningen (SNF), *Miljökriterier för godstransporter, Kriteriedokument,* Naturskyddsföreningens förlag, Stockholm 1997.

SPINE 1999	SPINE, *CPM LCA database*, LCI data for Steel from Virgin materials, April 1999 (Available at http://deville.tep.chalmers.se/SPINE_EIM/toppage1.htm)
Steen 1996	Steen B., *EPS-Default Valuation of Environmental Impacts from Emissions and Use of Resources.* Version 1996, Report AFR 111 from Swedish Environmental Protection Agency, April 1996
Stripple 1995	Stripple H., *Livscykelanalys av väg, En modellstudie för inventering*, IVL rapport B1210, Göteborg, November 1995.
Tarkowski 1977	Tarkowski J., Johnsson L., *Prissättning av transporttjänster*, Affärsekonomi Förlag AB, 1977
TFK 1998	TFK, *Transportköparens miljöhandbok - godstransporter*, TFK Rapport 1998:4, ISBN 91 88752 11 9, Stockholm, Augusti 1999.
Thomas 1969	Thomas A.L., *The allocation Problem in Financial Accounting Theory*, Studies in Accounting Research #3, American Accounting Association, Evanston, Illinois, 1969.
Thunberg *et.al* 1997	Thunberg et.al, *Transportsektorns avgasutsläpp - Identifiering, motivering och systematesering av behovet av forskning och utvecklingsarbete*, KFB-Information 1997:14, Stockholm 1997
Trafikministeriet 1996	Trafikministeriet, *TEMA - En model for transporters emissioner*, Dokumentationsrapport, 1996-04-30, Dokument 25458-1, rev. 4, COWI Rådgivende Ingenjorer AS, Lyngby, Denmark
Volvo 1997	Volvo truck corporation, *Lastvagnar och miljön*, Volvo Lastvagnar AB, Information & omvärldsfrågor – Miljö, Göteborg 1997
Volvo 1998	Volvo Car Corporation, *Miljövarudeklaration, Volvo S80*, 1999 Europa, Volvo, October 1998.
Woxenius 1998	Woxenius J., *Development of small-scale intermodal freigth transportation in a systems context*, Doctoral thesis, report 34, Dept. of Transportation and Logistics, Chalmers University of Technology, 1998.

Öjmerts 1998	Öjmerts B., *Materials Handling from a Value-Adding Perspective,* Doctoral thesis report 37, Dept. of Transportation and Logistics, Chalmers University of Technology, 1998.

REPORTS FROM THE DEPARTMENT OF TRANSPORTATION AND LOGISTICS, CHALMERS UNIVERSITY OF TECHNOLOGY

TITLE AND AUTHOR	NO	YEAR
Mechanical stresses during sea transport Thomas Trost Thesis for the degree of Licentiate (in Swedish)	1	1986
Local information support Stellan Svensson, John Wedel Thesis for the degree of Licentiate (in Swedish)	2	1986
Terminology for management and control of transportation systems Carl-Erik Redin Thesis for the degree of Licentiate (in Swedish)	3	1986
Physically handicapped persons in public transportation - Guidelines for vehicle design Jan Petzäll Thesis for the degree of Licentiate (in Swedish)	4	1986
Transfer technology and unit load carriers in intermodal transport - A description of a system Thore Hagman Thesis for the degree of Licentiate (in Swedish)	5	1988
Safety at level crossings on secondary rail lines - A collision analysis and a review of emergency brake concepts Mohammad Shahriari Thesis for the degree of Licentiate (in English)	6	1989
Cargo carrier flow and utilization - A study of transport solutions for Swedish international trade Jennie Thalenius-Adolfsson Thesis for the degree of Licentiate (in Swedish)	7	1989
The interlink between product quality and materials flow quality Magnus Strand Thesis for the degree of Licentiate (in Swedish)	8	1989
Comfort in mass transit Börje Johansson Thesis for the degree of Licentiate (in Swedish)	9	1989
The evolution of the Swedish concept of materials administration from a conceptual perspective to an established discipline Maria Green Thesis for the degree of Licentiate (in Swedish)	10	1989

TITLE AND AUTHOR	NO	YEAR
Product design and materials handling in mixed-model assembly Mats Johansson Thesis for the degree of Doctor of Philosophy (in English)	11	1989
Automatic shop floor data capture and its impact on the internal material flow Roger A. Lindau Thesis for the degree of Licentiate(in Swedish)	12	1990
Routing of dangerous goods transports in a quantitative risk perspective Göran Stjernman Thesis for the degree of Licentiate(in Swedish)	13	1990
The dynamic logistic analysis in the Scandinavian Link Study - A methodologic evaluation Horst Mueller Thesis for the degree of Licentiate(in English)	14	1991
Strategic choices in a changing aluminium industry - An analysis of the aluminium industry and the strategic choices among the most important producers Marianne Jahre Thesis for the degree of Licentiate (in English)	15	1992
Long distance freight transport from the regional aspect Joakim Sjöholm Thesis for the degree of Licentiate (in English)	16	1992
Break point distribution to distant markets Maria Helmroth Thesis for the degree of Licentiate (in Swedish)	17	1993
Energy logistics - Life-cycle assessment on motor fuels Magnus Blinge Thesis for the degree of Licentiate (in Swedish)	18	1993
Safety at Rail/Road Level Crossings Mohammad Shahriari Thesis for the degree of Doctor of Philosophy (in English)	19	1993-09
Design for accessibility - The development of public transport vehicles with regard to mobility impaired passengers Jan Petzäll Thesis for the degree of Doctor of Philosophy (in English)	20	1993-09

TITLE AND AUTHOR	NO	YEAR
Logistic models for circulation and utilization of cargo carrying equipment Lars Hultén Thesis for the degree of Licentiate (in English)	21	1993-09
Product and process descriptions supporting assembly in long cycle time assembly Lars Medbo Thesis for the degree of Licentiate (in English)	22	1994-03-25
Resource utilisation in line-based road traffic Håkan Buskhe Thesis for the degree of Licentiate (in Swedish)	23	V1993
Modelling european combined transport as an industrial system Johan Woxenius Thesis for the degree of Licentiate (in English)	24	1994-06-08
The work situation for seamen on merchant ships in a Swedish environment Martin Olofsson Thesis for the degree of Licentiate (in English)	25	1995-03-24
Evaluation of kitting systems - Implications for kitting system design Henrik Brynzér Thesis for the degree of Licentiate (in English)	26	1995-03-24
Activity analysis to achieve increased materials flow effectiveness Birgitta Mathisson Thesis for the degree of Licentiate (in English)	27	1995-03-24
The impact of high-quality information on performance in manufacturing Roger Lindau Thesis for the degree of Doctor of Philosophy (in English)	28	V1995
Logistics systems for recycling - efficient collection of household waste Marianne Jahre Thesis for the degree of Doctor of Philosophy (in English)	29	V1995
Measuring transport quality in line-based road traffic Johan Hellgren Thesis for the degree of Licentiate (in English)	30	1996-02-08

TITLE AND AUTHOR	**NO**	**YEAR**
Lead-time reductions in manufacturing - from initiation to realization John E. Wedel Thesis for the degree of Doctor of Philosophy (in English)	31	1996-09-31
Container logistics and its management Lars A.R. Hultén Thesis for the degree of Doctor of Philosophy (in English)	32	1997-10-32
Logistic time requirements in fast sea transportation Thore Hagman Thesis for the degree of Doctor of Philosophy (in English)	33	V1998
Development of small-scale intermodal freight transportation in a systems context Johan Woxenius Thesis for the degree of Doctor of Philosophy (in English)	34	V1998
ELM: Environmental assessment of fuel supply systems for vehicle fleets Magnus Blinge Thesis for the degree of Doctor of Philosophy (in English)	35	1998-06-03
Significance of input data quality for materials flow analyses Per Medbo Thesis for the degree of Licentiate (in English)	36	1998-10-09
Materials handling from a value-adding perspective Birgitta Öjmertz Thesis for the degree of Doctor of Philosophy (in English)	37	1998-10-29
Information in Transportation Chains Thomas Kanflo Thesis for the degree of Licentiate (in English)	38	1999-01-22
Networks in Road-Based Traffic Ola Hultkrantz Thesis for the degree of Licentiate (in English)	39	1999-01-22
Public transportation in a systems perspective A conceptual model and an analytical framework for design and evaluation Stig Franzén Thesis for the degree of Doctor of Philosophy (in English)	40	1999-04-26
Port Logistics from a Network Perspective A generic model for port terminal optimisation Jonas Waidringer Thesis for the degree of Licentiate (in English)	41	1999

TITLE AND AUTHOR	NO	YEAR
Logistics in an Information Perspective Gunnar Stefansson Thesis for the degree of Licentiate (in English)	42	1999
GRSA- Goods Requiring Special Attention and their Effects On Intermodal Transportation Systems Per Olof Arnäs Thesis for the degree of Licentiate (in English)	43	1999-12-03
Discrete Event Operational Simulation in the Manufacturing System Michael Andersson Thesis for the degree of Licentiate (in English)	44	1999-11-26
Environmental Performance Calculation in Transport LCI - Allocation Method Design Issues Sebastian Bäckström Thesis for the degree of Licentiate (in English)	45	1999-12-17

……

"Do not capacitate the action
if you appreciate that previous generations
did not"

……