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Input/Output analysis - Shortcuts to life cycle data?

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1 Introduction

The report contains the papers presented to a workshop held in Copenhagen on the 29th of September 2000, as well as a résumé of the subsequent discussions, and a few additional papers on the topic.

1.1 BACKGROUND

Can Input-Output Analysis (IOA) data and methodologies be used to improve the performance of Life Cycle Assessment (LCA)? And if so, are there any specific initiatives that need to be taken for Danish LCAs to take advantage of this? These are the key questions that this report seeks to elucidate.

The workshop and this report has been financially supported by the Danish Environmental Protection Agency and has been followed by a supervisory group composed of the project manager Bo Weidema, 2.-0 LCA consultants, Erik Hansen, COWI, Mariane Hounum, The Danish EPA, Anders Schmidt, dk-TEKNIK, and Søren Varming, Elsamprojekt A/S.

The international nature of the workshop was only possible due to the in-kind contributions of the foreign participants (see also Annex B), for which we wish to express our special gratitude.

1.2 OUTLINE OF THE TOPIC AND THE CONTENT OF THE REPORT

LCA has traditionally been performed as a bottom-up process analysis, based on linking the specific processes in a supply chain. Exceptions to this approach may be found, especially in the early LCA work in Japan, which was often based on IOA. The process-based method is explained in more detail by Marianne Wesnæs in Chapter 3, who also points out its capability for detail as a significant advantage of this approach. However, a major problem in process-based LCA is the likelihood that important parts of the product systems are left out of the analysis, simply because it is a very difficult task to follow the entire supply chain in detail. As pointed out by Manfred Lenzen in Chapter 4, up to 50% of the environmental exchanges related to a product can be left out, thus possibly leading to erroneous conclusions.

IOA is a top-down approach in which the statistical data on production and consumption in individual industrial sectors allows a complete allocation of all activities to all products. By linking this with statistical information on environmental exchanges for the same sectors, an LCA-like result can be obtained. The procedures involved are described by Anne Merete Nielsen in Chapter 4 and an example is provided by Jesper Munksgaard in Chapter 6. The Danish IO-tables and their application to physical and environmental accounting are described by Ole Gravgård Pedersen in Chapter 7. IOA has the advantage of being complete with regard to inclusion of all relevant activities related to a product. However, the IOA is not very detailed, since it relies on a grouping of activities in a limited number of sectors (ranging from below 100 in Germany to around 800 in Japan). This makes it difficult to use for detailed LCA purposes, except for very homogenous sectors. Also, the necessary environmental statistics is not always available, which means that for some environmental exchanges, adequate information will be missing.

Combining process-based LCA and IOA in what has become known as “hybrid analysis” can yield a result that has the advantages of both methods (i.e. both detail and completeness). This is further elaborated by Manfred Lenzen in Chapter 4 and by Anne Merete Nielsen in Chapter 8. In the update of Dutch LCA methodology guide (Guinée et al. 2000), the use of a hybrid approach is also recommended as a procedure for filling data gaps.

Most often IOA has covered only energy related emissions, but the examples in Chapters 10, 11 and 12 clearly demonstrate that IOA and similar approaches can be expanded to include many diverse types of environmental exchanges and effects.

The basis of IOA in national production and consumption statistics is the cause of another limitation of IOA, namely the assumption that imports are produced in the same way as domestic production. This assumption is especially problematic in very small and open economies with large imports and exports. It is well known, also from process-based LCA, that production technologies vary significantly between geographical regions. A possible solution to the import assumption is a multi-regional IOA-model as suggested by Sangwon Suh and Gjalt Huppes in Chapter 13.

For process-based LCA, an important methodological improvement has been the introduction of prospective, market-based methods for identifying the processes and technologies to include in the studied systems (see e.g. Weidema 1999). This provides a more realistic modelling of the consequences of a change in product output as compared to the traditional use of average, historical data. IOA is also extensively used for prospective purposes (predicting the consequences of a suggested change) in spite of its clear basis in historical average data. Thus, an important improvement to the current IOA could be the development of IO-tables that take into account dynamic aspects such as technologies ability to change over time. In Chapter 14 Tom Gloria addresses part of this issue with his dynamic life cycle approach based on temporal IO-modelling.

1.3 THE MAIN CONCLUSIONS

The discussions following the presentations in Chapters 2 to 14 were divided in two:

- Those taking place immediately on the workshop (and reported in Chapter 15) involving all workshop participants (see the participants list in Annex A).
- Those taking place mainly among the foreign experts on their separate meeting on the day after the workshop (and reported in Chapter 16).

Both discussions reached similar conclusions, which may be summarised as follows:

There was general agreement that product related questions could not be answered adequately by IOA alone. Thus, it is not a question of IOA or process-based LCA, but rather a question of improving process-based LCA by the addition of IO-based data or IOA methods, i.e. in the form of hybrid methods.

A very promising hybrid approach seems to be the one proposed by Treloar (1997). First, the assessment is carried out merely with IO-data. Secondly, the chains are ranked according to the relative contribution to the total result, thus implying a data collection strategy. Third and finally, process data can be collected until the desired level of accuracy is reached. The method may be especially useful if combined with (possibly estimated) uncertainties for each value in the IO-model.

To supply currently available environmental IO-data in a form suitable for LCA-software and -databases is a relatively simple task, and does not necessarily demand any particular software, although the use of hybrid approaches may be facilitated by such software as suggested by Greg Norris and Sangwon Suh.

A need was identified to inform those responsible for collecting statistics (both environmental and economic) about the requirements from the side of environmental product assessment.

There was general support for the idea of overcoming the import assumption in current IO-data through the development of a multi-regional IOA-model.

There was general agreement that the introduction of dynamic and market-based (marginal) modelling to IOA would be an important improvement for (prospective) decision support and a topic for future research. It was agreed that it is mainly a data problem to identify the constraints that the technologies are subject to.

As a follow-up of the expert meeting in Copenhagen, Greg Norris, Gjalt Huppes of Leiden University, and Bo Weidema held a meeting with Japanese researchers (Yuichi Moriguchi, Hiroki Hondo, Masanobu Ishikawa, and others) in Tsukuba on the 1st of November 2000. At this meeting Japanese support for the multi-regional model was obtained. Also in Japan, Greg Norris and Bo Weidema agreed with Dolf Gielen and Yuichi Moriguchi of the National Institute of Environmental Studies to start investigating the options for developing a dynamic, market-based, environmental IO-table.

Specifically for the Danish situation, the following initiatives may be proposed:

- Providing the available environmental IO-data in a form directly applicable in current Danish LCA software and LCA databases.
- Establishing procedures for updating and improving such data from the perspective of LCA practice, in cooperation with those responsible for collecting environmental and economic statistics.
- Using Danish environmental IO-data (possibly with the addition of estimated uncertainties) to test the approach of Treloar (1997) on a Danish LCA case study.
- Providing Danish input to the multi-regional IO-model under development by CML in Leiden.
- Providing Danish input to the development of a dynamic, market-based, environmental IO-table.

It should be noted that the above interpretation of the discussion and its conclusions are the sole responsibility of the authors of this report.

1.4 REFERENCES

Guinée J B, Gorree M, Heijungs R, Huppes G, Kleijn R, Wegener Sleeswijk A, Udo de Haes H A, de Bruijn J A, van Duin R, Huijbregts M A J, Lindeijer E, Roorda A A H, van der Ven B L, Weidema B P. (2000). LCA - An operational guide to the ISO-standard. Leiden: Centrum voor Milieukunde, Leiden University. (Available from http://www.leidenuniv.nl/interfac/cml/lca2/).

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2 Sammenfattende artikel

INPUT/OUTPUT ANALYSE – EN GENVEJ TIL LIVSCYKLUSDATA?

BO WEIDEMA, 2.-0 LCA CONSULTANTS

Data fra national-statistikkens Input/Output-tabeller kan gøre livscyklusvurderinger mere fuldstændige og hjælpe til at forenkle den krævende dataindsamling. Dette var nogle af konklusionerne fra en workshop om Input/Output-analyse og livscyklusvurdering, afholdt i København d. 29 september 2000.

En inviteret australsk ekspert, Manfred Lenzen, gav eksempler på, at traditionelle livscyklusvurderinger udelader op til 50% af miljøeffekterne fra et produkt sammenlignet med resultatet fra en Input/Output-analyse. Livscyklusvurderinger er gode til at afsløre vigtige detaljer i et produktsystem, men den traditionelle proces-analyse, der sammensætter produktsystemet proces for proces, kan ofte komme til at udelade store dele af produktsystemerne, simpelthen fordi det er meget vanskeligt og tidskrævende at følge alle processernes inputs og outputs i detaljer. For hver proces i en livscyklus kan der nemt være 10-100 leverandører, hver med 10-100 underleverandører, osv. En detaljeret undersøgelse af alle leverandører er naturligvis umulig.

Mens livscyklusvurderinger populært sagt kæler for detaljen, sikrer Input/Output-analyse (IOA) overblikket. IOA er baseret på national-statistikkens opgørelser over forbrug og produktion i de forskellige industrielle sektorer, 130 sektorer i alt. Alle sektorerne er knyttet sammen i en Input/Output-tabel, således at man kan beregne, hvor meget en industriel sektor forbruger fra alle de andre sektorer. Ved samtidig at opgøre miljødata for de samme 130 sektorer får man et værktøj, der kan give en slags livscyklus-resultat for gennemsnitsprodukter for hver af de 130 sektorer. Fordelen ved dette resultat er, at det er uden ”huller”, da de 130 sektorer dækker hele samfundets samlede aktivitet. Ulempen er selvfølgelig manglen på detaljer: Et gennemsnitsprodukt, f.eks. fra den kemiske industri, kan jo dække over meget forskellige produkter og dermed ikke være særlig brugbart for en analyse af et meget specifikt produkt indenfor denne sektor, f.eks. et vaskemiddel.

2.1 HYBRID-ANALYSE

Ved at kombinere detaljen i en traditionel livscyklusvurdering (LCA) med fuldstændigheden i IOA kan man få det bedste af to verdener. Dette kaldes en *hybrid-analyse*. En af de vigtigste anvendelser af hybrid-analyser er til at fylde ”data-huller” i en traditionel LCA. I den opdaterede vejledning fra det hollandske metodeprojekt (Guinée mfl. 2000) anbefales det netop at bruge hybrid-analyser på denne måde.

En speciel form for hybrid-analyse er blevet udviklet af Graham Treloar fra Deakin Universitet i Australien (Treloar 1997). Denne form for hybrid-analyse kan bruges til at få et overblik over hvilke data, der er de vigtigste i en LCA, og dermed til at opstille en prioriteret liste til dataindsamlingen. I Treloar’s metode udføres en livscyklusvurdering alene baseret på IO-miljødata. Derefter opstilles de forskellige forsyningskæder i prioriteret rækkefølge efter deres bidrag til det samlede resultat. Til sidst indsamles detaljerede procesdata, indtil den ønskede grad af nøjagtighed er opnået. Treloar's metode kan yderligere forbedres ved at inkludere usikkerhederne for de enkelte værdier, der indgår i den IO-model, der bruges som udgangspunkt.

2.2 FORBEDRINGER I IOA

Miljømæssig IOA kan forbedres på flere punkter. For det første er det vigtigt at få IOA til at omfatte alle udvekslinger med miljøet. Dette afhænger primært af den måde de nationale data for forskellige miljøeffekter opgøres på, i Danmark f.eks. hos Danmarks Statistik og Danmarks Miljøundersøgelser. I dag opgøres f.eks. kun luftemissionerne SO_2, NO_x, NH_3, NMVOC, CO, CH_4 og N_2O. Jo flere udvekslinger der opgøres i forhold til IO-tabellernes sektoropdeling, f.eks. emissioner til vand, flere toksiske stoffer osv., jo mere fuldstændig vil IOA også være i forhold til miljøeffekter.

Et andet væsentligt problem med IO-tabeller i deres nuværende udformning er den grundlæggende antagelse at importerede varer er produceret på samme måde (og med samme miljøbelastning) som de samme varer produceret i Danmark. Denne antagelse skyldes at IO-tabellerne er baseret på de nationale statistikker over forbrug og produktion. Antagelsen er særlig problematisk for meget små og åbne økonomier, som den danske. Jo større de geografisk betingede forskelle er for de anvendte teknologier og deres miljøeffekter, jo mere problematisk er antagelsen. Det er velkendt, også fra traditionelle LCAer, at teknologier kan variere meget mellem forskellige geografiske områder. En mulig løsning på problemet med import-antagelsen er at udvikle en global eller multi-regional IO-model. Sangwon Suh og Gjalt Huppes fra Leiden Universitet i Holland har for nylig taget initiativ til udviklingen af en sådan global, miljømæssig IO-model.

Endelig er anvendelsen af IOA til konsekvensvurderinger, som f.eks. i LCA, problematisk fordi IO-tabellerne i deres nuværende udformning er baseret på "historiske" gennemsnitstal (f.eks. fra 1995), dvs. uden hensyn til dynamiske aspekter som f.eks. teknologiernes evne til at forandre sig over tid. En af de væsentligste, nyere metodemæssige forbedringer i proces-baseret LCA (udviklet bl.a. i det danske LCA metodeforbedrings og –udviklingsprojekt, der for tiden er under afrapportering fra Miljøstyrelsen) er netop introduktionen af fremadrettede, markedsmæssige metoder til bestemmelse af hvilke processer og teknologier der skal inkluderes i de undersøgte produktsystemer (se f.eks. Weidema 1999). Sammenlignet med de traditionelt anvendte historiske gennemsnitsdata giver de nye metoder en mere realistisk modellering af konsekvenserne af en ændring i produktmængder. Et vigtigt supplement til den nuværende IOA vil derfor være udviklingen af IO-tabeller, der tager højde for dynamiske, markedsmæssige aspekter.

2.3 ANBEFALINGER

Disse emner var genstand for diskussion på en workshop i København d. 29. september 2000 med deltagere, heraf 7 fra udlandet, herunder Australien, U.S.A, Holland, Finland og Sverige. Workshoppens ekspert-indlæg og diskussioner er efterfølgende dokumenteret i form af nærværende rapport.

Rapporten giver tre typer anbefalinger til det videre danske arbejde med anvendelse af IOA i forbindelse med LCA: 1) Sikring af data-tilgængelighed, 2) Et demonstrationsprojekt, 3) Danske bidrag til det internationale arbejde med forbedring af miljømæssig IOA.

Det er en forholdsvis simpel opgave at gøre de eksisterende miljømæssige IO-data tilgængelige i en form der egner sig til integration i eksisterende LCA-software og –databaser. Derudover bør der etableres procedurer for løbende ajourføring og forbedring af disse data ud fra de behov der er i LCA-arbejdet. Dette kræver en involvering af de institutioner der er ansvarlige for indsamling af såvel miljøstatistik som økonomisk statistik.

For at vise hvorledes IO-data kan anvendes i LCA, vil det være hensigtsmæssigt at gennemføre et demonstrationsprojekt på et dansk LCA case studie. Et sådant demonstrationsprojekt kan baseres på Treloar's metode, evt. forbedret ved brug af (anslåede) usikkerheder.

Danske bidrag til det internationale arbejde med forbedringer af miljømæssig IOA kunne omfatte dels et dansk bidrag til den multi-regionale IO-model, der er under udvikling under ledelse af CML ved Leiden Universitet, dels et dansk bidrag til udviklingen af dynamiske, markedsbaserede, miljømæssige IO-tabeller.

2.4 HENVISNINGER

Guinée J B, Gorree M, Heijungs R, Huppes G, Kleijn R, Wegener Sleeswijk A, Udo de Haes H A, de Bruijn J A, van Duin R, Huijbregts M A J, Lindeijer E, Roorda A A H, van der Ven B L, Weidema B P. (2000). LCA - An operational guide to the ISO-standard. Leiden: Centrum voor Milieukunde, Leiden Universitet. (Kan fås fra http://www.leidenuniv.nl/interfac/cml/lca2/).

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3 Introduction to LCA

MARIANNE WESNÆS, 2.-0 LCA CONSULTANTS

This is an introduction to LCA, presented at the Workshop on Life Cycle Assessment (LCA) and Input/Output-Analysis (IOA) 29th September 2000, Copenhagen. The presentation gives a short introduction to the questions:

- What is LCA?
- Why use LCA?

3.1 WHAT IS LCA?

Life cycle assessment (LCA) is a method for evaluating the environmental impacts associated with a product or service from "cradle to grave". The LCA includes the entire life cycle of the product from extraction of raw materials, processing of these raw materials, manufacturing of the product, transport, distribution, use, re-use, maintenance, recycling and final disposal.

LCA is typically conducted in the following steps:

- Goal and Scope definition (Description of the goal of the LCA, definition of the product or service, definition of the functional unit, geographical and temporal scope, definition of what to include and what to exclude etc.)
- Inventory analysis (Collection of data for each step in the life cycle and addition of these. Data is typically consumption of energy and raw materials, emissions to air and water and amounts of waste. The results of the inventory analysis are presented in e.g. "kg CO_2").
- Impact assessment (An evaluation of the environmental impacts – "kg CO_2" is calculated into "Global warming" and the environmental impacts are weighted in order to evaluate how serious the environmental impacts are).

In principle, *all* the processes affected by the life cycle of the products shall be included. For a wine bottle the processes in the life of the wine bottle are:

- Extraction and processing of raw materials: Sand, limestone, soda etc.
- Manufacturing the wine bottle at a glasswork
- Filling of wine into the wine bottle and corking
- Use (drinking the wine)
- Recycling (rinsing and refilling) or recycling (remelting at a glasswork)
- Use
- Recycling….
- Disposal as household waste (in Denmark it is mainly waste incineration)
- Transport in between all these processes.

Furthermore, these processes demand a lot of other processes, e.g.:

- Production of electricity and other energy types and extraction of raw materials for this
- Production of water (for rinsing)
- Production of chemicals for rinsing the wine bottles
- Production of materials for all the suppliers of the glasswork, for the soda production etc.
- Production of buildings, machines, trucks, tyres, roads etc. and production of materials for this (e.g. steel) – also for all the suppliers and for building the electricity work etc.

This list is endless. The glassworks has suppliers, and each of these suppliers has suppliers, and these suppliers also have suppliers……..

Hence, it is never possible to include all the processes in practice, because the work of collecting data would be enormous. It means that a LCA will never be "perfect", and when interpreting the results of an LCA it is very important *not* to believe or pretend that the results are "the whole truth".

3.2 WHY USE LCA?

LCA is the answer to questions like:

- Are matches or lighters to prefer from an environmental point of view?
- Which supplier should my company chose from an environmental point of view?
- Does it give environmental benefits to collect more wine bottles for refilling within the existing collection system in Denmark?
- What if the extra wine bottles cannot be sold in Denmark and has to be transported to wine producers in Spain? Does the extra transport counterbalance the environmental benefits?

There are two characteristics of LCA that are very different to the Input-Output Analysis (IOA):

- The bottom-up approach in LCA gives information on minor details with large impact. In LCA, details are important!
- By the use of LCA important aspects of the *real* systems are discovered. In LCA it is important that the results reflects *realities* – and that demands knowledge of the specific systems, not "average data".

This is illustrated by two examples.

3.2.1 LCA of a Television

The LCA of a Television from Bang & Olufsen showed that significant environmental improvements could be obtained by changing some of the components (Wenzel et al. 1997).

The LCA showed that the environmental impacts from a TV was closely related to the energy consumption - as is often the case in LCAs. Approximately 70% of the energy in the TVs life was consumed when the user watches TV and another 8 % when the TV was standby, waiting for the user to turn on the TV. Of course this result is very dependent on the exact TV and on the exact user of the TV (some people watch TV 4 hours a day leaving the TV at standby 20 hours, other people watch TV only twice a week. A TV uses more energy when turned on than in standby mode).

This energy consumption could be reduced considerable by choosing circuits, which use less power, by reducing the mains voltage and by changing to component types, which use less power. The energy consumption in the standby mode could be further reduced by using components specially designed for standby mode (e.g. a separate power supply – the power supply in a television will be designed to be able to handle the maximum power required in use).

Hence, it was possible to obtain considerable environmental benefits in a TVs life by focussing on a very little "details" – the components in the electronics.

3.2.2 LCA of the Danish recycling system for wine bottles

The LCA of the Danish recycling system for wine bottles showed that it is of environmentally importance that as few bottles as possible are crushed during the collection. In Denmark the wine bottles are rinsed and refilled, hence preventing new bottles from being produced (Nejrup and Wesnæs 2000).

During the work with the LCA we went "out in the real world" to see the system, to follow the wine bottles around the recycling system. In this process we realised that a lot of the wine bottles were crushed during the collection and handling – due to unnecessarily rough handling by some of the truck drivers that empties the cubes with recycled bottles. The truck drivers were paid "to empty the cubes" instead of "to bring back as many unbroken bottles as possible" – and this "detail of reality" was of significant importance for the environmental performance of the system.

3.3 CONCLUSIONS

It is clear that LCA is not "perfect" and not covering all the processes affected by a products life – as it in principle should. A possibility could be to "fill out the data gaps" with information from IOA. In many cases, this will be a very good idea. Adding information from IOA will give us a more total picture – but we shall keep in mind that neither LCA nor IOA can give us "the truth"!

I am not convinced that the overall conclusion in the above mentioned examples would have been changed significantly if an IOA had been added for filling out the data gaps. Hence, I believe that in some cases reasonable results can be obtained by performing simple LCAs combined with an estimate of the uncertainties and common sense!

3.4 REFERENCES

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4 Uncertainty in IO-based LCI

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Parts of this article has been submitted for publication in Journal of Industrial Ecology.

4.1 ABSTRACT

Conventional process-analysis-type techniques for compiling life-cycle inventories (LCIs) suffer from a truncation error, which is caused by the omission of resource requirements or pollutant releases from higher order upstream stages of the production process. The magnitude of this truncation error can be in the order of 50%. The only way to avoid such significant errors is to incorporate Input-Output Analysis (IOA) into the assessment framework, resulting in a hybrid LCI method. Uncertainties of such IO-based LCIs can be calculated using Monte-Carlo simulations.

4.2 INTRODUCTION

The inventory phase of a life-cycle assessment (LCA) requires the assembly of a database on resource requirements and pollutant releases occurring in the life of a product or process. The system boundary of the inventory is to be chosen to include, at a minimum, all regions involved in the various stages of the life cycle, including countries supplying inputs (Fava et al. 1993). In LCAs performed as set out by the Society for Environmental Toxicology and Chemistry (SETAC), the inventory is set up using process analysis or similar bottom-up techniques. Within process analysis, the resource requirements and pollutant releases of the main production processes and some important contributions from suppliers of inputs into the main processes are assessed in detail (for example by auditing or using disparate data sources), and the system boundary is usually chosen with the understanding that the addition of successive upstream production stages has a small effect on the total inventory.

LCAs based on process analysis and IOA yield considerably different results (see (Lenzen and Dey 2000 and Hendrickson et al. 1998). In general, even extensive process analyses will not achieve reasonable system completeness, given the high number of significant input paths. As a result, environmental impacts will be systematically underestimated in conventional LCAs, thus leading to unreliable or incorrect conclusions (compare Lave et al. 1995). In contrast, LCAs based on IOA inherently cover infinite orders of upstream production stages. IOA, however, suffers itself from errors from various sources. In this article these sources will be discussed, and attempts of quantifying the associate standard errors of IO-based LCIs will be presented for the example of Australian data.

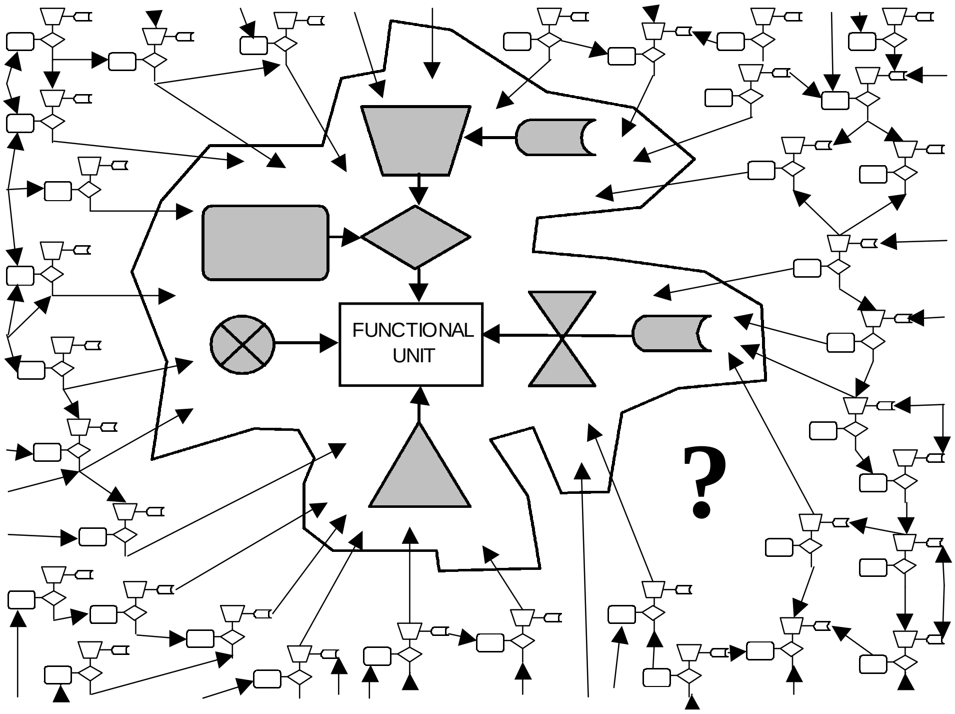

Figure 4-1: Process-based LCA only cover a limited amount of the whole system. What is excluded due to the truncation of the system boundary is usually not known. It can be shown quantitatively that the outside contribution to the functional unit - illustrated by the question mark – is of the same order of magnitude as the contribution of the processes contained within the conventional system boundary. Thus, conventional LCA carries truncation errors.

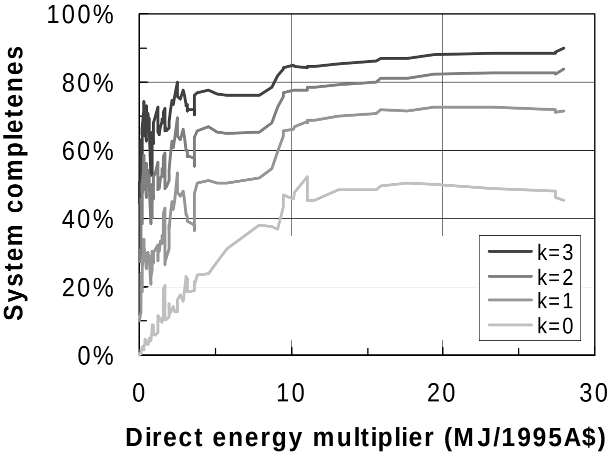

Figure 4-2: Energy-intensive sectors tend to be more complete at lower orders of upstream production stages than energy-extensive sectors. However, even for second-order analyses, that is considering about 10,000 input chains, system completeness is only between 50% and 80%. This means that the truncation error of even extremely detailed process analyses can be in the order of 20-50%.

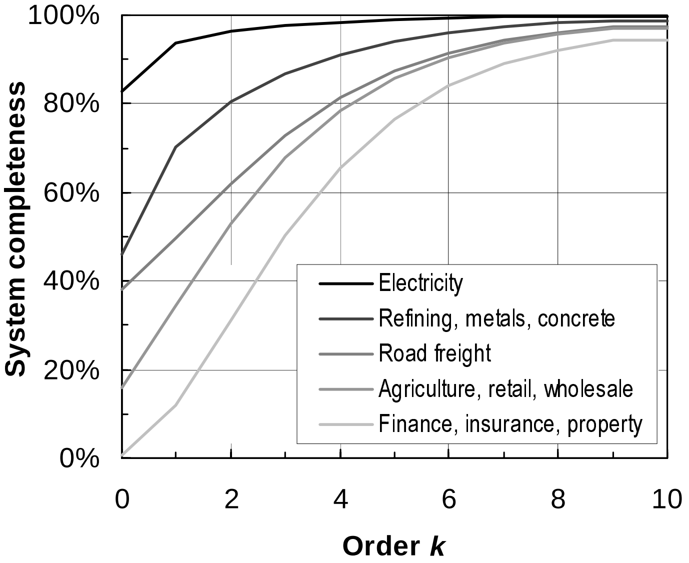

Figure 4-3: Convergence towards system completeness in detail: acceptable completeness is reached for electricity generation at first order, that is after evaluating 100 suppliers. However, for all other systems, even evaluating 10,000 inputs of second order will yield completeness below 80%. Note that the convergence to system completeness is sector-dependent!

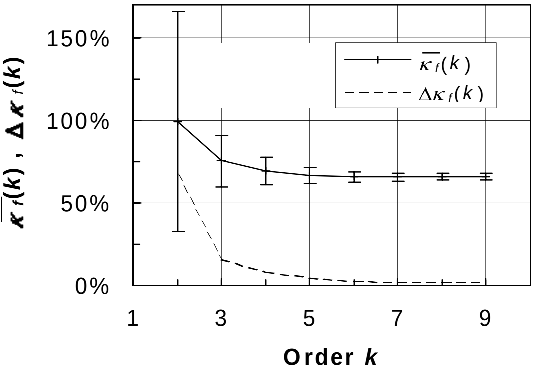

Figure 4-4: Convergence towards system completeness revisited: $\kappa_f(k)$ shows the (sector-average) relative growth in system energy with when progressing from order k-1 to order k. In other words: $\kappa_f(3) = 75\%$ means that when progressing from order 2 to 3, the additional embodied energy (in order 3) is about 75% of that contained in order 2. $\Delta\kappa_f(k)$ shows the variation of $\kappa_f(k)$ across sectors. Note that even for orders 2 and 3, there is a considerable fluctuation in convergence speed. This means that a process-based LCA of, say a plastic bottle and a glass bottle, are not necessarily comparable, even when the system boundary was truncated in a systematic and comparable way. This is simply because the "plastic system" might, at a specified order k, be more (or less) complete than the "glass" system.

4.3 INPUT-OUTPUT ANALYSIS

Input-Output Analysis (IOA) is a top-down economic technique, which uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. The result of generalised IOA is an $f \times n$ matrix of *factor multipliers*, that is embodiments of f production factors (such as labor, energy, resources and pollutants) per unit of final consumption of commodities produced by n industry sectors. A multiplier matrix M can be calculated from an $f \times n$ matrix Q containing sectoral production factor usage, and from an $n \times n$ *direct requirements* matrix A according to

$$M = Q\,(I-A)^{-1}, \tag{1}$$

where I is the $n \times n$ unity matrix. A should comprise requirements from current as well as capital intermediate demand of domestically produced and imported commodities. The $f \times 1$ *factor inventory* F of a given functional unit represented by a $n \times 1$ commodity inputs vector y is then simply

$$F = M\, y. \tag{2}$$

An introduction into the IO-method and its application to environmental problems can be found in papers by Leontief and Ford (1970) and Proops (1977).

4.4 UNCERTAINTIES IN INPUT-OUTPUT-BASED LCI

While being able to cover an infinite number of production stages in an elegant way, input-output analysis suffers from potential uncertainties arising from the following sources: (1) uncertainties of basic source data due to sampling and reporting errors, and uncertainties resulting from (2) the assumption made in single-region IO-models, that foreign industries producing competing imports exhibit the same factor inputs as domestic industries, (3) the assumption that foreign industries are perfectly homogeneous, (4) the assumption of proportionality between monetary and physical flow, (5) the aggregation of IO-data over different producers, and (6) the aggregation of IO-data over different products supplied by one industry. The calculation of all components is described for the case of Australian energy multipliers in the following sub-sections.

4.4.1 Source data uncertainty

Standard errors for monetary values in all basic Australian IO-tables can be calculated from performance data collected by the Australian Bureau of Statistics (ABS 1995), while those for energy data have to be obtained from informed judgment. Figure 4-5 shows for the example of performance data that standard errors decrease with increasing magnitude of the data item. This is because generally, large data values are obtained from a summation over a large number of survey data, and because the uncertainty Δs of a sum s of n summands s_i with stochastic uncertainties Δs_i decreases approximately with $\sqrt{n}$:

$$\frac{\Delta s}{s} = \frac{\sqrt{\sum_{i=1}^{n} \Delta s_i^2}}{\sum_{i=1}^{n} s_i} \approx \frac{\sqrt{\sum_{i=1}^{n} \left(\sum_{j=1}^{n} \Delta s_j / n \right)^2}}{\sum_{i=1}^{n} s_i} = \frac{1}{\sqrt{n}} \frac{\sum_{j=1}^{n} \Delta s_j}{\sum_{i=1}^{n} s_i} = \frac{1}{\sqrt{n}} \frac{\overline{\Delta s}}{\bar{s}}, \tag{3}$$

where $\overline{\Delta s}$ and $\bar{s}$ are arithmetic means over $\{\Delta s_j\}_{j=1,\ldots,n}$ and $\{s_i\}_{i=1,\ldots,n}$, respectively.

4.4.2 Imports assumptions uncertainty

In single-region IO-models, it is commonly assumed that foreign industries supplying imports for the domestic market have factor intensities, which are identical to those of domestic industries. The output of the motor vehicles industry, for example, consists partly of assembly work undertaken in Australia, while imports consist only of vehicles and vehicle parts. The energy multiplier of assembly work is likely to be about 4 MJ/A$, while the energy multiplier of producing vehicles and parts is probably higher at around 12 MJ/A$. Thus, by assuming equal energy multipliers for foreign and domestic motor vehicle industries, the energy embodied in motor vehicle imports is, in this case, underestimated. However, since information on factor inputs of Australian imports is not readily available, a worst-case standard error of 50% was used for all entries in the imports table.

Due to a lack of available information, it must be assumed that foreign industries are perfectly homogeneous, that is, that they produce only one (the primary) commodity type. In Australian IO-tables, secondary products usually represent less than 5% of each industry's total output. Hence, assuming that foreign industries have a similar structure with regard to joint production, the assumption of perfect homogeneity for foreign industries introduces an uncertainty of that magnitude into entries in the imports table. This uncertainty is negligible compared to the uncertainty arising from the assumption of equal factor inputs for imported and domestically produced commodities.

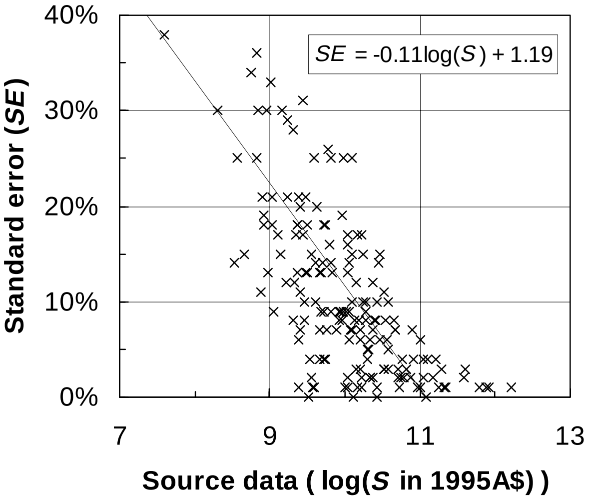

Figure 4-5: Standard errors of performance data (after ABS 1995).

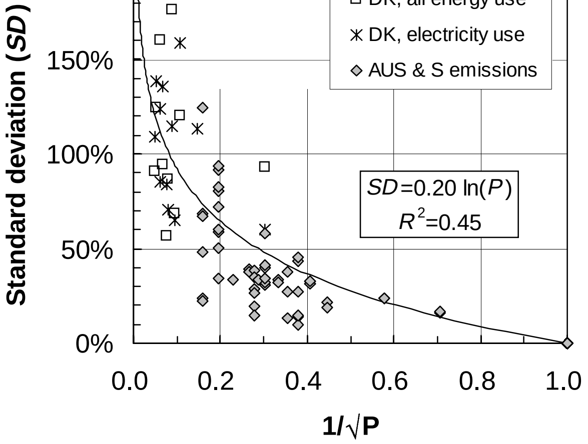

Figure 4-6: Regression of standard deviations of energy and emissions intensities.

4.4.3 Proportionality assumption uncertainty

Using monetary IO-tables for the calculation of multipliers of physical quantities implies that the physical flow of commodities between industries can be represented by the monetary values of the corresponding inter-industrial transactions. For example, the content of 100 A$ of electricity supplied to aluminium smelters is assumed to be equal to the energy in 100 A$ of electricity supplied to travel agencies. However, electricity prices vary considerably amongst industries, thus violating the proportionality assumption. The associated uncertainty can in principle be overcome by replacing monetary entries in all basic IO-tables with entries in physical units. This cannot be achieved for most of the industries classified in the Australian IO-tables, partly because physical data is unavailable, and partly because many industries are too heterogeneous with regard to their product range. In this work, monetary entries could be replaced by entries in physical units only for coal, oil and gas mining, petroleum refining, electricity, gas and water supply, resulting in *mixed-units* tables (A $ for monetary flow, MJ for energy industries, and L for water supply).

4.4.4 Aggregation uncertainty

Input-output and factor data are generally aggregated over a number of producers within one industry. The fact that the number and identity of producers involved in a particular inter-industrial transaction is generally unknown leads to uncertainties in factor multipliers. In general, this uncertainty depends on the geographical and technological variability of production in the respective industry sector. Production scale may also influence factor multipliers, but this could not be confirmed by Hanssen and Asbjørnsen (1996), who found “only minor differences between small and large pulp and paper plants in environmental efficiency”.

Consider the case of energy as a factor to be analysed. One path contributing to the total energy multiplier of iron ore mining, for example, is the amount of energy required for the railway transport of iron ores. It is only a small portion of the monetary output of the Australian railway transport industry that is absorbed by iron ore mining, and iron ores are hauled by only a few railway freight operators. The amount of energy used by operators participating in the transport of iron ores might deviate from the average energy use of all railway freight operators, thus leading to an *aggregation uncertainty* in the energy requirement path “diesel for railway transport for iron ores”. In contrast, the supply of meat from the beef cattle industry to the meat products industry, for example, represents almost the total output of the beef cattle industry. It can therefore be concluded that almost all beef cattle farms participate in the supply to the meat products industry. Hence, although individual beef cattle farms might vary with regard to their energy use, the amount of energy required per unit of output into the meat products industry is well described by the average energy use in the beef industry, and the aggregation uncertainty is low.

In general, the aggregation uncertainty associated with a particular inter-industrial transaction A_{ij} from industry i into industry j decreases with (1) decreasing number P_i of producers in the supplying industry aggregate i, and (2) increasing number p_{ij} of producers participating in that transaction. Firstly, using energy multipliers of Danish manufacturing sectors (Danmarks Statistik 2000), energy and greenhouse gas multipliers of various Australian transport operators (Lenzen 1999), and emission data for Swedish sulfate pulp mills (Hanssen and Asbjørnsen 1996) and for Australian fossil-fuelled power plants (NGGIC 1998), a proportionality of the standard deviation of single-producer intensities to ln(P) can be established (see Fig. 4-6). Secondly, assuming that $k=1,...,p_{ij}$ producers contribute $a_{ij,k}$ to a particular inter-industrial transaction $A_{ij}=\Sigma_k\, a_{ij,k}$, the aggregation uncertainty $\Delta A_{ij}/A_{ij}$ of the transaction can be approximated as

$$\frac{\Delta A_{ij}}{A_{ij}} = \sqrt{\sum_{k=1}^{p_{ij}} \left(\frac{\Delta a_{ij,k}}{a_{ij,k}}\right)^2 \left(\frac{a_{ij,k}}{A_{ij}}\right)^2} \approx \sqrt{\sum_{k=1}^{p_{ij}} SD^2 \left(\frac{1}{p_{ij}}\right)^2} \approx \frac{SD}{\sqrt{p_{ij}}}\ , \tag{4}$$

where $\Delta a_{ij,k}/a_{ij,k}=SD$ is the relative standard deviation of the contribution $a_{ij,k}$ of all producers as regressed in Fig. 4-6. In this approximation, it is assumed that $a_{ij,k}/A_{ij}\approx 1/p_{ij}$, that is, all producers contribute about the same proportion to the transaction. Inserting for SD, the aggregation error of the transaction A_{ij} can be expressed as

$$\frac{\Delta A_{ij}}{A_{ij}} \approx \rho p_{ij}^{-1/2} \ln(P_i)\ , \tag{5}$$

with the regression constant $\rho=0.2$. In practice, the number p_{ij} of participating producers can be estimated for any transaction from the ratio of the monetary value A_{ij} of that transaction and the total inter-industrial output $\Sigma_j A_{ij}$ of the supplying industry i, via $p_{ij}\approx P_i\times A_{ij}/\Sigma_j A_{ij}$.

4.4.5 Allocation uncertainty

Entries in IO-tables represent transactions of whole industry classes, and are aggregated over the product range in the respective class. This aggregation is equivalent to assuming that each industry class is perfectly homogeneous with regard to its product range, that is, it produces only one type of commodity. This assumption clearly ignores product diversity and joint production between industries, and leads to an *allocation uncertainty* in IO-data A_{ij}, if the corresponding inter-industrial transaction involves only a few product types out of the whole output range of the supplying industry.

The Australian ship and boat manufacturing industry, for example, supplies ships and boats mainly for commercial fishing, water transport, defence, and private households. Obviously, this output is far from being homogeneous, since it comprises fishing boats, ferries, cruise liners, navy vessels, sailing boats, and aluminium dinghies. These different types of ships and boats might require different factor inputs, causing an allocation uncertainty in the output coefficients of the ships and boats manufacturing industry. In contrast, the water supply industry produces only one commodity, which is mains water, so that the allocation uncertainty for water supply is zero.

Allocation uncertainties can be estimated by comparing factor multipliers calculated using IO-models of different aggregation level. Figure 4-7 shows the relative frequency distribution $f(\Delta)$ of deviations Δ of multipliers for 43 production factors in a 132-commodity IO-model from averages over 2, 5, 10, and 100 randomly selected commodity groups. Each distribution contains about 500,000 draws. Deviations increase with increasing number of contained sub-groups, and are mostly below 50% for an aggregation of 2→1, and mostly below 100% for an aggregation of 100→1. The asymmetry of the distributions result from the fact that for most production factors, multipliers are high for a few commodities (such as coal for electricity, water for crops, and land for grazing), and low for all others.

The deviations shown in Fig. 4-7 represent a worst case, because commodities were selected randomly. In practice, aggregation is usually based on similarity of commodities. Allocation uncertainties can in principle be overcome by further disaggregation of the IO-model.

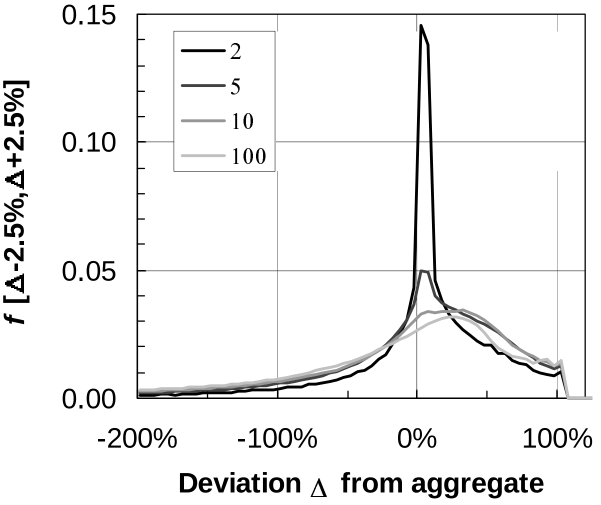

Figure 4-7: Relative frequency distribution *f*(Δ) of deviations Δ of multipliers for 43 production factors in a 132-commodity input-output model.

Table 4-1: Truncation errors of primary energy multipliers for 0th to 3rd order process analysis (PA 0-3), and total errors for input-output (IO) analysis.

Industry sector	PA 0	PA 1	PA 2	PA 3	I-O
Electricity generation and supply	17%	6%	4%	2%	7%
Gas production and distribution	33%	27%	20%	14%	7%
Air and space transport	39%	27%	20%	14%	8%
Bus and tramway transport	47%	36%	27%	19%	10%
Bricks and other ceramic products	49%	24%	14%	9%	12%
Petrol refining, iron and steel, concrete	55%	30%	20%	13%	16%
Basic chemicals	59%	29%	16%	9%	32%
Glass and glass products	63%	38%	24%	15%	15%
Crude oil extraction	75%	57%	41%	28%	13%
Wheat growing	86%	68%	48%	32%	18%
Coal mining	87%	49%	33%	23%	24%
Newspapers and books	89%	70%	45%	28%	23%
Health care	89%	68%	50%	35%	17%
Food products	89%	70%	51%	35%	20%
Hospitality, personal services	93%	71%	52%	36%	16%
Communication, education	96%	73%	54%	37%	18%
Banking and insurance	100%	85%	66%	47%	17%

4.4.6 Total uncertainty

The overall uncertainty of factor multipliers is calculated in two steps. Firstly, the total relative standard error $\delta R_{ij}=\Delta R_{ij}/R_{ij}$ of input-output coefficients R_{ij} is calculated from relative standard errors $\delta R_{ij,comp}$ of components described in the previous sub-sections via

$$\delta R_{ij} = \sqrt{\delta R_{ij,source}^{\;2} + \delta R_{ij,imports}^{\;2} + \delta R_{ij,prop}^{\;2} + \delta R_{ij,aggreg}^{\;2} + \delta R_{ij,alloc}^{\;2}}\ . \tag{6}$$

Note that the proportionality error could not be quantified in this study due to a lack of price data. The subsequent estimation of standard errors of multipliers is not so straightforward, because standard errors of the *Leontief inverse* $(1\text{-A})^{-1}$ in Equation (1) cannot be calculated analytically, but by using a Monte-Carlo technique to simulate the propagation of uncertainties (see Bullard and Sebald 1988). Following early work by Quandt (1959), it is assumed that errors in the elements of Q and A are normally distributed. Such errors can be simulated by generating two matrices δQ and δA, which contain random, normally distributed perturbations of Q and A, with zero mean and standard errors $\{\delta A_j\}_{i,j=1,\ldots,n}$ as in Equation (6). The uncertainty δM of a multiplier M resulting from a single perturbation is then

$$\delta M = (Q+\delta Q)\ [I-(A+\delta A)]^{-1} - M\,. \tag{7}$$

While relative standard errors δA_{ij} of IO-data A_{ij} range mostly between 20% and 80%, the relative standard errors of the IO-based energy multipliers are much smaller at about 10-20% (see Tab. 4-1). This can be explained as follows:

considering that $(I-A)^{-1}=I+A+A^2+A^3+...$, the calculation of multipliers involves numerous additions of coefficients A_{ij}, so that the corresponding relative errors δA_{ij} cancel out due to their stochastic nature. This feature is particularly helpful in IO-based LCAs of functional units with many components (for example an overseas holiday, or a residential dwelling), because the inventory uncertainty decreases with the number of components comprised in the inventory (travel agent service, air travel, accommodation, food, entertainment, or bricks, glass, concrete, structural metal, furniture, appliances, etc). Such reductions do not apply to the systematic truncation errors inherent in process analyses. While for energy supply, transport, and upstream manufacturing, IOA ranks between second and third order process analysis in terms of uncertainty, it is preferable to third order process analysis for raw materials extraction, downstream manufacturing, and services.

4.5 CONCLUSIONS

Conventional (SETAC) life-cycle assessments suffer from an irreducible, systematic error caused by the truncation of the production system boundary. This truncation error is case-dependent, but can be in the order of 50%, which can render results and conclusions of conventional life-cycle assessments unreliable or even invalid. Truncation errors can be avoided by employing a hybrid assessment method, which combines process and IOA. IOA in turn suffers from various errors, which can be estimated using Monte-Carlo simulations.

4.6 ACKNOWLEDGEMENTS

Thomas Bue Bjørner, AKF, København, calculated statistics for direct energy intensities of Danish manufacturing sectors at company level, shown in Fig. 4-6.

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5 Introduction to IOA

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National statistics monitor trade between different industry sectors. Such data can be used for a variety of analyses. In this chapter the basic definitions of Input/Output Analysis (IOA) are described.

5.1 WHAT IS AN INPUT/OUTPUT-TABLE?

An IO-table gives an overview of the trade in a national economy. It shows how products are being sold from producers to either be used by final consumers or to contribute to further production in other industry sectors. The buyers and suppliers on the market are grouped in production sectors and sectors for final use. The number of sectors and their definition vary from country to country.

Table 5-1: The R-matrix. A simplified input-output table for Denmark, 1975 (Lihn Jørgensen, 1982). All figures in $1*10^9$ DKK.

	To :	Input to production sectors						Final Use				Total
Supplied from:		Agriculture	Industry	Building	Trade	Private services	Public services	Private consumption	Public consumption	Gross-investments	Exports	
Domestic prod.	Agriculture	3,0	15,7	0,4	0,0	0,1	0,2	2,1	-	-0,6	3,1	24,0
	Industry	3,5	24,2	8,9	1,8	4,8	3,1	25,5	-	4,5	41,4	117,7
	Building	0,4	0,8	0,0	0,8	4,3	1,9	-	-	26,9	-	35,1
	Trade	1,5	3,9	1,8	0,4	1,7	1,0	20,2	-	2,2	4,9	37,6
	Private services	1,2	5,7	3,4	4,0	8,5	7,0	40,1	-	0,7	8,9	79,5
	Public services	0,0	0,2	0,0	0,1	0,3	0,1	2,1	53,2	-	0,0	56,0
Import	Agriculture	0,3	6,4	0,0	0,0	0,1	0,1	0,9	-	0,4	0,5	8,7
	Industry	2,8	18,8	4,0	0,7	2,6	1,9	10,7	-	7,7	2,4	51,6
	Building	-	-	-	-	-	-	-	-	-	-	-
	Trade	-	-	-	-	-	-	0,0	-	0,0	0,0	0,0
	Private services	0,0	0,0	0,0	0,0	0,1	0,0	0,0	-	0,0	0,0	0,1
	Public services	-	-	-	-	-	-	-	-	-	-	-
	Other import	0,2	0,1	0,0	0,0	2,5	0,2	- 1,5	-	0,1	5,2	6,8
Primary Factors	Indirect taxes	0,1	0,1	0,2	1,0	1,7	1,9	19,8	-	3,2	- 1,5	26,5
	Wages	2,1	29,9	10,3	16,2	24,2	37,2	-	-	-	-	119,9
	Other factorincome	8,9	11,9	6,1	12,6	28,6	1,4	-	-	-	-	69,5
Total		24,0	117,7	35,1	37,6	79,5	56,0	119,9	53,2	45,1	64,9	

Table 5-1 shows a simplified version of the IO-table for Denmark in 1975. Such a set of data is also called a matrix of requirements, in short the R-matrix. In the rows the total sales from each supply sector can be seen. The supply sectors are divided into a number of domestic production sectors, foreign production sectors (import) and primary production factors.

In the columns the input to the demand sectors is seen. The demand sectors are divided into domestic production sectors and different categories of final use. The domestic production sectors are identical to those found on the supply side. The categories of final use are consumption by private or public bodies, gross investments (investments minus depreciation) and export. Trade includes the profit earned by the industries. That is the reason why buying and selling prices adds up to the same value.

From Table 5-1 can be seen that Danish agriculture in 1975 sold goods worth 24 billion DKK in total. The majority of these goods were bought by Danish industry, that purchased an amount worth 15.7 billion DKK. 3.0 billion DKK of the remaining sales were purchased by Danish colleagues within the agricultural sector, and products worth 3.1 billion DKK were exported.

To simplify further calculations, the R-matrix can be normalised, thus showing how the average DKK sold from each sector is distributed. The normalised matrix is called an A-matrix. Table 5-2 shows an example in which we have grouped the sectors further, into just two separate sectors: agriculture and industry (based on the same data as Table 5-1).

Table 5-2: The A-matrix. IO-coefficients.

From/to (DKK/DKK)	Agriculture	Industry	Others
Agriculture	0,13	0,11	0,01
Industry	0,16	0,22	0,25
Others	0,71	0,67	0,74
Sum	1,00	1,00	1,00

The A-matrix shows the input to each sector as a percentage of the total input. For example, it is seen from Table 5-2 that for each DKK spent by the industry sector, 0,11 DKK is spent on agricultural products, 0,67 DKK is spent on imported goods and wages, and the remaining 0,22 DKK remains within the sector, i.e. purchases from other producers within the industry.

IO-data in the form of A or R-matrices can be used to assess impacts from changes in production on e.g. environment or employment if the input of the relevant factors to the different production sectors are known. Such factor input can be presented in a Q-matrix as shown in Table 5-3.

Table 5-3: The Q-matrix. Direct input of factors (f) to production sectors (n). The figures shown are presented as an example only (not real data).

N / F	Energy (J/DKK)	Labour (hours/DKK)	Emissions (mg/DKK)	.....
Agriculture	3	-	-	.....
Industry	107	-	-	.....

Table 5-3 shows the relationship between the production and the factor input to one sector. The inputs may be use of labour, energy, or resources, but data on release of emissions may also be entered in this way.

5.2 BEYOND THE SIMPLE MATRICES

However, the data presented in section 5.1 only show the effects in the first stage in an infinite cascade of productions. Production in one sector is based on inputs produced in all sectors. But the production of these inputs is based on inputs from all sectors. And these inputs again are based on inputs from all sectors, and so forth.

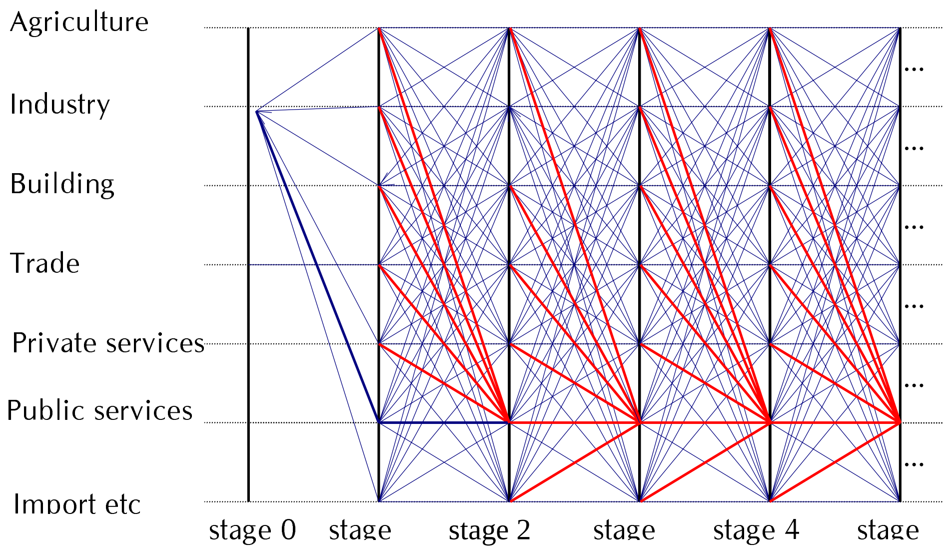

Figure 5-1: The direct demand for an industry product and the related, indirect demands for inputs from all sectors. Figure based on Treloar (1998).

5.3 EXAMPLE: HOW MUCH ENERGY DOES IT TAKE TO PRODUCE A PRODUCT WORTH 1 DKK BY DANISH INDUSTRY?

In this section a calculation is carried through to serve as illustration of the difference between the direct and indirect effects discussed above. In this example we try to answer the question: *how much energy is used, directly and indirectly, when a product worth 1 DKK is produced by Danish industry?*

In this example we stay in the two-sector economy as presented in Table 5-2 and Table 5-3. The total energy consumption can be calculated in two different ways, either by an approximation of an infinite number of additions or by means of matrix-calculation.

5.3.1 The easy math solution

The accumulated result, M, can be calculated as the sum of the energy consumptions in each stage of production:

$M = Q + Q_1 + Q_2 + Q_3 \ldots + Q_\infty$

Q is the direct energy consumption by industry. From Table 5-3 follows that Q is 107 J.

Q1 is the energy consumption to produce inputs at stage 1. The inputs come from either agriculture or industry. Table 5-2 shows that it takes 0,11 DKK of input from agriculture and 0,22 DKK of input from industry to produce the industry product.

Table 5-3 shows how much energy has been used to produce the inputs in agriculture respectively industry. Therefore Q_1 can be calculated:

$Q_1 \quad = \quad 0{,}22*107 + 0{,}11*3 = 23{,}87$

Q_2 is the energy consumption to produce inputs at stage 2. There are four paths for the inputs. Using data from the A and Q-matrix as above, Q_2 can be calculated:

$Q_2 \quad = \quad 0{,}22^2*107 + 0{,}22*0{,}11*3 + 0{,}11*0{,}13*3 + 0{,}11*0{,}16*107 = 7{,}18$

Q_3 is the energy consumption to produce inputs at stage 3. There are eight paths for the inputs. Q_3 can be calculated:

$Q_3 \quad = \quad 0{,}22^3*107 + 0{,}22^2*0{,}11*3 + 0{,}11*0{,}13*0{,}16*107 + 0{,}11*0{,}16*0{,}22*107 + 0{,}22*0{,}11*0{,}13*3 + 0{,}11*0{,}13*0{,}16*107 + 0{,}11*0{,}13*0{,}13*3 + 0{,}11*0{,}16*0{,}13*3 = 2{,}08$

If a high level of accuracy is needed, the calculation can be continued to Q_4, Q_5 and further. For this example, we will end here:

$M \quad \approx \quad 150$

5.3.2 The matrix calculation

Basic mathematics teaches us that the infinite sum presented in section 5.3.1 can be calculated as a finite calculation by use of matrix calculation.

$M = Q + Q_1 + Q_2 + Q_{3\,\ldots.} + Q_\infty \;\Leftrightarrow\; M = Q\,(1\text{-}A)^{-1}$

Following the basic rules of matrix calculation, we obtain:

$$M = Q * (1 - A)^{-1}$$

$$M = \begin{pmatrix} 3 \\ 107 \end{pmatrix} * \left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} 0{,}13 & 0{,}11 \\ 0{,}16 & 0{,}22 \end{pmatrix}\right]^{-1} \Leftrightarrow$$

$$M = \begin{pmatrix} 3 \\ 107 \end{pmatrix} * \begin{bmatrix} 0{,}87 & -0{,}11 \\ -0{,}16 & 0{,}78 \end{bmatrix}^{-1} \Leftrightarrow$$

$$M = \begin{pmatrix} 21{,}7 \\ 142{,}0 \end{pmatrix}$$

The above calculation shows the precise answer to our question: When Danish industry produces a product worth 1 DKK, agriculture will use 21,7 J and industry itself 142 J.

5.4 REFERENCES

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6 Applications of IO-Models for LCA: Some experiences from the energy area

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6.1 ABSTRACT.

Founded in the life cycle approach, this paper aims at giving a brief overview of two applications of integrated Input-Output Analysis (IOA) in the energy area. First, a study on energy and CO_2 embodied in household consumption. Second, a study on transport energy and CO_2 embodied in food. Besides presenting design of analysis, modelling, data sources and results, the paper highlights some of the shortcomings and benefits of using IO-modelling for Life Cycle Assessment (LCA). Although lacking “specificness” we conclude that IOA is very operational and might result in studies of high relevance.

6.2 INTRODUCTION

IOA is a tool of high relevance for LCA-studies, since it takes into account all production inputs of infinite order caused by the demand for a specific good. Using integrated IO-models make it possible to investigate the linkage between consumption, production, energy use and environmental effects.

In this paper we show how IO-modelling has been used for LCA oriented studies focusing on energy and CO_2 embodied in goods consumed by households. Two applications (cases) are described: *First*, a study in which the total CO_2 impact from Danish household consumption is analysed, (Munksgaard et al. 2000a,b; 1999, 1998 and Wier et al. 2000). Energy and CO_2 embodied in 72 commodities are analysed and the influence from different causes influencing CO_2 emissions over time are analysed. *Second*, an ongoing study on transport energy and CO_2 embodied in different food products. This study is a preproject (phase 1) aiming at developing a methodology that can be used in a fullscale project.

The outline of the paper is as follows: In Section 6.3 the design of analysis applied in the two studies is described. In Section 6.4 the basic IO-model is documented. The kind of data used for the two studies are described in Section 6.5. Some results of the studies are presented in Section 6.6. Section 6.7 is highlighting shortcomings and benefits of the model approaches applied. Finally, some concluding remarks are given in Section 6.8.

6.3 DESIGN OF ANALYSIS

The design of analysis applied in the two studies is illustrated in Figure 6-1 and Figure 6-2 respectively.

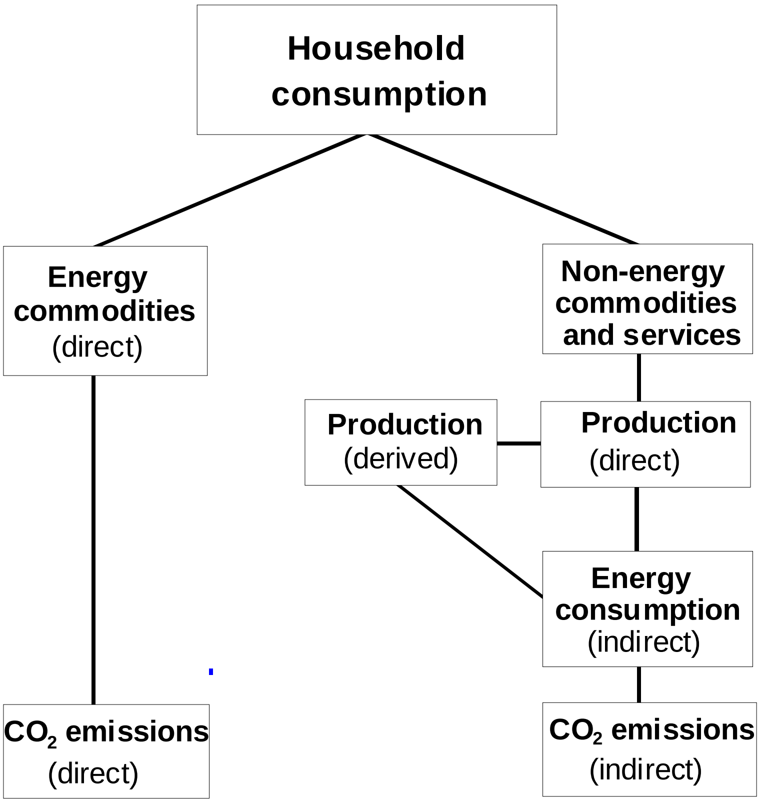

Figure 6-1: Energy and CO_2 in household consumption: design of analysis

In Figure 6-1 there is a distinction between energy and non-energy commodities and services. In analysing the energy and CO_2 impact of Danish household consumption, we make a distinction between direct and indirect energy consumption. *Direct* energy consumption is energy used directly by households (i.e. for heating, lightning and gasoline in private cars). *Indirect* energy consumption is energy embodied in goods and services consumed by households. This kind of energy is actually used by the industries producing the goods and services used by households. CO_2 emissions from direct energy use is simply estimated by multiplying CO_2 emission coefficients by energy use in physical terms. Emissions from indirect energy use is calculated by using an integrated IO-model, cf. model (1) in Section 6.4.

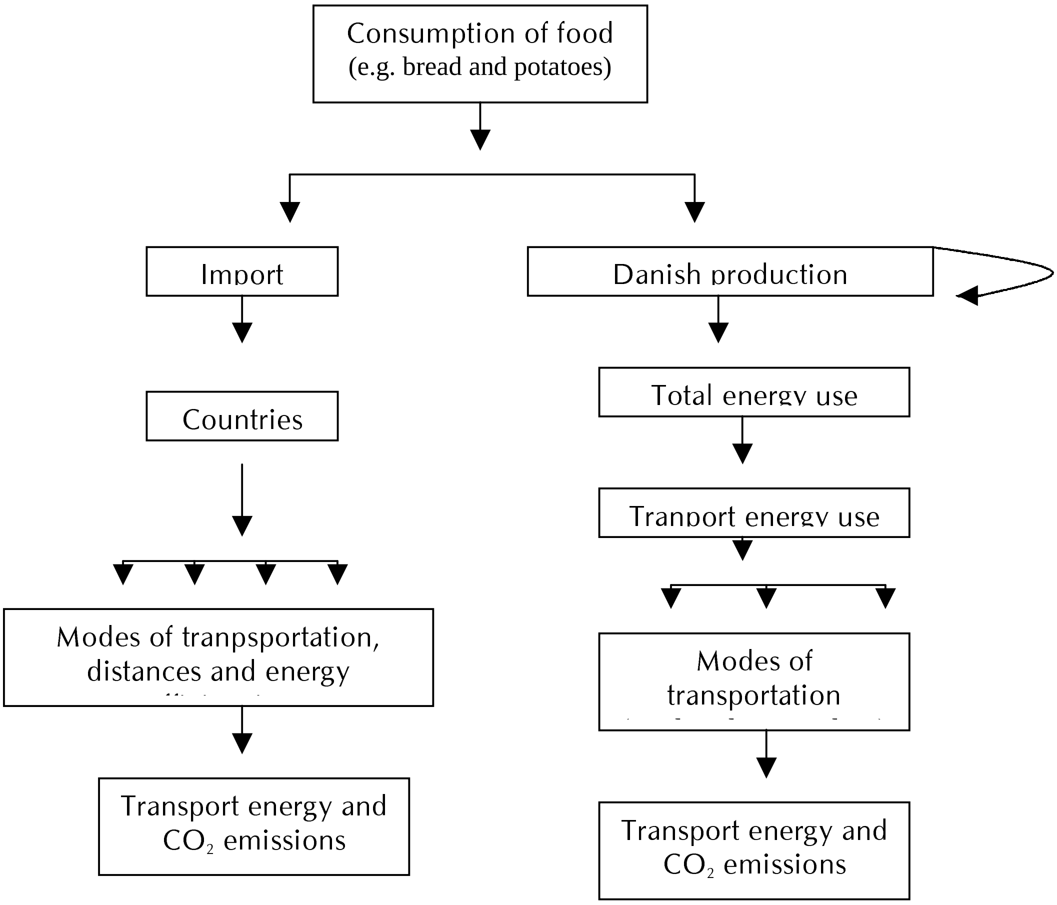

Figure 6-2: Transport embodied in food: design of analysis

The design of analysis applied for the study on "transport embodied in foods" is somewhat different as shown in Figure 6-2. As international transport is of special interest in this study, we apply a hybrid modelling approach in which we distinguish between Danish and foreign transportation and production technologies. Foods and inputs produced in Denmark are analysed by using an IO-approach only, whereas foods and inputs imported to Denmark are analysed by using process analysis including data on importing countries, travel distance, transport mode and energy efficiency.

6.4 IO-MODELLING

The basic model applied in the two studies is an extended IO-model based on Danish IO-tables plus energy flow matrices and CO_2 emission factors. These can be linked together due to the use of common classifications. The strength of the model is that it covers all sectors of the economy and operates at a very disaggregated level. Moreover, it covers the entire energy production and consumption cycle, and is able to distinguish between direct and indirect (embodied) uses of energy.

In the household consumption study, we focus on total energy use and CO_2 emissions associated with Danish household consumption, distinguishing between direct and indirect emissions. The *direct emissions* are emissions associated with the consumption of energy commodities in the households, i.e. electricity, district heating, gas and other liquids. The *indirect emissions* (embodied emissions) are emissions associated with the production of all other commodities for households, i.e. emissions that takes place in the industry producing furniture, food, clothes, services etc. used in households.

Model (1) below estimates the indirect CO_2 emissions from household consumption by using the extended IO-model as introduced by Leontief and Ford (1972).

$$E_p = F\ (M_p \# R_p)\ (I-A)^{-1}\ C\ c\ c^N \qquad (1)$$

where

E_p denotes total indirect CO_2 emissions from the production of goods for household consumption
F is CO_2 emissions per unit of energy consumption
M_p is the fuel mix in the production sectors
R_p is energy intensities, i.e. total energy consumption per unit of production
$(I-A)^{-1}$ is the Leontief inverse matrix
C is the composition of consumption commodity aggregates, i.e. 72 private consumption commodity aggregates apportioned by production sectors
c is commodity mix in private consumption, i.e. demand for 72 commodities per unit of total consumption, and
c^N denotes total private consumption.

The analyses made in the study on household consumption is based on model (1) whereas the study on embodied transport in food will be based on a further development of the model, e.g. including industry investments, foreign production technologies and a bottom-up approach to international transport.

As a first step we have developed the model (1) by introducing a matrix (*R*) defining which energy types are used for transport (road, rail, sea and air):

$$E_p = F\ (R^t \#\ (M_p \# R_p)\ (I-A)^{-1}\ C\ c\ c^N \qquad (2)$$

The direct energy used for transporting imported goods to Denmark is computed by process analysis according to model (3):

$$En_t^i = I^j \# v \# d^i{}_t \# m^i{}_t \# e_t \qquad (3)$$

where

En_t^j denotes energy used for transporting the goods from country *j* to Denmark by transportation mode *t*
I^i is the value of goods imported from country *j*
v is the weight of the goods in tonnes pr unit value
d_t^i is distance in km from country *j* to Denmark depending on transportation mode *t*
m_t^i is the share of good *i* transported by transportation mode *t*
e_t is specific energy use pr tonne-km (energy efficiency) depending on mode of transportation *t.*

6.5 DATA SOURCES

IO-modelling is founded in IO-tables supplied by national statistical bureaus, e.g. Statistics Denmark. These tables are detailed annual accounts including the economic flows from production to final demand (end use). Danish energy balances corresponding to the IO-tables are available, making it possible to develop integrated IO-models including the linkage between economic activity and energy use in physical terms. Thereby it is also possible to link emissions of e.g. CO_2 to economic activity.

Other kind of national data sources have been applied in our studies, e.g. national consumer surveys and foreign trade statistics. An overview of some data types used in the studies is given in Table 6-1 below.

Table 6-1: Economic, energy and emission data. Sources: E.g. Statistics Denmark, EU, Risø/DMU.

Data on:	Details:	Unit:
Production structure	130 x 130 industries	DKK
Household consumption	72 commodities	DKK
Consumer survey	1.334 commodities	DKK
Investments	10 categories	DKK
Foreign trade	2.900 commodities	DKK/tons
Energy intensities	130 industries	DKK/GJ
Energy mix	40 energy types	DKK/GJ
Emissions	CO_2, SO_2 and NO_x	tons/GJ

In the study on “transport embodied in food” energy used for international transport of goods from foreign countries to Denmark is estimated by the use of specific data on transport. These data includes data on:

- Import in tons on country basis
- Transport mode on country basis: road, rail, sea and air
- Energy efficiency (GJ per ton-km)
- Kind of transport energy used
- Distance (depending on transport mode).

6.6 RESULTS

Some results based on the models presented in Section 6.4 are shown in the tables below. Table 6-2 shows total CO_2 emissions in 1966 and 1992 from private consumption divided on eight commodity groups.

Table 6-2: CO_2 emissions in 1966 and 1992 by commodity groups. All figures in million tonnes CO_2. * Includes vehicles and public transport services.

Commodity group	1966	1992	Change in emissions
Foods	5,5	5,5	1%
Beverages and tobacco	0,8	1,0	25%
Clothing	2,3	1,6	-30%
Household appliances (and operation)	3,2	2,8	-10%
Health	0,6	0,7	18%
Recreation and entertainment	2,4	3,9	59%
Services	0,3	1,1	234%
Transport*	2,0	3,0	54%

Since 1966, CO_2 emissions associated with the consumption of clothing and household appliances (incl. operation) decreased by 30% and 10% respectively. Emissions associated with consumption of the remaining commodities increased in some cases significantly. Thus, emissions from consumption of services (mail and telecommunication, law and financial services, private teaching and day-care) have increased by 234%, while emissions from consumption of recreation increased by 59% and emissions from transportation (vehicles and purchased transport services) increased by 54%.

Policies directed towards household consumption of commodities other than energy offer considerable potential for reducing CO_2 emissions. As the differences in CO_2 intensities for various goods are significant, changes in commodity mix towards less CO_2 intensive goods could be of significant importance. Table 6-3 illustrates the large variation in CO_2 intensity listing the five commodities with the highest and the lowest CO_2 intensity in 1966 and 1992.

Table 6-3: Commodities with the highest and lowest CO_2 intensity (kg/DKK)

Highest/lowest	1966		1992	
Top 5	Fruit and vegetables Sport/camping equipment Sugar Wine and liquor Margarine etc.	0,38 0,33 0,30 0,30 0,28	Transport Margarine etc. Other foods Fruit and vegetables Sugar	0,30 0,22 0,22 0,21 0,20
Bottom 5	Life insurance etc. Health insurance Housing Private organisations Domestic servants	0,05 0,05 0,04 0,03 0,00	Education Medical care Housing Private organisations Domestic servants	0,06 0,05 0,03 0,03 0,02

In 1992 the most CO_2 intensive commodity is transport. Second came margarine etc. followed by various food products. The five commodities with the lowest CO_2

intensities are various types of services. This implies that greater demand for services together with reduced consumption of commodities such as transport, foods and beverages will be accompanied by major decreases in CO_2 emissions. The reduction potential of altering the commodity mix suggests policies directed towards this end.

Now we turn to the study on transport embodied in foods and show some preliminary results for two cases considered: bread and potatoes. The results are based on the assumptions that the imported goods are produced by using the same technology as used for similar goods produced in Denmark (the process energy use is computed according to model 1), the Danish direct and indirect transportation energy is calculated according to model 2, and energy used for international transportation is calculated according to model 3.

In Table 6-4, energy and CO_2 embodied in annual household consumption of bread and potatoes are shown. A distinction is made between energy used for production only (process energy) and energy used for transportation. Also, a distinction is made between Danish and foreign activity (import).

Table 6-4: Energy and CO_2 embodied in bread and potatoes (per year)

	PROCESS USE			TRANSPORT		
Energy in TJ	Danish	Imported	Total	Danish	Imported	Total
Potatoes	394	287	681	83	88	171
Bread	1357	847	2399	196	49	295
CO_2 in tonnes						
Potatoes	34	23	57	6,1	6,5	13
Bread	106	62	168	14	3,7	18

It is interesting that the two cases are very different with regard to the composition of Danish and international transport energy and CO_2. International transport energy for potatoes is higher than total Danish transport energy use and in total transport amount to as much as 20% of the total energy used for production of potatoes. With regard to bread, energy used for Danish transport is four times the amount of energy used for international transport. Comparing total transport and process energy use, it is interesting that total transport amount only to 12% of the total energy used for production of bread.

In Table 6-5, mode of transportation is shown for the cases of bread and potatoes and for the aggregated commodity groups of relevance: “Bread and cereals” and “potatoes”. Most of the transport energy is due to road transport. Almost all potatoes imported to Denmark are transported by road. Comparing bread and potatoes, it is interesting that 20% of bread imported to Denmark is transported by ship, whereas this is true for only 1% of potatoes imported to Denmark.

The high figures for domestic air transport might be due to data problems. The figures might include transport energy from passenger transport as well.

Table 6-5: Transportation energy split on mode of transportation (%)

	Road	Sea	Rail	Air
	Danish transportation profile			
Bread and cereals (aggr.)	83	3	2	12
Potatoes (aggregated)	81	3	2	14
	International transportation profile			
Bread (case)	80	20	0,7	*
Potatoes (case)	99	1	0,5	*
	Aggregated transportation profile when import is transported different from Danish goods			
Bread (case)	82	6	2	10
Potatoes (case)	86	6	1	6

6.7 SHORTCOMINGS AND BENEFITS

From the point of view of life cycle assessment the studies considered in this paper have some shortcomings and benefits. These are summarised briefly below.

The study on “household consumption”:
Shortcomings:

- *No investments included.* It can be argued that a life cycle assessment has to include investments in industries in order to maintain production capacity. This aspect is not included in our study.
- *Import treated as Danish production.* We apply the standard assumption often used in IOA, that imported commodities has been produced in the same way as similar Danish commodities. However, this assumption is not necessarely valid.

Benefits:

- *All commodities included.* The study includes all kind of commodities used in households. The level of aggregation used is 72 commodity groups.
- *All infinite effects.* As an IO-methodology is used all induced production effects of infinite order are included in the assessment
- *Only energy and CO_2.* The study is only investigating energy use and CO_2 emissions. Therefore, other kinds of effects are not taken into account. In this way it becomes easier to compare the results for different kind of commodities.

The study on “embodied transport in food”:
Shortcomings:

- *Double counting.* There is risk of double counting in trying to distinguish between domestic and foreign transport energy use. The problem is that Danish energy balances include energy sold in Denmark, i.e. also energy bought by foreigners.
- *Foreign data structure different.* Data structure (e.g. classifications and aggregation levels) in foreign IO- and energy statistics might be different from that used in Denmark.

Benefits:

- *Foreign production technologies.* Data on foreign technologies will be included (i.e. data on production structure and industrial energy use)

- Investments included. To make the life cycle more complete, investments done in industries in order to maintain production capacity will be considered.

6.8 CONCLUSION

Based on our experiences of using IOA in studies on the embodiment of energy and CO_2 in different consumer goods we have the opinion that lack of “specificness” can restrict the use of IOA. However, the methodology has proved to be very operational, data is easily available and of high quality and the studies made are of relevance from a practical as well as a scientific point of view. At present, the challenge is to include information on foreign production technologies in IO-modelling in order to produce better estimates of global effects of domestic consumption. That is of special relevance for open economies like Denmark, having a significant trade with other countries.

6.9 ACKNOWLEDGEMENTS

This paper is part of a research project “Transportation embodied in foods - a preproject” financed by the Danish Board of Transport (Transportrådet).

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7 NAMEAs and Physical IO-Tables for Denmark

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In relation to physical flows of resources, residuals, and products two types of accounting frameworks can be distinguished: National accounting matrices including environmental accounts (NAMEA) and physical input-output tables (PIOT). The two frameworks are connected, but differ with respect to detail and extent.

7.1 NAMEA

A NAMEA is a so-called satellite account related to the traditional national accounts. This means that the starting point is a matrix representation of parts of the national accounts. In the Danish NAMEA this starting point is the Danish monetary IO-tables, which show, among other things, the value of products supplied from one industry to another as well as the value of products supplied from industries to final demand (i.e. private and government consumption, gross fixed capital formation, exports, etc.). The classification used in the Danish IO-tables includes 130 industries.

The main idea in the NAMEA is to supplement the economic information (NAM) with accounts on resource and environment related aspects (EA), which follows the same classifications and definitions as used in the national accounts. This way, it is possible to analyse the information on resources and environment in relation to the economic information.

The Danish environmental accounts included in the NAMEA deals with the use of 40 types of energy (in various physical units as well as DKK), the reserves of natural gas and oil in the North Sea (physical units), emissions to air of eight types of substances, and transboundary flows of these substances to and from Denmark.

NAMEAs including these accounts are published on a yearly basis from Statistics Denmark. Under development are accounts for water extraction, water use, the value of reserves of natural gas and oil in the North Sea as well as accounts for environment related taxes and subsidies.

The structure of the basic flow accounts in the Danish NAMEA is shown in Figure 7-1. The figure illustrates how the same classifications are used throughout the different accounts and how the IO-table has a central role to play in the system.

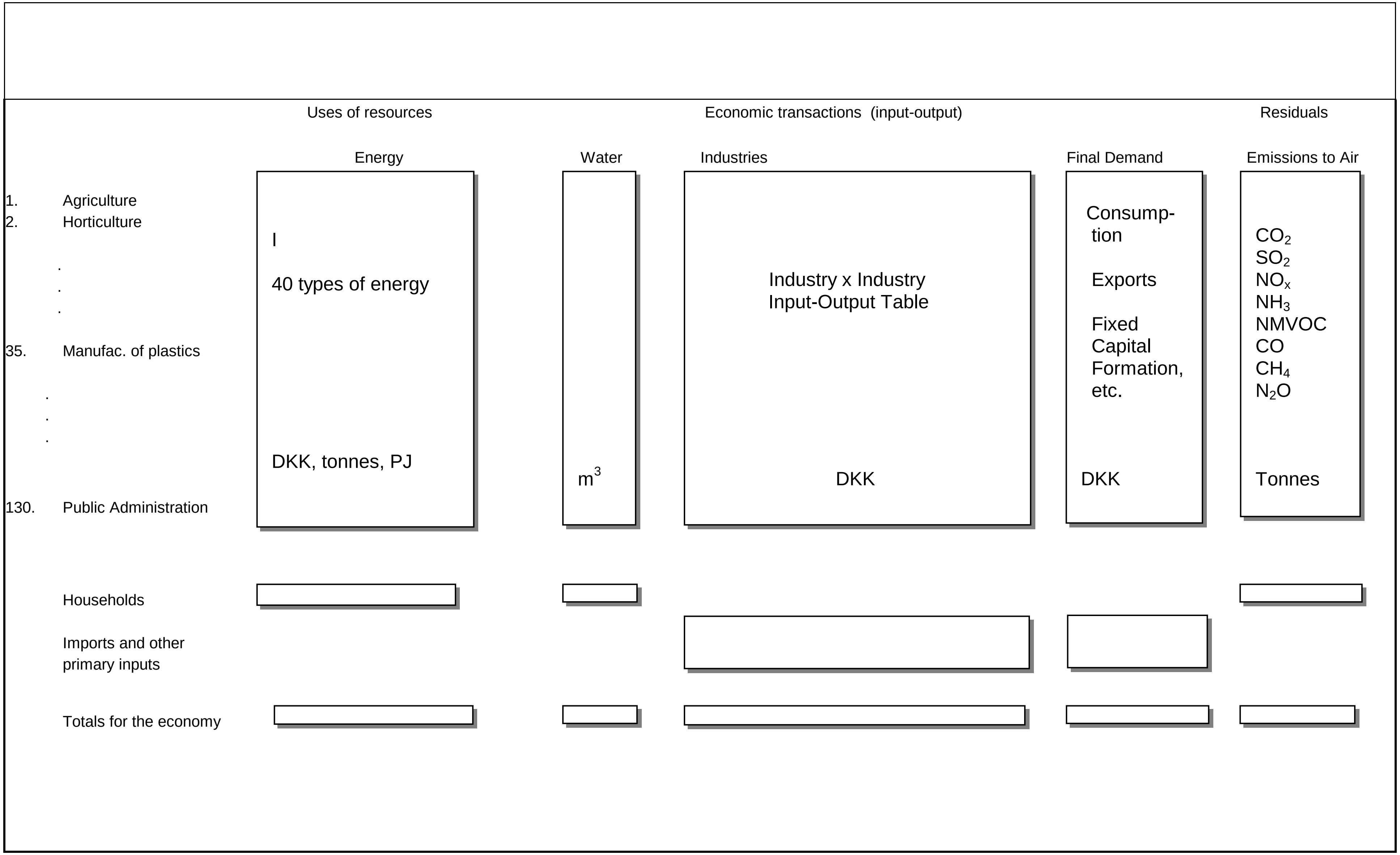

Figure 7-1: Some basic Danish NAMEA matrices.

Table 7-1, Table 7-2 and Table 7-3 give examples of the actual information included in the system in relation to energy, water and emissions to air.

Table 7-1 shows the industries' and households' use of energy. As mentioned, the system operates with 130 industries at the most detailed level. For the purpose of presentation here, these have been aggregated to 8 main groups of industries. Likewise, the 40 different types of energy have been aggregated to three types in the table. The energy use shown is actual energy use. This means that there is some redundancy double counting in the sense that both primary energy (coal, natural gas, fuel oil, etc.) and converted energy (electricity, district heating, etc.) are included. The actual energy use is a good starting point for the estimation of emissions related to the energy use (included in Table 7-3 below). However, in relation to some other analysis of energy use it is more appropriate to look at the net energy use in which the converted energy has been substituted by primary energy used for the conversion. For those kinds of analysis matrices of net energy use are also included in the NAMEA system.

Table 7-1: Use of energy 1998. All figures in Petajoule.

	Total	Primary Energy	Oil Products	Converted energy
Total	1402.6	847.8	339.7	215.1
Households	256.1	37.2	118.7	100.2
Industries, total	1146.5	810.7	220.9	114.9
Agriculture, fishing and quarrying	75.9	31.9	34.5	9.5
Manufacturing	478.0	390.6	46.4	41.0
Electricity, gas and water supply	391.9	375.7	14.4	1.8
Construction	15.3	0.2	14.2	0.9
Wholesale and retail trade; hotels, restaurants	42.6	4.1	16.0	22.5
Transport, storage and communication	88.2	0.5	81.2	6.5
Financial intermediation, business activities	13.3	1.8	4.0	7.5
Public and personal services	41.3	5.8	10.3	25.2

Note: Primary Energy includes crude oil, natural Gas, coal etc. Converted energy includes electricity and district heating.

Table 7-2 shows the use of water by main groups of industries and by households. It is seen from the table that various kinds of water has been included: Ground water, surface water, seawater, and tap water. This table too reflects a double counting in the sense that both ground water used for production of tap water and produced tap water have been included. This double counting might look confusing at first sight. However - as in the case of energy - the double counting serves a purpose in the most the detailed NAMEA accounts because it gives a picture of the conversion of ground water into tap water.

Surface water has been included in the NAMEA in order to give a full picture of the economy's dependence of water with special reference to international comparisons.

Table 7-2: Use of water 1994. All figures in Millions m^3.

	Total	Ground water	Surface water	Sea water	Tap water
Total	6739	917	24	5363	434
Households	301	16	0	0	285
Industries, total	6438	901	24	5363	149
Agriculture, fishing and quarrying	412	366	10	0	35
Manufacturing	203	39	11	109	44
Electricity, gas and water supply	5757	494	3	5254	6
Construction	2	0	0	0	2
Wholesale and retail trade; hotels, restaurants	16	0	0	0	15
Transport, storage and communication	3	0	0	0	3
Financial intermediation, business activities	4	0	0	0	4
Public and personal services	42	2	0	0	40

Table 7-3 shows the emissions of CO_2, SO_2 and NO_x to air. Included in the numbers are both energy related emissions and non-energy related emissions. In the Danish NAMEA data is also included when it comes to emissions of NH_3, NMVOC, CO, CH_4, and N_2O.

Table7-3: Emissions to air 1998. All figures in 1000 tonnes

	CO_2	SO_2	NO_x
Total	67 395	97	262
Households	11 346	5	53
Industries, total	56 049	92	209
Agriculture, fishing and quarrying	5 027	6	47
Manufacturing	7 312	19	15
Electricity, gas and water supply	33 876	54	67
Construction	1 086	1	11
Wholesale and retail trade; hotels, restaurants	1 349	0	7
Transport, storage and communication	5 913	10	53
Financial intermediation, business activities	389	0	2
Public and personal services	1 096	1	7

The accounts for air emissions associated with the combustion of energy are based on calculations of technical coefficients expressing the content of pollutant per unit of energy consumption. The numbers for energy consumption are taken from the energy part of the system.

For cars data are furthermore calculated on the basis of a breakdown of the energy use into 187 different kinds of cars in order to make the calculations for each industry and for households more precise. Besides the estimations of emissions from technical coefficients, numbers for measured emissions from power plants are included in the system. Most of the information on emissions – including information on non-energy related emissions – is obtained from the CORINAIR database managed by the National Environmental Research Institute in Denmark.

7.2 INPUT-OUTPUT MODELLING

The consistent use of the same classifications and definitions in the various parts of the Danish NAMEA system makes it easy to analyse the relationship between economic activity and resource use on one side and emission on the other side.

Table 7-4 shows results of an input-output calculation of the direct and indirect CO_2-emissions linked to the categories of final demand. The effects of various groups of private consumption are included. As an example, it is seen that transport and communication created direct emissions at 4.6 mill. tonnes. These are the emissions related to e.g. use of petrol for private cars. The Danish direct and indirect emissions were 7 mill. tonnes. This number includes the 4.6 mill. tonnes of direct emissions but also all indirect emissions from Danish industries necessary to produce the output for the consumption group transport and communication.

As an example, emissions from busses and trains used for public transportation falls under the indirect emissions. So does emissions from Danish industries which indirectly delivers goods to the public transportation companies, e.g. electricity for heating in administration buildings, paper for brochures, machinery for repairs and so on.

The global direct and indirect emissions at 8.2 mill. tonnes from Danish private consumption of transportation and communication include not only the emissions in Denmark but also all indirect emissions created in other countries as a result of the production of products exported to Denmark.

The NAMEA accounts as well as results of input-output calculations of both energy use and emissions to air are published yearly by Statistics Denmark in Danish in *Input-output tabeller og analyser – import, beskæftigelse og miljø.*

7.3 PHYSICAL INPUT-OUTPUT TABLES

The NAMEAs are characterised by representing information in mixed units. For the economic information DKK is used as unit, while for resource and environment information physical units (m^3, tonnes, PJ, etc.) are used. Furthermore, the NAMEAs can be said to focus mainly on the input to and output from the economy as far as the physical flows are concerned.

In contrast to this, complete physical IO-tables (PIOTs) are made up in physical units only, and they describe the flows *within the economy* as well as input to and output from the economy.

For the flows within the economy PIOTs corresponds exactly to the monetary IO-tables except for the fact that all flows are in tonnes and not in DKK. This means that the PIOT shows how many tonnes of materials that are supplied from one industry to another and from one industry to a category of final demand.

Table 7-4: CO_2-emissions by final demand categories 1992.

	Direct	Direct and indirect		Direct	Direct and indirect	
		In Denmark	Globally		In Denmark	Globally
	1000 ton			ton per mill. DKK final demand		
Food	-	2 723	4 677	-	41	70
Beverages and tobacco	-	589	934	-	21	33
Clothing and footwear	-	376	1 010	-	16	44
Gross rent, fuel and power	5 094	18 102	19 084	41	144	152
Household equipment and operation	-	623	1 299	-	23	47
Medical care	-	192	315	-	21	34
Transport and communication	4 609	7 012	8 244	68	103	122
Recreation, entertainment, etc.	-	1 095	1 831	-	24	40
Miscellaneous goods and services	-	1 553	2 239	-	31	45
Purchases in DK by non-residential households	- 675	-1 559	-2 051	26	60	79
Purchases abroad by res. households	-	-	-	-	-	-
Cons. by private non-profit inst.	-	47	66	-	8	12
Total private consumption	9 029	30 754	37 648	20	69	84
Government consumption	-	5 009	6 304	-	25	31
GFCF, construction	-	2 596	3 729	-	34	50
GFCF, machinery, transport equip. etc.	-	995	2 913	-	16	46
Exports of goods and services	675	16 393	33 851	2	58	119
Other final demand	-	447	363	-	20	16
Total final demand	9 704	56 194	84 809	9	53	80

So far, PIOTs exist for Germany and Denmark. Both are for the reference year 1990.

For Denmark PIOTs exist for all products taken together and for various groups of products individually: Animal and vegetable products; stone, gravel and building materials; energy; wood and paper; metals and machinery; and chemical products and fertilisers. Also PIOTs for packaging materials and the nitrogen content of products have been constructed.

On the basis of the PIOTs an overall material balance for the Danish economy can be extracted. This balance is shown in figure 5. The supply side includes mainly imports and Danish resource extraction, while the largest components on the use side are accumulation of materials in the economy and residuals from the economy ending up in the environment. The figure shows that the physical trade balance for Denmark is negative in the sense that imported products weighs more than the exports.

The total supply at 123.6 mill tonnes of materials entering the economy equals the total mass accumulated and leaving the economy. Thus, there is a material balance for the economy.

Table 7-5: General material balance for the Danish economy. All commodities 1990.

Origin/supply		Destination/use	
	Million ton		Million ton
Imports	38.3	Exports	25.2
Danish resources	79.6	Accumulation	58.7
Water added to products	2.4	Changes in stocks	-3.1
Recycling of residuals	3.3	Residuals	42.8
Total	123.6	Total	123.6

Note: Only water added to products is included. No industry-internal recycling is included.

As an example of detailed information for industries included in the PIOTs table 6 shows the material balance for agriculture. First of all, it is seen that the total input at 26 mill tonnes into agriculture equals the total output from agriculture.

The table shows how much that was delivered to agriculture from the various Danish industries and from abroad. Furthermore, the amount of materials/biomass extracted from nature by agriculture is represented on the input side. On the output side we find supplies from agriculture to other industries, households and exports. Besides these outputs of products there is an output of residuals in the form of carbon (included in CO_2 emissions), sulphur (included in SO_2 emissions), other energy relates residuals, and other residuals.

The physical IO-tables for Denmark are described in Ole Gravgård Pedersen: Physical input-output tables for Denmark – Products and materials 1990, Air emissions 1992. Statistics Denmark, 1999.

Table 7-6: Physical input and output in relation to agriculture, etc. 1990 - All materials. All figures in 1000 ton.

Input to agriculture from:		Output from agriculture to:	
Agriculture, etc	2 713	Agriculture, etc.	2 713
Forestry and logging	3	Forestry and logging	0
Fishing	75	Fishing	0
Mining and quarrying	1 712	Mining and quarrying	0
Manuf. of food, beverages, tobacco	3 465	Manuf. of food, beverages, tobacco	12 071
Textile, clothing, leather industry	0	Textile, clothing, leather industry	6
Manufacture of wood products, incl. furniture	4	Manufacture of wood products, incl. furniture	37
Manufacture of paper, printing, publishing	7	Manufacture of paper, printing, publishing	0
Chemical and petroleum industries	952	Chemical and petroleum industries	0
Non-metallic mineral products	203	Non-metallic mineral products	0
Electricity, gas and water	50	Electricity, gas and water	324
Construction	20	Construction	0
Restaurants and hotels	-	Restaurants and hotels	85
Producers of government services	-	Producers of government services	40
Total input from Danish industries	9 205	Total output to Danish industries	15 279
Total input of imported goods	3 897	Private consumption	1 156
		Exports	4 297
Danish resource extraction - biomass	12 426	Other final demand	540
		Total output to final demand	5 992
		Carbon, C	454
		Sulphur, S	2
		Other energy related residuals	108
		Others	3 693
		Total output of residuals	4 257
Total input	25 528	Total output	25 528

8 Hybrid LCA

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As pointed out by Manfred Lenzen in Chapter 4, process-based analyses, while accurate, are incomplete in framework and suffer from a truncation error of an unknown size. Therefore conventional Life Cycle Assessment (LCA) is likely to ignore processes connected to services, small inputs, and the manufacture of complex products from basic materials. Input-output analysis (IOA) methods, while comprehensive in framework, are subject to inherent errors due to the use of economic data to simulate physical flows and the aggregation of the whole economy into one relatively simple matrix.

Several attempts have been made to unite LCA and IOA. In such hybrid analysis, process analysis data and IO-data are combined, with the aim of reducing these errors. The hybrid analyses take starting point in either process-based or IO-based analysis.

8.1 PROCESS-BASED HYBRID ANALYSIS

The basis of all process-based hybrid analysis methods is the assumption that the errors in the IO-model for the sector which produces a particular product can be avoided or decreased by defining the inputs into the main process in terms of physical units. Inherent in IOA lies the assumption that within one production sector, environmental effects are proportional to the price of the product. Process-based hybrid analysis replaces the price-proportionality assumption with an assumption of proportionality according to physical units.

In a process-based hybrid analysis the product quantities for the individual product are collected as is done in a conventional LCA, but the environmental data are derived using IOA. Many researchers have demonstrated this method, (in Treloar (1998) the following are mentioned: Bullard *et al.* (1978), Oka *et al.* (1993), McArdle *et al.* (1993), Pullen (1995), and Fay (1998)).

Like conventional process-based LCA, also the process-based hybrid analyses suffer from the problem of incompleteness, although it is limited to the first stage of the inventory, i.e. the description of the product quantities. The truncation error remains, although diminished.

Another problem is that process-based hybrid analysis offers no method to estimate the incompleteness of the study, making the choice of which data to collect and improve subjective. The most time-consuming part of a process-based analysis is often the data collection; therefore it is a clear weakness if this time is likely to be spent inefficiently.

In summary, the hybrid version of process-based analyses offers the IO-tables as an additional source for data collection, but the problems concerning truncation and efficient data collection is only partly solved.

8.2 INPUT-OUTPUT-BASED HYBRID ANALYSIS

IO-based hybrid methods all take starting points in a conventional IOA of one or more environmental impacts. Single data in the IOA are substituted with process analysis data, or one or more groups of data in the IOA are substituted with process analysis data by adding a column to the IO-model. The products or processes considered most important may be split out to form individual "sectors" within the IO-model. (Cobas-Flores et al. 1996 cf. Treloar, 1998).

Substituting single data may introduce unwanted indirect effects, since all data, whether reflecting direct or indirect effects, are mixed. Treloar (1998) suggests that this is likely to exacerbate the effects of the homogeneity and proportionality assumptions inherent to the IO-model.

Furthermore it is likely that the selection of sectors for further investigation will involve a subjective decision-making process. Therefore a procedure is needed to identify the most important data to improve. Such a method is suggested by Treloar (1997): First, the assessment is carried out merely with IO-data. Secondly, the entire production system is decomposed into groups of processes, called paths. The chains are ranked according to the relative contribution to the total result. Finally, process data can be collected until the desired level of accuracy is reached. The clear force of this IO-based hybrid method is that it implies a data collection strategy, aiming at using time for data collection efficiently.

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9 Empirically-derived distributions of life cycle emissions

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9.1 INTRODUCTION AND MOTIVATION

LCA researchers are developing and refining methods for impact assessment, which integrate a variety of approaches to fate and exposure modeling as well as (in some instances) effects modeling. This is true for a variety of impact categories. Researchers also continue to develop and refine methods to treat uncertainty quantitatively in life cycle inventory analysis. For both avenues of research, there is a need to assess the information differences (uncertainty reductions), which are achieved *in LCA results* by different approaches along spectra such as from generic to site-specific.

Evaluation of the proposed methodological advances, and insight to guide their continued development, requires quantitative information about what life cycle inventories really look like, in general. In particular, the field needs quantitative answers to the following questions: from how many sites, in what percentages, with what geographic and temporal distributions, do life cycle emissions originate? How do these results depend on the class of pollutant? How do they depend on the class of product or process whose life cycle is being considered?

9.2 APPROACH

We have undertaken empirical investigations into this subject using input/output LCA (IO-LCA) models of the US economy. The research has been undertaken with a 500-sector IO-LCA model for the US that has been constructed from databases published by the US government. Databases from the US Department of Commerce describe the flows of goods and services among the sectors in monetary terms. These can be used to estimate tier-by-tier the economic activity in the supply chain for each of 500 commodity groups. Together these 500 commodities span the entire spectrum of commodities bought and sold in the US.

Separate databases from the US EPA report annual pollution releases from each sector. These data are divided by the annual economic output from each sector to derive annual average pollution coefficients for each sector. These coefficients are used with the supply chain computations to estimate supply chain pollution upstream of each commodity.

The concept of supply tier is straightforward. The set of all suppliers of the direct inputs to a given using sector are termed that using sector's “first tier suppliers.” The set of all the direct suppliers to these first-tier suppliers comprise the second supply tier of the original using sector, and so on. Tier “zero” is the final sector manufacturing the commodity itself.

9.3 RESULTS

First, we computed "percentiles" for the cumulative upstream pollution by tier for the full set of US commodities, for each of the US EPA's "criteria air pollutants" (NO_x, VOCs, particulates, CO, and SO_2), for CO_2, and for toxic releases to air, water, land, and underground as reported in the US Environmental Protection Agency's Toxic Release Inventory (TRI). The tier-wise cumulative percentiles indicate the share of total commodities for which cumulative emissions up to and including that tier in their upstream life cycle account for less than that percentage of the commodity's total upstream emissions for that pollutant. Thus, the percentiles can be used to judge the probability that for some randomly chosen commodity, modeling a given number of tiers will capture a given fraction of total upstream emissions for a given pollutant.

As an example, Figure 9-1 presents the cumulative percentiles for emissions of sulfur dioxide, SO_2. The curve for the 5th percentile in Figure 9-1 indicates for only 95 percent (100% – 5%) of commodities (goods and services) produced in the US economy, upstream models that include the 0th through 3rd tiers will capture at least 75% of the total upstream emissions of SO_2. The figure also indicates, for example, that for 75% of the commodities, models that span tiers 0 through 4 will capture at least 90% of the total upstream emissions of SO_2.

Figure 9-2 presents similar results for releases of volatile organic compounds (VOCs). The differences between Figure 9-1 illustrate that the *speed of convergence* – that is, the probability or percent of commodities for which a given number of tiers captures the bulk of the upstream emissions – this speed of convergence varies from pollutant to pollutant. These differences are captured and summarised in Figure 9-3, which presents the 25th percentiles for all of the pollutants or pollutant categories in the IO-LCA modeling system. These curves indicate that toxic releases to water and to land are the slowest pollutants to converge, with 25% of all commodities still missing, approximately 40% of their total upstream emissions after tiers 0 through 3 have been modelled. At the other end of the spectrum are CO_2, toxic releases to air, and a measure of total manufacturers' waste treatment and disposal costs ("Waste T&D") all converge more rapidly, with tiers 0 through 3 accounting for over 80% of the upstream total for at least 75% of the commodities.

Next, we have used nested regional economic input/output models for the US for a geographically diverse selection of 6 US states in order to characterise the degree and speed of geographic dispersion in the supply chains of the 500 commodities. With this subset of the analysis we estimate what share of the total upstream pollution is occurring in each of a set of nested regions around the originating activity. We also estimate the nested region shares of economic activity and pollution on a tier-by-tier basis. As an example of these results, we have found that for building and construction taking place in the relatively large US state of Texas, generally less than 15% of the total upstream pollution is generated by economic activities located within the state of Texas; fully 85% or more of the upstream environmental burden occurs outside the state. The out-of-state share will be larger for most sectors, since building and construction require a relatively high share of very massive (and thus locally-sourced) inputs.

Third, we look within the tiers to estimate percentiles for the numbers of individual sites contributing the bulk of the emissions for each pollutant for each tier in the supply chains of each originating commodity. Figure 9-4 presents the results for a specific pollutant (CO_2), while Figure 9-5 presents the results for the 10th percentile, or 90 percent of commodities. Figure 9-5 indicates that depending upon which pollutant is selected, capturing 90% of the first tier's emissions for 90% of the commodities requires modeling only the top 5 polluters in the tier for SO_2, while it requires modeling the top 23 emission sources in the tier for toxic releases to air.

Finally, we have investigated the implications of these findings for the expected uncertainty reductions in Life Cycle Impact Assessment results, which are achieved using regionalised characterisation factors. We do this for three LCIA impact categories for which regionalised (state level) characterisation factors have been recently developed for the US EPA: acidification, eutrophication, and smog. The results confirm that appreciable uncertainty reductions are achieved by using region-specific characterisation factors in place of national average characterisation factors for any single site. They go on to demonstrate, however, that for the bulk of US commodities, the expected uncertainty reductions achieved by applying these regionalised factors beyond the first supply tier are much smaller due to the number of participating sites.

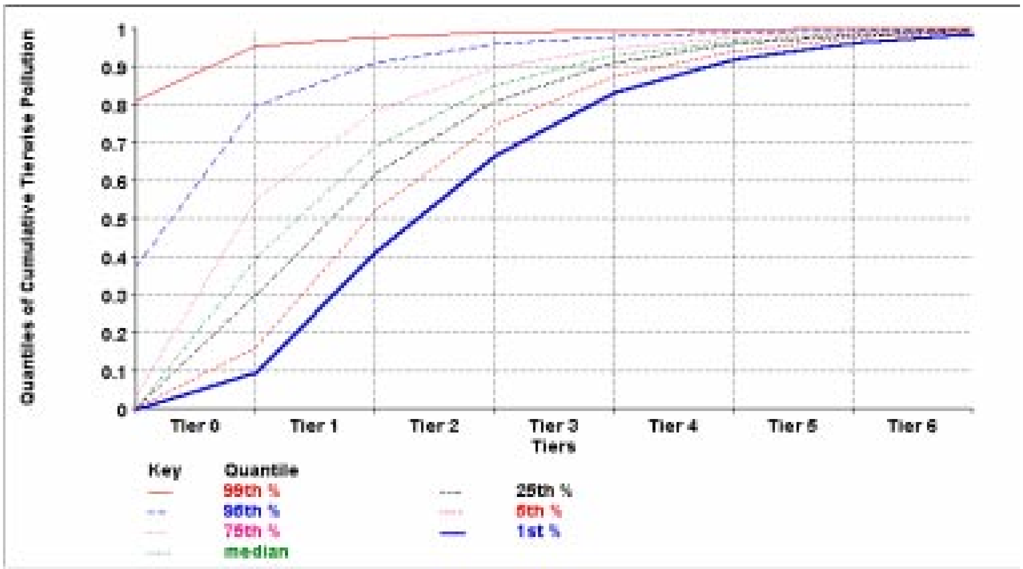

Figure 9-1: Cumulative percentiles for SO_2-emissions from the US economy.

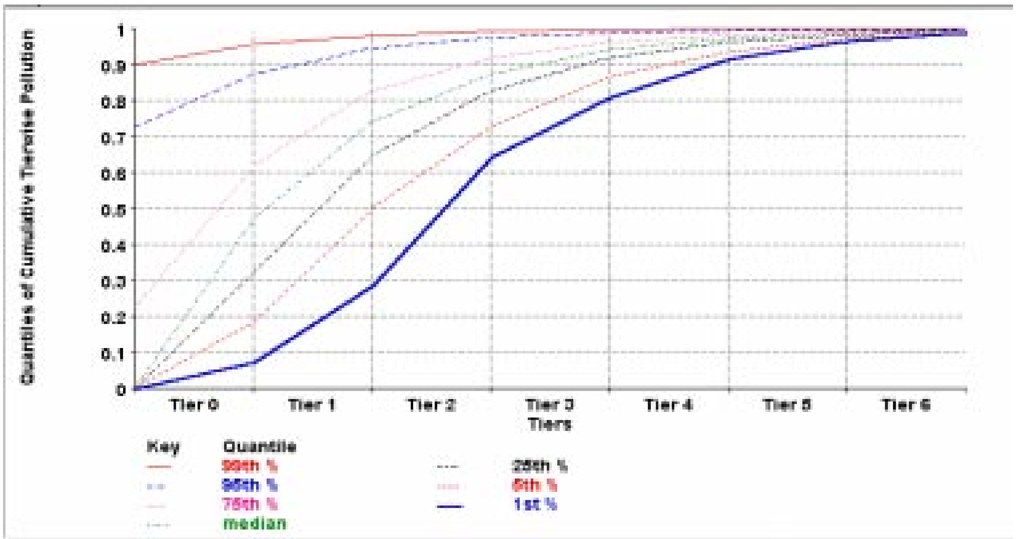

Figure 9-2: Cumulative percentiles for VOC-emissions from the US economy.

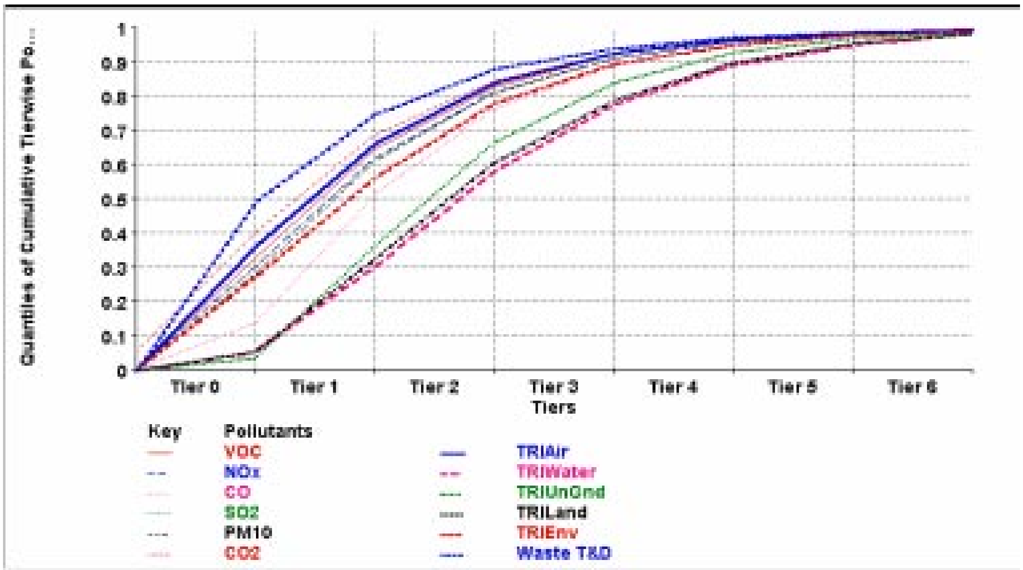

Figure 9-3: Percentage of different pollutants, accounted for when 75 % commodities are included.

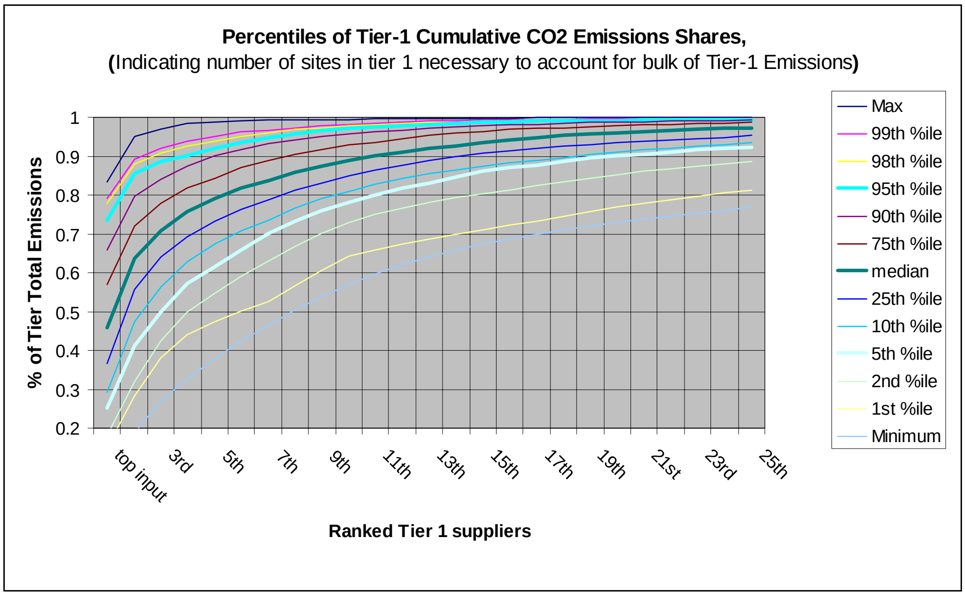

Figure 9-4: Percentage of CO_2-emissions captured within tier 1 as a function of individual sites, depending on percentiles of commodities covered.

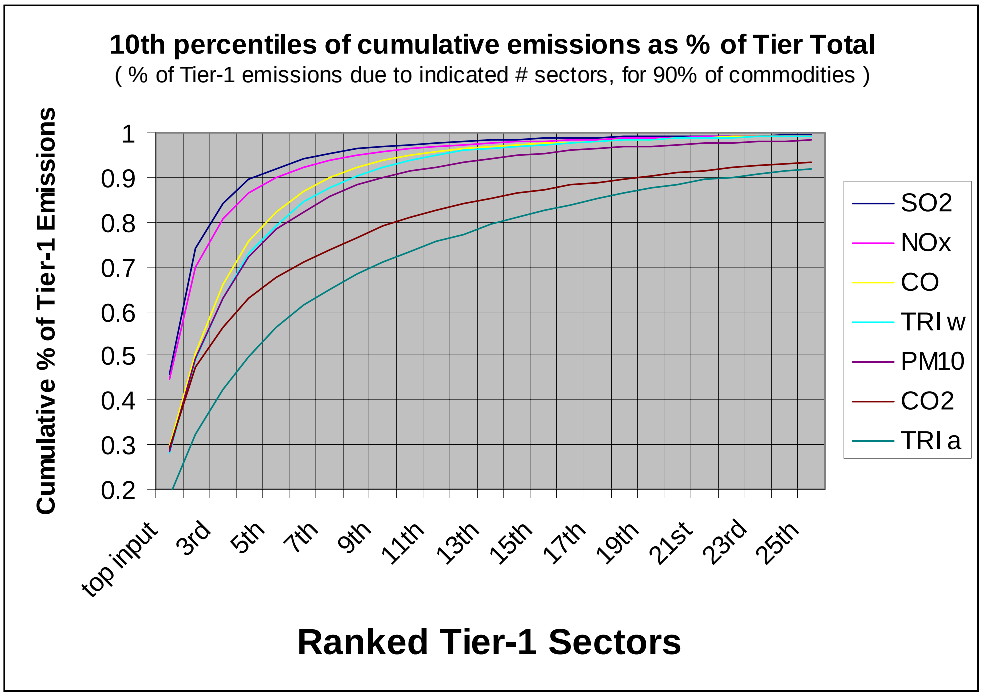

Figure 9-5: Percentage of emissions captured within tier 1 when including 90 % of all commodities as a function of number of individual sites.

10 Literature on environmental IOA

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In this Chapter a few Input/Output Analyses (IOAs) are presented as examples to illustrate the development of the methodology, and the scope and conclusions of studies performed up till now.

10.1 AIR POLLUTION

In 1972 Leontief and Ford presented a paper on the dependence of air pollutants and economic input-output structure. The study is limited to five air pollutants: particles, SO_x, HC, CO and NO_x. The basis for the calculations is the historic and projected IO-tables for the period 1958-1980. The source of the historic tables is the U.S. Department of Commerce, where the original 370 sectors table were aggregated into a 90-sector table. The future tables are based on already available forecasts.

The technical pollution coefficients were derived from sampling estimates, i.e. primary data on pollution from industry plants had to be collected for this study.

The results were used for estimating the price effect of four air pollution control strategies on product and services from 90 production sectors. The authors expected a better statistical basis for pollution coefficients to be compiled soon. Therefore this study is presented as a framework with empirical examples, and conclusions and recommendations are modest.

10.2 WATER POLLUTANTS

In 1976, Førsund and Strøm published a study, where the generation of 35 different kinds of emissions are analysed for the Norwegian economy in 1970. The emissions are different heavy metals, acids and bases, different organic compounds, pesticides and others.

The basis for the calculations is the IO-table for the year 1964 (the latest data generally available in 1976), compiled by Central Bureau of Statistics of Norway.

Also for this study, the technical pollution coefficients could not just be found in literature or already existing statistics, so data on residual discharges are based on a questionnaire investigation of the Norwegian industry for the year 1970.

From these calculations it is seen that export from the sectors “Pulp and paper” and “Metals and minerals” are the main contributors to the flow of emissions generated each year.

The authors trust their data enough to analyse further. They estimate whether the negative effect of the pollution is bigger or smaller than the positive effect of the production. They compare the economic value of the produced goods and services to the size of the emissions multiplied by the damage and abatement costs found in litterature. From these calculations they conclude that humanity gains from the production, and if sulfur emissions must be decreased, it should be done by applying abatement technology, not by stopping production.

10.3 AREA

In 1998, Bicknell and colleagues presented a new methodology for calculating ecological footprints. An "ecological footprint" is defined as the amount of productive land required to support the consumption of a given population indefinitely, i.e. to answer how much land is necessary to, in a sustainable manner, supply all resources for production of goods and services consumed by an average citizen in a given culture.

The concept was introduced by the Canadian researchers Rees and Wackernagel in 1992. They based their work on scientific results from many countries and a variety of statistics.

Bicknell and colleagues suggest an IO-methodology, because it will standardise the production and facilitate comparison of ecological footprint results. IO-tables are directly taken from Statistics New Zealand. Technical land requirement coefficients are found in different established statistics.

The authors reach two conclusions. First, it takes 3.49 hectares of ecologically productive land per year to sustain the average New Zealander's current level of consumption. Second, New Zealand is a net-exporter of land, directly and indirectly used for making products, i.e. because of international trade, consumption in other countries put claim on more New Zealand area than vice versa.

10.4 NATURAL RESOURCES

In 1998, Lange publishes a study aiming at giving Indonesian politicians a tool for making more informed decisions concerning future development of natural resources. He focuses on the resources receiving closest attention in Indonesian planning: preservation of arable land for food self-sufficiency, air pollution, and availability of water of sufficient quality for agriculture, industries and households.

In this study, the technical coefficients were found more easily than the data on economic input and output to and from industrial sectors.

Data on resource use in different sectors were directly found in satellite accounts to the Indonesian system of national accounts.

The IO-data, on the other hand, was forecasted until 2020 by use of a dynamic model. The model was based on the accelerator principle: investments in capacity expansion is determined by the expected growth in each sector's output, the technologies in use, and the rates of capacity utilization.

Six different scenarios were established to mirror the uncertainty faced by politicians concerning the level of economical growth and technological change.

When it comes to conclusion, Lange wisely refrains from choosing the best policy for Indonesia. The conclusion is therefore just that such a study can provide useful information, which can form the basis for political discussions ending up in informed, democratic decisions.

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11 The statistical basis for integration of the working environment in LCA

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11.1 INTRODUCTION

The present paper gives a short overview of the basic statistical information used in the development of a new methodology for life cycle assessment of the working environment (WE-LCA) and for establishing the database used together with the methodology.

The new methodology is based on two types of Danish statistical information regarding economic sectors, i.e. information on the amounts being produced (in weight units) in a number of sectors, and information on the number of reported work-related diseases and damages in the same sectors. By combing these statistics, it is possible to calculate working environmental impacts per produced unit, which can be used as a supplement to information on the impacts on the external environment.

The general methodology uses two types of statistical information to derive the database:

- Statistics on work-related accidents and reported diseases from the Danish National Labour Inspection Service (Arbejdstilsynet). In Denmark, all notified occupational accidents and occupational diseases are recorded by the Registry of Occupational Injuries, which is a part of the Danish National Labour Inspection Service.
- Statistics on the amounts of produced goods in Denmark (Varestatistikken). The Danish statistics on goods production is based on a questionnaire produced by Danmarks Statistik. The questionnaire is sent out to all industrial companies with more than 10 employees, and includes questions on what the company produces, the value of the produced goods, and some kind of quantity (in units such as tons, meters, pieces etc.). Value is the only parameter that is common for all the sectors. By combining the result from the questionnaires with the statistics for the foreign trade, it is possible to convert all the amounts of produced goods to a weight unit, no matter what they was given in initially.

The basic equation used to derive the information for a sector can be expressed in the following way:

$$\text{Impacts per "functional unit"} = \frac{\text{Number of accidents / damages in sector}}{\text{Produced amount in sector}}$$

In practice, a five-step procedure was used to derive the information. The five steps are described in the following and to some extent exemplified. For a detailed description of the methodology, the reader is referred to the Technical Report and the Guidelines from Subproject 3 in the Danish LCA-methodology and Consensus-project, which is under publication by the Danish Environmental Protection Agency.

11.2 THE FIVE-STEP PROCEDURE

The five steps in the procedure have the following headings:

- Selection of sectors
- Specifying the production in the sector
- Calculating the total weight of the products
- Accounting for the working environmental impacts
- Calculating the working environmental impacts per weight unit

11.2.1 Step 1 - Selection of sectors

The first step is selecting sectors and sub-sectors with a significant number of work-related accidents and diseases. By choosing sectors with a significant impact on the working environment the statistical uncertainty regarding the number of impacts is reduced.

Another important criterion is that the sector can be characterised by one or more unit processes that are of interest in relation to LCA. The sector “Production of plastics packaging” (NACE-code 252200) thus comprises processing of almost all types of plastics using extrusion, injection moulding etc., but it is not possible to achieve a higher level of detail. Another example is the sector “Production and first processing of lead, zinc and tin” (NACE-code 274300) which - as the title indicates - comprise both production and processing of all three materials.

11.2.2 Step 2 - Specifying the production in the sector

The second step is to identify in the goods statistics the products that are being produced in the selected sectors. The products are identified by an 8-digit code that is unequivocally related to an economic sector. As an example, products made in the sector “Production and first processing of lead, zinc and tin” (NACE-code 274300) all start with the numbers 78 (lead), 79 (zinc) and 80 (tin), respectively.

It is strongly suggested that this step - and the subsequent calculations in step 3 - is performed by a professional statistician from a governmental statistical agency with access to the basic statistics given by the companies.

11.2.3 Step 3 - Calculating the total weight of the produced amounts in a sector

The third step is to produce an aggregate of the produced amounts (in tons) for all goods in the chosen sectors. The basic information in the goods statistics is exemplified in Table 11-1.

Table 11-1. Example of basic statistical information from the goods statistics used in the calculation of produced amounts in a sector.

Product	Amount in tons	Value in 1000 DKK
Rigid PVC-tubes, seamless	?	150.000
Rigid PVC-tubes, with seam	22.400	287.400
Flexible PVC-tubes with seams	5.902	103.494
Flexible PE-tubes, seamless	1.904	24.473
Rigid PE-tubes, seamless	10.533	210.291
Rigid tubes of condensation plastics	?	17.296
Sum	40.739 + ?	792.954

When information on the weight of the products was not available, e.g. as indicated by the questionmarks in Table 11-1, additional information from the foreign trade statistics was used to calculate the weight of the production. Information from the companies to be used in the foreign trade statistics must contain information on the weight and the value of exported products, and the average value per weight unit of the export was used to calculate the weight of the total production of a given product:

$$\text{Total production of product (in kg)} = \frac{\text{Value (in kr)}}{\text{Average value per weight unit (kr/kg)}}$$

This additional information was necessary for all those products where the produced amounts are reported in other units than weight in the goods statistics, most pronounced in the textile sector.

With the additional information from the foreign statistics, the weight of the produced amount in a sector can be calculated by simple addition.

11.2.4 Step 4 - Accounting for the working environmental impacts

The sixth step is not a calculation, but simply accounting for the work-related injuries and damages for the activities in the same sector as the produced volume was calculated for.

In Denmark, all notified occupational accidents and occupational diseases are recorded by the Registry of Occupational Injuries, which is a part of the Danish National Labour Inspection Service. The information is treated statistically and is published annually on a 2- or 3-digit DB93/NACE-code level. The Danish National Labour Inspection Service is however able to specify the statistics in more detail upon request, i.e. on the 4- or 5-digit level, and this detailed information was used in the calculation procedure.

Although the work related accidents and damages are sorted and registered into 15, respectively 18 different categories, only nine categories are used in the calculations. The reason for this is that the frequency of some types of damages is very low, causing uncertainties in the subsequent interpretation of the results. The included impact categories are:

Accidents

- Fatal accidents
- Total number of accidents. This effect category is in the statistics subdivided into nine types of damages, e.g. amputations, concussions, wounds and poisonings. The nine types of damages have been aggregated into one category, the main purpose of which is to create an overview of the potential for unwanted and acute incidents.

Diseases

- CNS function disorder
- Hearing damages
- Cancer
- Muscular-skeletal disorders
- Airway diseases (allergic)
- Airway diseases (non-allergic)
- Skin diseases
- Psycho-social diseases

11.2.5 Step 5 - Calculating the impacts per functional unit (weight unit)

The seventh and final step is to calculate the working environmental impacts per functional unit by dividing the information from step 4 with the information from step 3.

In order to minimise the statistical uncertainties, an average for the years 1995-1997 is used for both the produced amounts and the accidents/damages in a sector.

11.3 DISCUSSION

The methodology outlined in the paper exemplifies that it is possible to combine information from two statistical sources in an input/output analysis in order to produce meaningful results in a LCA.

When the inventory calculations have been made, it is possible to obtain an overview of what processes or materials contribute most to each of the impact categories. It is also possible to present figures for the absolute contribution to the different impacts, e.g. how many accidents can be expected during the production of an office chair. Following normalisation, where the impacts in the life cycle of the products are compared to the average work-related impacts on a Danish citizen, it can be demonstrated what working environmental impacts are most affected

Obviously, the results should be interpreted in view of the inherent uncertainties. A major uncertainty in relation to LCA is that average values for large sectors are used in the calculations. Thus it is not possible to achieve or use knowledge about the working environmental impacts from specific companies. However, the goal of the methodology, i.e. to give the possibility of examining whether environmental product improvements are implemented at the expense of a deteriorated working environment, is fulfilled by the methodology.

The method is recommended as a general assessment of the changes in working environmental impacts induced by changes in the choice of materials and processes. This knowledge can subsequently be combined with more specific knowledge about potential hazards in relevant sectors and form the basis for a dialogue between the actors in a product chain. WE-LCA can thus be seen as a natural component in the efforts for development of products with less impact on the environment and human health.

In relation to the use of available statistics for other LCA-purposes, the procedure for calculation of produced amounts outlined in the present paper is recommended. The produced amounts can be calculated for about 300 sectors with a relatively high degree of precision. This gives the possibility of relating information on different types of environmental impacts to a wide variety of sectors and – eventually – also to a large number of product groups. However, neither the level of detail nor the precision can match that obtained by performing a regular LCA.

12 Non-energy related emissions in IOA

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12.1 ABSTRACT

Input/Output LCA models can address more than energy-related emissions. They can be expanded to address releases of a wide array of pollutants. They can also include extractive flows of resources from the environment, and non-flow-based environmental impacts such as land use as well. This paper describes briefly the data sources and methods used to date to accomplish these extensions for IO-LCA models in the USA. It includes a discussion of some of the method and data alternatives where relevant, and also indicates some of the sources of uncertainty that arise, based on characteristics of the databases underlying the models.

12.2 DATA SOURCES AND THEIR INTEGRATION TO CREATE US IO-LCA MODELS

12.2.1 Economic and Energy Data

Input/Output LCA models in the US make use of the detailed US Input/Output data from the US Department of Commerce's Bureau of Economic Analysis (BEA), together with Federal data on pollution releases by sector (from the US Environmental Protection Agency, or EPA) and Federal data on fuel-specific energy consumption by sector (from the Department of Energy's Energy Information Administration). Below a description is provided of the data sources and their use in creating the "LCNetBase" IO-LCA modeling system.

The US Bureau of Economic Analysis' 1992 detailed Input/Output Accounts provide a starting point for modeling inter-industry flows. The BEA's "Make" and "Use" tables are used directly in our analysis, to enable tier-by-tier assessment of results. The "Make" matrix reports industry outputs: the value of each commodity produced by each industry. The "Use" matrix reports industry inputs: the value of each commodity used in the production of each industry's output.

We retained 498 industries from the BEA tables, including government enterprises such as the US Postal Service, and the 488 BEA commodities produced by these industries. For most manufacturing industries, the BEA industries and commodities match the US four-digit Standard Industrial Classifications (SICs) one-for-one. Outside of manufacturing, some BEA industries represent aggregations of 4-digit SICs, while other BEA industries are composed of portions of one or more 4-digit SICs.

Many establishments in the economy manufacture more than one type of product. This product diversity is even more pronounced among the full set of establishments classified within a single Standard Industrial Classification (SIC) category (Streitwieser, 1991). The industries and commodities are created by BEA in order to provide a characterisation of the inputs and outputs of more homogeneous producing units than those which would arise from developing and publishing the tables on a purely SIC basis - that is, simply using the total production and consumption data for all establishments which are assigned to each SIC as the basis for defining industries as SICs.

Next, fuel-specific energy consumption data (in Btu per dollar of sectoral output) is integrated into the system. The US Census of Mining reports fuel-specific energy consumption for the mining industries. Electricity consumption in kWh is also reported for all manufacturing industries (by 4-digit SIC) by the 1992 Census of Manufacturing, as is cost of other purchased fuels. Note that not all *purchased* fuels are actually combusted; some are used as feedstocks to product production, as in the use of petrochemicals as feedstocks in manufacturing plastics or fertilisers.

The Department of Energy’s Energy Information Administration (EIA) conducts biennial surveys of manufacturing industry energy consumption, by fuel and end-use, and reports both costs and quantities in energy units. The EIA data report the quantities of each fuel combusted. Data for fuel combustion from the 1991 Manufacturing Energy Consumption Survey (EIA 1994) were used in creating the recent version of LCNetBase.

Fuel-specific manufacturing energy combustion data and the fuel-specific census of mining energy consumption data were converted to provide fuel-specific consumption totals by BEA industry. For nearly all manufacturing industries, the mapping from four-digit SIC to BEA industry is one-to-one; in a few cases, multiple SICs are assigned to a single BEA industry. The match-up from SICs to BEA industries for the 1992 Input/Output accounts is published by the BEA.

For the major energy consuming sectors, the Department of Energy’s Manufacturing Energy Consumption Survey (MECS) reports fuel-specific combustion by four-digit SIC. For sectors that consume smaller amounts of energy, MECS reports fuel-specific combustion by 3-digit or 2-digit SIC. These fewer-digit SICs consist of multiple 4-digit SICs. In these cases, the (1991) MECS-reported fuel *shares* fuel prices for an aggregated sector were combined with the (1992) Economic Census-reported total cost of fuels for each detailed sector, in order to derive estimated fuel-specific combustion quantities by detailed sector. The total fuel-specific combustion within each 2-digit and 3-digit sector will match those reported by MECS.

EIA also reports fuel-specific sectoral prices for the following non-manufacturing sectors: residential & commercial, industrial, transportation, and electric utilities. These prices (for 1992, concurrent with the BEA consumption data in the Input/Output accounts) were used to convert the non-manufacturing BEA industry fuel and electricity consumption data from dollars to energy units (EIA 1993).

12.2.2 Pollution Data

12.2.2.1 Carbon Dioxide

Fuel-specific sectoral energy combustion data are used to calculate fossil fuel-based carbon emissions by sector, using the fuel-specific carbon emissions coefficients at full combustion provided in Table A1 of (EIA 1995). These emissions were converted from metric tons of carbon to metric tons of CO_2, and were then divided by each sector’s 1992 value of product output to obtain CO_2 emission intensities, in units of metric tons of CO_2 per dollar of 1992 product output.

An alternative approach taken by researchers at Carnegie Mellon University is to use directly the Department of Commerce (DOC) data on fuel purchases. This approach avoids the task of estimating MECS data for suppressed 4-digit industries, but introduces two sources of error and an upward bias. First, whereas MECs reports physical consumption as well as costs, the CMU approach applies average fuel prices to estimate physical quantities purchased based on the DOC fuel cost data (Joshi 2000). Second, assuming that all purchased fuels are combusted entails ignoring feedstock uses, and thus will overestimate emissions. Ax useful research project would be to compare the results from the two approaches and to estimate the uncertainty in each method's results.

12.2.2.2 Conventional Air Pollutants

A priority set of air pollutants in the US is termed the "criteria air pollutants" because the US EPA has issued air quality criteria which states must monitor, report annually, and take steps to achieve. This set of pollutants includes NO_x, VOCs, SO_2, CO, and particulates. Until recently the monitored measure of particulates was "PM-10" – particulates less than 10 microns in diameter. The upper-bound particle size was recently changed to 2.5 microns: "PM-2.5." As with CO_2, there are two different approaches used to create sector level emissions coefficients for use in IO-LCA models in the US.

For LCNetBase, we use annual emissions inventories for each pollutant and each 4-digit SIC published by the US EPA. These emissions are divided by sector output for the data year to compute the emissions coefficient (in tons per million dollars of output). As with CO_2 emissions, Carnegie Mellon researchers use the Census of Manufacturers data on fuel costs together with average fuel prices and average combustion emission factors for various fuels published by the US EPA to estimate emissions (Joshi 2000). Again, it would be useful to compare the results of these two approaches and estimate their uncertainties.

12.2.2.3 Toxic Releases

The US EPA publishes annually the Toxic Release Inventory (TRI), which includes media-specific emissions inventories for a set of toxic pollutants for a subset of companies required to report. Reporting requirements have changed over the years since the first TRI reporting year of 1987. For 1996, the most recently published emissions data, facilities required to report are those classified in the *manufacturing* sectors, with the equivalent of 10 or more full-time employees, whose manufacturing or processing of a TRI chemical exceeds 25,000 pounds per year, or whose level of "otherwise using" the chemical is 10,000 pounds per year. Reporting facilities must only report concerning those TRI-listed chemicals for which the usage thresholds are exceeded (EPA 1999).

Reporting facilities must report the amounts of each reported chemical released on-site to the air, water and land as well as injected underground, resulting from routine releases as well as accidental and fugitive releases. The amounts can be estimated; they are not required to be measured. Companies report the basis of each estimate as either:

- Monitoring data or measurements
- Mass balance calculations
- Published emission factors
- Other approaches

Thus, the TRI data provide at once a very powerful source of data for IO-LCA, but also a data source with considerable uncertainties. Factors contributing uncertainty include:

- Measurement, estimation, and reporting error at the facility level

- Missed below-threshold emissions from reporting facilities
- Missed emissions from non-reporting facilities in the reporting sectors
- Missed emissions from non-reporting sectors.

TRI chemical emissions factors are developed for use in IO-LCA by dividing reported annual release totals for each 4-digit SIC by the annual product output from those sectors. This requires that economic output data for the TRI reporting year be used, or else an additional source of error will be introduced. It also introduces an as-yet un-quantified downward bias in the emissions factors for TRI chemicals, both for the reporting sectors and for the supply chain as a whole.

12.3 SUMMARY

IO-LCA models can and have been expanded to include pollution sources beyond those directly tied to energy. They can also be expanded to include the extraction/consumption of resources besides energy as well. These expansions make IO-LCA a more powerful and comprehensive tool. They also introduce a variety of data quality and uncertainty issues that tend to be unique to each data set and its relationship to the economic data at the core of IO-LCA models. These sources of uncertainty have not been studied or quantified to date.

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13 Environmental IOA of the industrialised world - a project description

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13.1 GENERAL BACKGROUND

Our global society has to transform its technologies in an unprecedented way, to create the environmental space for a large and affluent world population. Just following the current path of growth will be impossible or will lead to disaster. We will have to adapt our growth by consuming differently and producing differently. This adaptation is not a unitary single step. It involves creating institutions, creating policies, developing new products and technologies, and creating markets, all embedded in the cultural changes that are needed to support these interrelated processes. Guiding smaller and bigger decisions in the right direction is required for all levels of change directed at a sustainable future.

Our focus is on technology changes. We would like to assess the overall consequences of a specific technology change on global sustainable development. This comprehensive assessment of consequences cannot be straightforward, because it involves processes like research and development and the implementation of its results, which, inter alia, depend on the aims such technological developments are targeted at. It is to the latter subject that our project intends to contribute: How to evaluate technology changes in terms of their contribution to sustainable development, in order to guide these changes in the right direction.

The main difficulty in the evaluation arises from the fact that all specific technologies are embedded in larger technological systems, and in social and cultural systems which together determine the influence a technology has on environment and welfare, in the short and in the longer term. The emission free car will run, for the time being, on electricity from power stations. If adopted broadly, other technologies will come available, as for in-car electricity production in fuel cells. These in turn may revolutionise electricity production in general. Predictive models for such developments do not exist. Instead of persuing an ideal integrated solution, for which the relevant accumulated knowledge is lacking, we here go for a partial model including available knowledge in a systematic way. Such a simplified but operational diagnostic model that can "predict" the effects of specific technology change, while neglecting real dynamic developments, as in global technologies and markets, and while leaving out the complex interplay between institutions, culture and technology. There are several options for simplification. Each simplified model catches only one or two relevant aspects of reality, while the combined (but mutually not fully compatible) application of several such models supports a broader view. Our basic aim in this project is to develop one such a simplified but operational model.

The project has started at a meeting in Vienna on the 22nd of April 1999.

13.2 INPUT-OUTPUT MODELS FOR DECISION SUPPORT

There are several ways in which one can use available knowledge in assessing new technologies in a systematic way. These involve on the one hand an analysis of the technology itself in its specific surroundings and on the other hand an analysis of more diffuse effects at an overall systems level, here in principle the world. This second part in the analysis is to make sure that local improvements are not offset by several modes of problem shifting which may occur: to other places, to other times and to other problems. In principle, general dynamic equilibrium models, with a worked out part on environmental influences, would do the job. Neither the models nor the data to run them are available however. For the operational analysis of problem shifting, several more simple analytic tools have been developed, aiming at specifying net improvements. They are not rich in the mechanisms operant in them. Although they give an only partial view on mechanisms, they are precise and quantified, allowing for a practical comparative assessment. There are three basic types of them, all input-output (IO) models and all based on the balance principle. All these models do not involve the dynamics of change, which we think at least partially to be resulting from free decisions and are rather not to be solved in a purely objective way.

These simple IO-models specify flows between processes, for each process keeping the ratio between input and outputs constant. The process itself is a black box. A main difference between these three models is in the way the flows between processes, as black boxes, are defined. SFA (Substance Flow Analysis) defines flows in terms of substances; LCA and MPC (Material-Product Chain Analysis) in terms of products; and IOA (Input Output Analysis) in terms of money. More complex models tend to be limited in their domain of application. Simple models, like those of the IO type, can be encompassing. So the three basic models for analysing consequences of a specific technology change all analyse adjustments the IO way: in volumes of flows in the economy. The way the flows are specified differs:

- IO 1: volumes of flows of substances (SFA)
- IO 2: volumes of flows of products (LCA, MPC)
- IO 3: volumes of flows of money (IOA).

The third IO type, if including additions for environmental application, we abbreviate as envIOA, still shorter: IOA. It is the core subject of this project. IOA derives its basic structure from national accounting, with the environmental aspects added as 'labels' to each cell, stating the environmental inputs and outputs from that cell as fixed to the volume of the total inflow/outflow of that cell. Environmental IOA models can have a threefold use. They can be used "stand alone", e.g. indicating the environmental consequences of quantitative sectoral developments. Their technological resolution is limited, so for analysing technology changes, they can have the function of full system back-up, on top of a more detailed analysis, in depth, of a core but partial system. Thus, they may be combined with economic models, as in micro-economic analysis in energy markets, with overall consequences specified through IOA. And they may be used as a background data set in the analysis of product systems, with central processes worked out at the product flow level and the remaining part of the economy linked through monetary relations. Possible links with substance flow models might be investigated.

13.3 STATE OF THE ART

Economic IO-models with an environment extension have been developed in many countries, see the list with references below. The most detailed model to date has been developed at Carnegie-Mellon University. It combines the quite detailed IO-table for the US with a substantial amount of emission data as primarily found in the TRI (Toxic Release Inventory). This IOA model has been set up in a way that allows for its use as an “add-on” model in LCA, after first specifying the central processes related to the function analysed. In Japan, detailed systems have been developed for smaller number of substances, at different institutes. In Germany, a simpler IO-table with a somewhat smaller number of substances has been produced. In the Netherlands, both simple IOA with many data and complex IOA with limited data have been developed. Similar work is going on in many countries.

In the current situation, neither of these models can be used as a general background model. There are no models covering the whole world or at least the industrial world, while most technologies are international in nature. The methods used are different between countries and research groups, and the relation of methods to the purpose of the models has been worked out only very partially. The numbers of cells discerned is different and the definition of cells is mutually incompatible between countries and research groups. Data on emissions of activities can and have been apportioned to cells in very different ways. Available data on resource use have not been linked. There are differences in statistical basis, e.g. using firms or activities as basic units. Some methods use negative coefficients to express recycling, others not, etc.

13.4 AIM

The basic aim of this project is to set up *a diagnostic IOA-model supporting the environmental analysis of technology changes.* It involves the construction of an operational IOA system for the whole industrialised world, specifying a broad range of environmental inflows and outflows, which then is used as a background system to a more detailed foreground analysis of the technologies analysed.
Main applications of this global IOA model are in:

- technology design and evaluation, by specifying the full surrounding system
- in LCA and MPC, as a general data base for all processes surrounding the central process or processes specified at a product level
- micro-economic analysis of market changes, adding all processes involved behind the markets specified (for marketed goods only).

13.5 GENERAL STRUCTURE

In the environmentally extended IO-table as required in applications, monetary flow data and data on resource extractions and emissions are combined. This IO-table may cover the whole world as one unit but for many applications some disaggregation in regions is desirable. Therefore the project output will cover some regionalised versions as well.

In all cases, the basic data available are transformed into the environmental IOA through a transformation model. By using an explicit transformation model, the subjectivity involved in the transformation, though unavoidable, can be objectified. The transformation thus becomes repeatable and transparent. Another advantage of this formalised way of transformation is that updates based on improved or newer data require less work. In the transformation, a first step is to normalise the data in the format as required. These data are fed into the transformation model, which "produces" the environmentally extended IO-table as required. A certain type of environmentally extended IO-table then may be used in one or more applications.

The first version of the global model will be based on data from USA, Canada, Europe, Japan, China and India. These countries/regions will sum up to 80 % of the global production.

13.6 Planning of the Dutch PhD project

Mr Sangwon Suh will start working in the project as a PhD student per 1 April 2000. The project specification depends on tasks others have in the project as a whole. It is safe to assume a limited contribution by others, with a broad set of tasks for CML. If others start contributing in the same framework subjects may be worked out in more detail.

Year 1
Inventories and rapid prototype:
- Survey of data sources on resource extractions and emissions in Europe
- Provisional survey of data sources on resource extractions and emissions in for the world
- Estimation model with quality indicators
- Provisional IO structure
- First estimates of resource extraction and emissions for Europe and the World
- Role of estimation model in arriving at outcomes
- Quality assessment of outcomes
- First purpose-adapted monetary IO table of Europe and the World
- International project coordination
- Detailed work programme for year 2

Papers:
- LCA related: normalisation data for Europe and the World
- IO structure for environmental analysis: criteria, main lines and options for choice.
- Data estimation on the basis of ill defined and incomplete data sources, theory and existing methods at institutes like WRI

Year 2
First full version global model; options for applications detailed

Year 3
Case applications of the model; first regionalised version

Year 4
Finalisation of data set; updating structure worked out; final thesis report

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14 A Dynamic Life-cycle Approach

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14.1 INTRODUCTION

This research presents and applies a dynamic distributed activities life-cycle emissions methodology based on the philosophy of Structural Economics and the constructs of temporal economic Input-Output (IO) interindustry modeling. Structural Economics provides a framework that allows for the integration of ecological economic concerns with environmental engineering concerns in a system-wide perspective that is suitable for comparing the implications of alternative future courses of actions.

The Structural Economic philosophy is implemented using a Sequential Interindustry Model (SIM) approach. SIM considers the time consuming nature of the production process and the corresponding timing of industry input. In essence, SIM unravels the ‘whirlpools’ of interindustry relationships, providing an empirical approach to investigate transient behaviour of finite economic activities.

A case study examining the environmental implications of introducing Fuel Cell Electric Vehicles into the U.S. Economy is presented to demonstrate the methodology. To simplify the example presented, the case study is streamlined by examining scenarios of life-cycle CO_2 emission trends over a time period of twenty years. Scenarios are developed that embrace the constructs of experimental design to achieve rigorous results.

14.2 DYNAMIC SEQUENTIONAL INTERINDUSTRY MODELING

The model applied in this research was the Sequential Interindustry Model (SIM). SIM is based on the Leontief static model where production is augmented by the specifics of production chronology. In SIM, sequences are important. SIM considers the time consuming nature of the production process and the corresponding timing of industry input. In general, the emphasis of SIM is on modeling interindustrial and intertemporal production activities in order to examine transient processes associated by final demand.

A simple example of baking bread is presented. In Figure 14-1, each batch of bread is defined by the time of the start of production t, to the end of production, σ. The pass-through time for one batch of bread production is indicated by h_j, where in this example, j is the bread making industry. This pass-through time is determined by the longest application period, h_{ij}, which indicates the time input is received by a supplying industry to the time of product completion.

In order to fully describe total production, activities required to produce the input to bread-making are also to be considered. The production of yeast associated with the production of bread making is then illustrated by superimposing the two production sequences as shown in Figure 14-2. A true *total* cross-sectional output production figure would include the activities necessary to produce the input of sugar, salt, flour and fuel for heat.

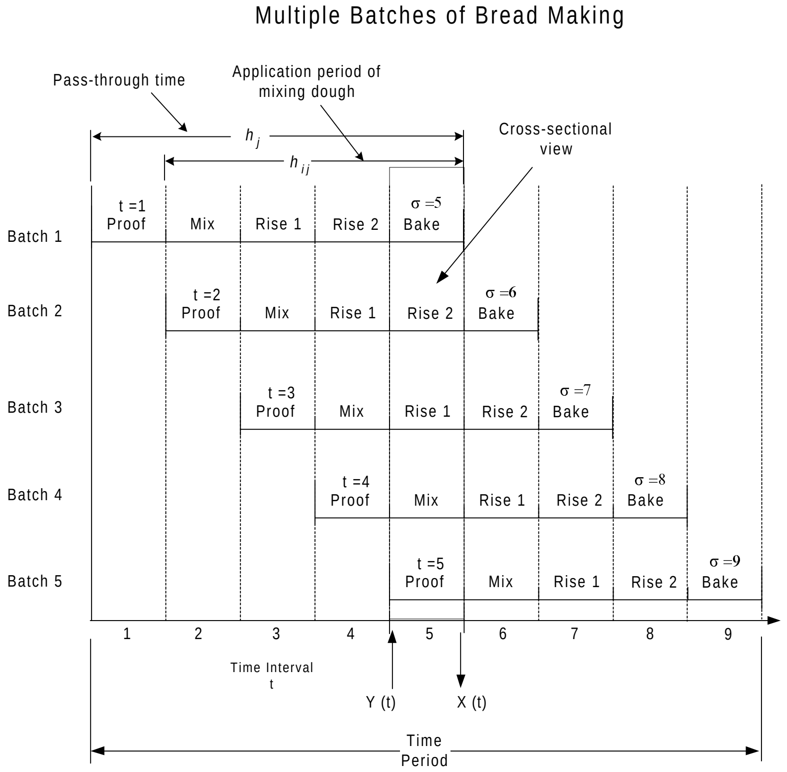


Figure 14-1: Multiple batches of bread making in SIM

In this simple example it is assumed that the processes do not change with time – they are time-invariant. Interesting issues arise when introducing the dynamics of technological change and changes in final demand. For example, in the production of baking bread one could account for a technological innovation that reduces bread rising time by half, shortening the pass-through time to four intervals. The transient associated with the adoption of this innovation would be described by concurrent use of both technologies at prescribed distribution levels.

14.3 A LIFE-CYCLE APPROACH

For life-cycle SIM the emphasis to capture activities expands to include the entire life-cycle of a commodity. In contrast to traditional IO-modeling, in life-cycle IO-modeling there are multiple input distributed over a commodity's entire life-cycle – not just within the interval of production, but also within the intervals of use and end-of-life. Moreover, there are multiple outputs distributed over the entire life-cycle of a commodity – multiple outputs within production as well as multiple outputs beyond production. For example, a simplified life-cycle SIM schema depicting the sequence of the life-cycle stages of automobiles distributed over time as shown in Figure 14-3. Within each interval, *t*, several model year vehicles are either being produced, in the early stages of their use phase, the later stages of the use phase or at end-of-life (EOL) disposition which includes dismantling of parts, reuse and recycling activities. In SIM, the sequence of the life-cycle of the vehicles by model year is preserved. The model captures the implementation of improving production techniques and fuel economy for each model year.

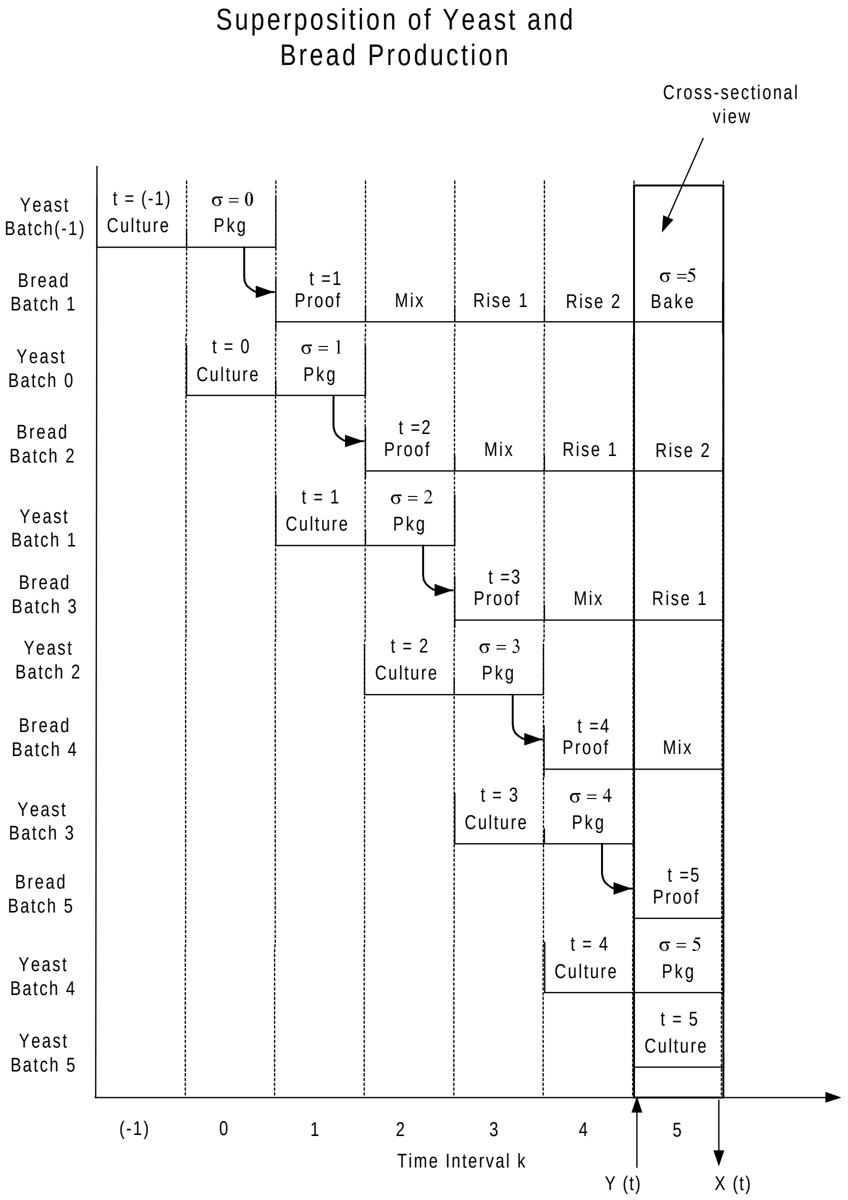
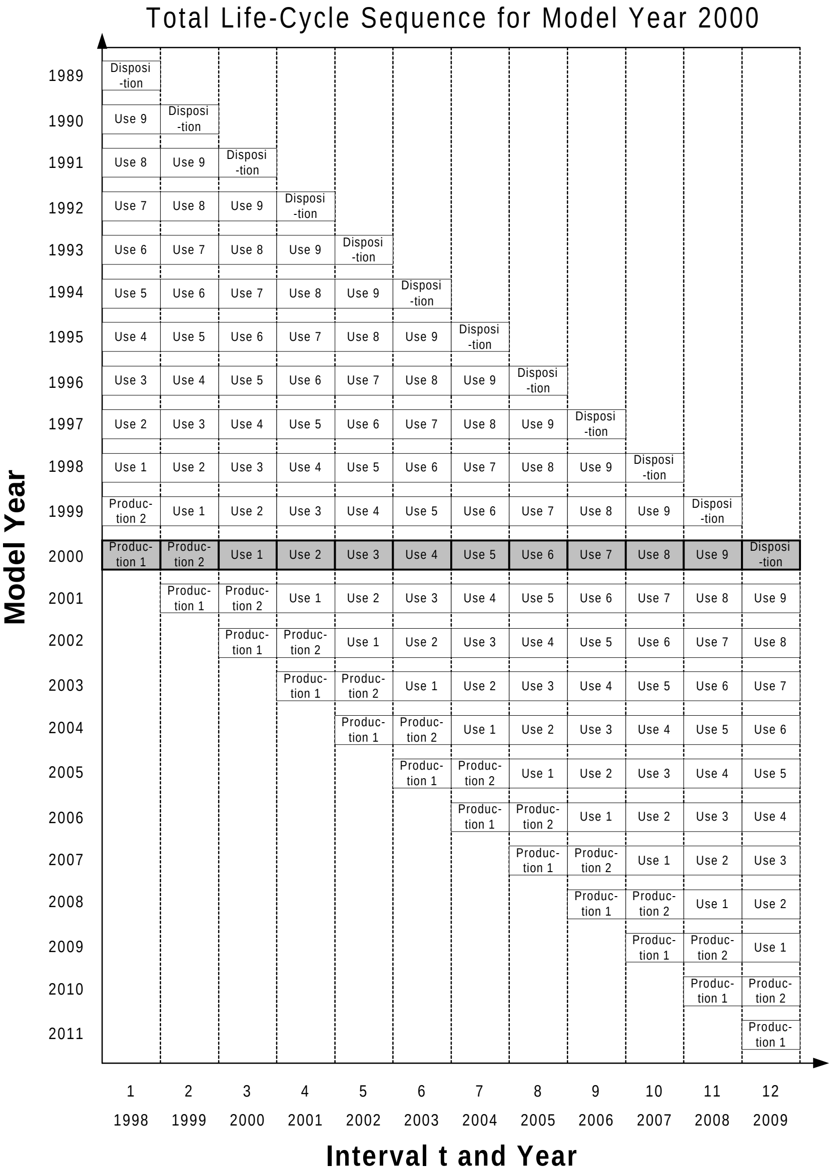


Figure 14-2: The superposition of yeast production and bread making production.

The estimate of the life-span of the automobiles depicted in Figure 14-3 is based on an expected value of operational life to be 9 years. A more accurate Life-cycle SIM schema would include the stochastic representation of the life-cycle of the population of automobiles for each model year. This would have a profound effect regarding the period of influence attributed to a specific model year. For example, the operational life of an automobile is described by a Weibull distribution. An automobile model year with an expected value of nine years would have a significant proportion of the vehicle still in operation at 12 or 13 years. Thus, within a single interval certain automobiles continue to be used while others reach their end-of-life (EOL) disposition state. Over the life span of a population of vehicles of a model year the ratio of the automobiles that continue as part of the consumption activities to the ones that have reached EOL declines in a manner consistent with its Weibull distribution.



Model Year	1 1998	2 1999	3 2000	4 2001	5 2002	6 2003	7 2004	8 2005	9 2006	10 2007	11 2008	12 2009
1989	Disposition											
1990	Use 9	Disposition										
1991	Use 8	Use 9	Disposition									
1992	Use 7	Use 8	Use 9	Disposition								
1993	Use 6	Use 7	Use 8	Use 9	Disposition							
1994	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition						
1995	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition					
1996	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition				
1997	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition			
1998	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition		
1999	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition	
2000	Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9	Disposition
2001		Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8	Use 9
2002			Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7	Use 8
2003				Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6	Use 7
2004					Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5	Use 6
2005						Production 1	Production 2	Use 1	Use 2	Use 3	Use 4	Use 5
2006							Production 1	Production 2	Use 1	Use 2	Use 3	Use 4
2007								Production 1	Production 2	Use 1	Use 2	Use 3
2008									Production 1	Production 2	Use 1	Use 2
2009										Production 1	Production 2	Use 1
2010											Production 1	Production 2
2011												Production 1

Figure 14-3: SIM schema of the life-cycle of the automobile.

To accommodate for this new expanded structure of economic activities, a technical matrix that describes distributed multiple input and output activities in an enhanced SIM model was developed by redefining the Make and Use table of the static IO-model. The Make table captures all commodities produced by a given industry and the Use table captures all commodities consumed by a given industry. The combination of the two tables can lead to analyses that have multiple inputs and outputs. For example, industries are allowed to produce more than one product and commodities are allowed to have multiples of the same input distributed over time.

The distinction of the expanded make and use tables is their representation of data stores of all possible industry and commodity activities in time. Moreover, there is a temporal link between the make and use matrices. That is, the set of distributed make and use tables as pairs represent all the recipes for production, both input and output that transform final demand stimulus into economic activity.

Typical ecological IOA examines the interindustry activities associated with the production of a commodity. Social accounting expands the analysis by examining the various categories of consumers – by geography, income, behaviour, age, or gender. A more appropriate analysis in this application of environmental Life Cycle Assessment (LCA), is the clustering of the production and consumption of commodities by the associated activities to fulfil a "functional unit". For example it is more appropriate to define the functional unit of personal transportation is satisfied by the purchase of an automobile that was produced within interval σ. The functional unit perspective facilitates the representation of alternatives. The LCA is not just of an automobile, it is an LCA study of personal travel.

14.4 MODEL EXAMPLE

As an illustration of the methodology presented, the following case study seeks to answer the question:

What are the environmental impacts/benefits of introducing an emerging fuel cell vehicle technology in the U.S. economy regarding the release of green house gases (GHGs) that may lead to global climate change? Specifically, what are the net increases or decreases of CO_2 air emissions by introducing Proton Exchange Membrane (PEM) powered Fuel Cell Electric Vehicles (FCEVs) in the U.S. economy for a period of 20 years, 2000 to 2020?

Production interindustry relationships were developed from existing Bureau of Economic Analysis (BEA) Make and Use tables at Two-Digit SIC level. The Two-Digit industry and commodity sectors were aggregated and disaggregated to form the 19 industry and commodity sectors defined in Table 14-1. The "Rest of the Economy" (ROE) sectors were included to provide context within the analysis.

Table 14-1: Interindustry and Commodity Sectors Defined.

Description	*BEA Number*
Mining	05+06, 07, 08, 09+10
Paper and Allied Products	24, 25
Chemicals	27A, 27B, 28, 29A, 29B, 30
Methanol	Based on 27A - 270100
Petroleum refining and related products	31
Gasoline	310101
Rubber	32
Iron/Steel and non ferrous metals	37, 38
Machined parts and general machinery	13, 39-52
Fuel cell system	Based on 58 - 580200, 580400, 580700
Fuel cell electric vehicles	Based on 59A – 590301
Internal Combustion Vehicles (passenger cars and trucks)	59A
Truck and bus bodies, trailers and motor vehicle parts	59B
Utilities (electric, natural gas, water)	68A, 68B, 68C
ROE 1 Agriculture and food industries	1, 2, 3, 4, 14, 15
ROE 2 Construction and Mfg.	11, 12, 16, 17, 18, 19, 20+21, 22+23, 35, 36, 64
ROE 3 Electrical equipment and Communications	26A, 26B, 53, 54, 55, 56, 57, 58, 62, 63, 66, 67
ROE 4 Services sector	33+34, 69A, 69B, 70A, 70B, 71A, 71B, 72A, 72B, 73A, 73B, 73C, 73D, 74, 75, 76, 77A, 77B, 78, 79
ROE 5 Other transportation	60, 61, 65A, 65B, 65C, 65D, 65E

Six factors (see table 14-2) were then defined to generate scenarios and conduct a formal experiment:

Table 14-2: Experimental Factors.

Factor	Low (-)	High (+)	Uncertainty
FCEV market penetration	0	25% of market	±20%
Vehicle miles travelled	Increasing trend	Increasing trend +10%	±10%
Fuel Economy of Passenger ICEVs	Current technology	20% Increase	±10%
Fuel Economy of Light Truck ICEVs	Current technology	20% Increase	±10%
Business Cycle	Increasing Trend	Cycle of contraction	±25%
Contributions by the largest emitter (Utility Industry)	Current Technology	1.8% Decrease in energy use per year	±10%

The six factors were analysed using a 2^f experimental design, where f is equal to six factors represented at two levels, low (-) and high (+). Monte Carlo simulation was then used to generate replications based on the probability density functions (PDFs) of the factors in the experimental design. The model calibration consisted of matching total CO_2 output in Million Metric Tons Carbon Equivalent (MMTCE) attributed to total economic output and for the output by passenger car use and light truck use.

The results are summarised using an analysis of contrasts depicted by Table 14-2. The analysis of contrasts summarises the amount of carbon emissions attributed by each factor, for both direct as well as two-way indirect effects. For example, in Table 14-2, the market penetration of FCEVs (FP) attributes to a reduction of 47.37 MMTCE in the year 2015. Experiment shown was normalised to vehicle purchase and use only. Normalisation to all production and use activities in the US economy was also done.

Table 14-2: Table of Contrasts for Vehicle and Fuel Purchases (in MMTCE).

Year	2000	2005	2010	2015	2020
Average	477.3	512.6	529.3	561.6	613.7
Standard Error	±0.2	±0.4	±0.4	±0.6	±0.8
Direct Effects					
FCEV Penetration (FP)	0.00	-0.04	-10.42	-47.37	-82.40
VMT Increase (VMT)	43.09	46.22	47.57	50.23	54.71
Passenger Vehicle Economy (PI-E)	-2.30	-13.09	-18.13	-22.88	-27.69
Light Truck Vehicle Economy (TI-E)	-2.36	-15.95	-27.28	-40.82	-56.83
Business Cycle (BC)	0.00	-9.06	-50.07	-42.17	-9.16
Utility Efficiency (U-E)	-0.18	-8.32	-16.22	-24.93	-34.70
Interactive Effects					
FP x VMT	0.00	0.00	-0.50	-2.26	-3.92
FP x PI-E	0.00	0.00	0.26	1.55	3.12
FP x TI-E	0.00	0.00	0.36	2.31	5.29
FP x BC	0.00	0.00	0.68	2.80	1.61
FP x U-E	0.00	0.00	0.31	1.38	2.75
VMT x PI-E	-0.11	-0.62	-0.86	-1.09	-1.32
VMT x TI-E	-0.11	-0.76	-1.30	-1.94	-2.70
VMT x BC	0.00	-0.38	-2.23	-1.91	-0.42
VMT x U-E	-0.01	-0.36	-0.70	-1.07	-1.48
PI-E x TI-E	0.00	0.00	0.00	0.00	0.00
PI-E x BC	0.00	0.11	0.85	0.92	0.31
PI-E x EU-R	0.00	0.11	0.28	0.50	0.77
TI-E x BC	0.00	0.14	1.28	1.48	0.32
TI-E x U-E	0.00	0.14	0.44	0.94	1.63
BC x U-E	0.00	0.15	0.88	0.76	0.14
Standard Error for Effects	±0.46	±0.92	±0.89	±1.13	±1.70

The experimental design utilised for the analysis of the case study allowed for the systematic creation of scenarios based on chosen factors that then led to immediate interpretation of primary effects and any interactive effects. The scenarios generated were based on using a simple 2^f experimental design, where f is equal to the number of factors represented at two levels, low (-) and high (+). Scenarios, also known as treatments, were then derived that represented all possible combinations of the levels of the factors. For this case study, 6 factors were chosen which resulted in the analysis of potentially 2^6 or 64 treatments. An exhaustive experiment that included all possible treatments allowed for the analysis of interactive effects. Techniques of fractional experimental design were then used to reduce the number of treatments without compromising analytical content. In the case study, the number treatments were reduced 50%, from 64 treatments to 2^{6-1} or 32 treatments. The end result of the experimental design was then a table of contrasts. The table of contrasts allowed for the immediate recognition of important factors, their main effects, their interactive effects and their rank order. This method allowed for a concise quantitative tabulation that was transparent to the complex interactions of the system simulated.

14.5 NOTABLE OBSERVATIONS

The simulation of the experiment normalised to vehicle production and use examined the introduction of a promising technology, FCEVs that would supplant an existing technology, ICEVs, through a 25% market penetration of new purchases. Although, the production and disposition of the two products' technologies were virtually the same and assumed to be identical statically, the emerging FCEV technology is far superior to the old regarding use phase characteristics. FCEVs emit 50% the amount of CO_2 when compared to the average ICE passenger vehicle and 40% for ICE light trucks. However, the static analysis does not provide insight regarding emission reductions when normalised to the present and future fleet of vehicles in use. By expanding the level of normalisation, the system becomes one that is dynamic.

The emissions generated by satisfying the functional unit of personal transportation over a period of 20 years involved changes in the production and use of the automobile. This involved the dynamics of:
- Production efficiencies,
- The number vehicles produced and in operation, by type and model year,
- Their distribution of actual miles travelled,
- The forecasted total vehicle miles travelled, and,
- Fuel economy by automobile type and model year.

These five areas of dynamics ultimately varied the demand for fuel both in the production of vehicles and their use over the period of analysis. Therefore, fuel consumption was dynamically determined, where future fuel demand and eventual consumption was based on the previous purchases of vehicles.

The insights revealed by simulating these dynamic factors were of the following:

First, the benefit of emissions reduction by introducing FCEVs was significant but not of a magnitude suggested by an apparent static analysis of a 50% reduction in emissions per vehicle mile travelled. FCEVs initially entered the market in year 2004 and emission reductions after 6 years on the market were only 2%. Despite 16 years of aggressive 25% market penetration, the final interval of simulation resulted in a maximum reduction of 13.4%. This difference from the static observation was mainly due to the relatively small number of FCEVs in operation compared to the rest of the fleet. FCEVs accounted for 21.5% of the vehicles in operation at the final interval.

Second, near the end of the simulation period, within the last 5 years, several interactive effects between the FCEV penetration and other factors became apparent: The more VMTs, the greater the benefit of FCEVs to reduce emissions. Conversely, the fewer VMTs the less the benefit of FCEVs to reduce emissions. However, overall increasing VMTs results in significant increases in emissions, i.e. increases in the reduction of emissions were only realised when there was overall more consumption. The market penetration of FCEVs reduced the benefits realised by fuel economy of light trucks, however, the FCEVs reduce emissions by a greater amount, hence net emission reduction was greater. The business cycle reduced the effectiveness of FCEVs to decrease emissions. This occurred for two reasons. First, the recession period of the business cycle indirectly reduces total VMTs, which as stated above also decreases the effectiveness of FCEVs to reduce emissions. Second, because during the recession period of the business cycle purchases of all vehicles are decreased, fewer FCEVs were in operation, which also decreased the effectiveness of FCEVs to reduce emissions.

Third, in addition to FCEV market penetration, other direct effects observed include the magnitude of reductions due to the combined improvements in fuel economy of ICE passenger vehicles and light trucks. In the last interval of the simulation, the improvements in their fuel economy led to reductions equivalent to those of FCEVs. However, as shown in Figure 14-4, the cumulative amount of reductions due to ICE fuel economy improvements over the period of analysis occurred sooner. Changes in their fuel economy benefited reductions in emissions much earlier than reductions due to FCEV operation. The existing market penetration of ICE passenger vehicles and light trucks is much greater (75%) than the market penetration of FCEVs. As long as ICEVs remain the predominate vehicle purchased, slight changes in the fuel economy of new vehicles will result in relatively larger reductions in emissions.

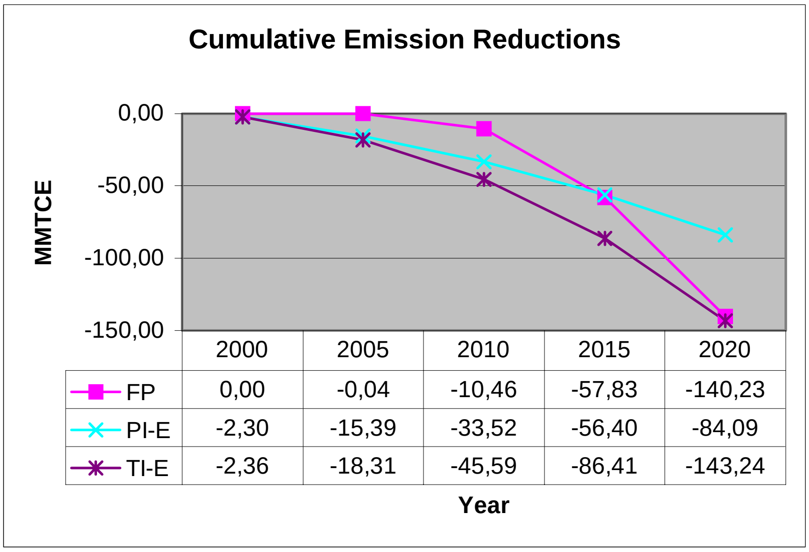


Figure 14-4: Cumulative CO_2 Emission Reductions.

Last, despite the limited boundary of this experiment to include only production related to vehicle manufacturing and fuel refinement, emissions reduction due to gains in energy efficiency were significant. This is due to the large contribution of GHGs in the generation of electricity in the utilities sector. Electricity used directly in the production of vehicles and their respective fuels, and any indirect effects contributed to the reduction in emissions.

In the expanded normalisation experiment, the rest of the economy was included in the simulation of vehicle production and use. The magnitudes of the quantitative results were surprising. As in the first experiment, the innovative technology, FCEVs were assessed to be environmentally superior in their reduction of CO_2 emissions when compared statically to similar vehicles. Plausible economic conditions were simulated to favour the introduction of the technology. Marginal improvements were made to competing technologies to gain insight as to the magnitude of their potential improvements. Within the larger context of the U.S. economy, the percentage reduction was 3%. This reduction was realised after considerable duration in the market with favourable characteristics of an aggressive market penetration and a far superior fuel economy, twice that of existing vehicles.

The normalisation to the rest of the economy illustrates the contextual importance of the 3% reduction of emissions. The U.S. economy becomes 1.8% more energy efficient each year. This slight trend in efficiency accounted for an 8.3% reduction in CO_2 emissions for the interval of year 2020. This is a reduction of nearly three times that of the 50% gain in efficiency by the new transportation technology of FCEVs. This disparity of influence is based on the magnitude and interdependence simulated and captured by the Life-cycle SIM model. Small reductions in fuel purchases by all industries, both directly and indirectly, lead to significant total reductions in emissions.

A further analytical observation regarding insight gained is the relevance to the principles of economic lock-in, that is, present and future purchases are a function of past purchases and production activities. The principle can be observed in two ways. First, based on previous purchases of vehicles the system described is inflexible to fuel purchases of the future. Simply, if there are no methanol fuel cell vehicles purchased today, there will be no consumption of methanol in the future. More precisely, there is a relationship of purchases of methanol and gasoline based on the several aspects of the current vehicles in operation. The vehicles in operation as demonstrated are directly related to the vehicles purchased. Second, because the system is inflexible, inefficiencies occur. In this case, although methanol fuel cell vehicles may be the overall superior technology, economically and environmentally, there still remains a large consumption of gasoline dictated by the previous purchases of automobiles that can only operate by combustion of gasoline.

14.6 CONCLUDING REMARKS

The conventional approach to LCA has traditionally been a static engineering or technical exercise with little concern towards social, economic and temporal aspects. In this paper a method to expand the LCA methodology to address these shortcomings was presented. This research developed and applied a dynamic life-cycle emissions methodology based on the philosophy of Structural Economics and the Sequential Interindustry Model (SIM). Specifically, this research examined:

- The importance of context in a cross-disciplinary perspective to create an appropriate analysis and presentation of results,
- The importance of a dynamic approach to environmental LCA,
- The application of a distributed activities economic IO-model applied to the environmental LCA methodology,
- The use of experimental design constructs to generate scenarios.

In conclusion, the dynamic simulation gives insight to the dynamics of a new technology and its diffusion into a dynamic economy and its ultimate change in resources used and emissions to the environment. Even though simplifications were made, insights beyond a static analysis are significant. The rate of introduction of a new technology and its effect on emissions reduction for an interval time can be determined. Further, cumulative emissions over the period of analysis can be simulated. This is especially important to estimate actual impact to the environment. The effects of the dynamics of the economic system and the relevance to the introduction of the new technology can be examined. Through experimental design, insight is gained regarding those interactive factors that counteract the new technology benefits, those factors that enhance them, and equally as important those factors that are insignificant. Moreover, policy decisions can be assisted regarding:

- The rate the new technology is to be phased in and an old technology to be retired,
- The amount of time the policy option is to be implemented to achieve its objectives, and,
- How long the policy option induces change or reaches a steady-state.

Historically, the dimension of time in LCA has been ignored or assumed to be infinite. The research in this study indicates that there is much to be gained through dynamic analyses. Although the constructs of LCA remain the same (Goal and Scope, LCI, LCIA and interpretation), their depth and breadth in a dynamic context are vastly more complex. Therefore, there is a need for discussion and consensus in the open literature regarding the philosophy and constructs of dynamic LCA.

15 Report from discussion

15.1 GENERAL DISCUSSION

This chapter summarises the general discussion, which followed the presentations.

The debate was structured around the following issues:
1.2 What role should IOA play in relation to Life Cycle Assessment (LCA)?
1.3 Advantages and disadvantages of increased use of IOA and IO-data in LCA
1.4 Market based LCA and IOA. Possibilities for more economic modelling and forecasting?
1.5 Need for further initiatives?

This chapter is based on notes taken during the discussion. It may contain errors or interpretations, which are solely the responsibility of the authors of this report.

15.2 WHAT ROLE SHOULD IOA PLAY IN RELATION TO LCA?

Anders Schmidt, dk-TEKNIK, felt that Manfred Lenzen had exaggerated the incompleteness of process-based LCA and the need for IO-data to expand the system studied. He suggested that the data left out in some cases might be similar in all studied systems, and therefore not important for the final assessment. He asked if similar products, like two plastic cups could be compared on 1st tier process-data?

Manfred Lenzen rejected the possibility for short cuts with the words: ”you don’t know how wrong or right you are, before you have done the calculations”. Greg Norris agreed that traditional LCA leave out processes in depth as well as in breadth, and that magnitude of this error is unknown.

Tapio Pento, University of Jyväskylä, saw other ways to increase certainty of LCA. He referred to his own research working with LCA on paper and steel for 10 years, in the last 5 years partly using IO-data. His experience was that IO-data was mainly relevant for services, while for materials IO-data would in some cases increase the error of the assessment compared to process data, since it hides the underlying variation of factor 2 to 10 in the measured data, both within and between mills. Many LCA data are published with little information on the conditions and limitations of the measurement. Also allocation gives rise to uncertainty, also or maybe even especially within IO-data, since there is little reason to believe that emissions are related to monetary costs.

Manfred Lenzen answered that process-based data are biased because of the truncation error. Proces-data will always be too low, whereas IO-data may be either too high or too low. He asserted that IOA should not be used as a stand-alone tool but in the form of hybrid tools.

Bo Weidema pointed out that the questions to be solved by LCA and IOA are not the same. Referring to Marianne Wesnæs’ presentation he argued that product development was hardly possible based on IO-data alone.

Greg Norris pointed out that the applicability of national statistics in respect to environmental assessments varies considerably between countries. In e.g. USA and Finland the organisations collecting production and trade data are different from the ones collecting the environmental data, and also applying different classification systems. In e.g. Denmark and Canada the national statistics to some extent collect both types of data, making it easier to combine the knowledge.

Ole Gravgård Pedersen, Statistics Denmark, explained about international work on standardising the system of classification, in order to facilitate usage of data on the national as well as international level. The work is done within EUROSTAT, and the task for now is to harmonise systems for national accounting matrices and environmental accounts (NAMEA). He suggested that IOA and LCA should be used in combination, researching the differences to adjust the results. In this way IOA should be used to scope the LCA.

Sangwon Suh argued that in spite of improvements in the classification system, classification problems would persist since IO table is constructed based on input homogeneity while emission data are available on an establishment basis. He also pointed that the Monte-Carlo type of uncertainty analysis in IOA will result in more certain outcomes than individual parameters that were used in the assessment because of the cancellation effects which can be characterised as “Garbage in, fancy things coming out”.

Bo Weidema concluded that the answer to the first question on the discussion agenda was that the role of IO-data in relation to LCA is to be used as a supplement, to give an overview of effects and to validate process data.

15.3 ADVANTAGES AND DISADVANTAGES OF INCREASED USE OF IOA AND IO-DATA IN LCA

Marie Münster, Rambøll, feared that the use of IO-data could be a sliding-lane leading to decreased accuracy. If we allow filling gaps with cheap IO-data, performers of LCAs with big gaps will be rewarded.

Manfred Lenzen responded by referring to a method introduced by Graham Treloar, Deakin University in Victoria, based on previous work by C. Bullard. First, the assessment is carried out merely with IO-data. Secondly, the chains are ranked according to the relative contribution to the total result, thus implying a data collection strategy. Third and finally, process data can be collected until the desired level of accuracy is reached.

Jesper Munksgaard said that the model’s level of complication should equal the level of details inherent in the questions asked by the decision makers. Anders Schmidt added that in his view most decision-making was done on basis of quite rough indicators, and that a certainty level of 75 % would satisfy most. Tapio Pento argued that decision makers regulate at industry level, and does not need much more detail with regard to single products.

Bo Weidema raised the question whether knowledge from IO-tables can be extrapolated geographically, or whether the data will differ from country to country.

There was a general scepticism towards geographical extrapolation. Sangwon Suh pointed that many developing countries are using IPPS of the World Bank (http://www.worldbank.org/nipr/polmod.htm) for emission data compilation; however, this system was originally based on US TRI data so that there is very limited applicability to other countries where technologies are different. Marie Münster added that many environmental problems are related to behaviour, and that behaviour therefore also should be similar.

Tapio Pento once more pointed to the value of process-based data by pointing to the national focus of IOA, giving rise to a geographic truncation error. In IOA all import is assumed produced using technologies similar to the domestic production.

There was a general agreement that IO-tables aggregated on international level could help to solve this import problem, and thus increase the reliability of IO-data. Sangwon Suh referred to the project at CLM, where an international IO-table is produced, covering 80 % of global production.

Christian Poll, Danish Environmental Agency, was concerned about the consequences for sustainable development, and asked whether the implicit economic focus in IO-data would not mean that the use of IO-data would work counter to the decoupling of economic growth and environmental problems.

Greg Norris answered that the current type of IOA could only be static, and give snapshots of current situation. Ole Gravgård Pedersen supplemented that IOA does have a static, historic perspective, but it consists of many different parts, which change. Therefore it is possible to distinguish between factors as level of consumption, energy demand in different sectors, energy efficiency etc.

Bo Weidema pointed out that traditional process LCA often leave out the actual economic implications of shifts between products, namely that a shift to an expensive product will prevent some other consumption. He felt that an IO-based analysis would be less likely to make this mistake, since it measures consumption in monetary terms.

15.4 MARKET BASED LCA AND IOA. POSSIBILITIES FOR MORE ECONOMIC MODELLING AND FORECASTING?

A question from the floor raised the issue of co-product allocation.

Greg Norris explained that IO-data by default are allocated according to value, and that this could imply errors. When using the data for LCA, some kind of physical modelling should therefore be preferred.

Bo Weidema added, that modelling is essentially what everybody wants, but whether it is actually done depends upon the resources available for the specific study. For LCA, co-product allocation is unnecessary, because it is possible in most cases to define the marginal technology, i.e. the technology that is actually affected and will increase or decrease the production capacity in order to accommodate the change in demand related to the product under study.

However, Bo Weidema raised the question whether such marginal analysis can be integrated in IOA.

There was a general agreement from the panel that it is possible in principle to make such integration, and that it is mainly a data problem to identify the constraints that the technologies are subject to.

Sangwon Suh pointed out that it was a difficult and time-consuming question. At the Dutch institute RIVM, a special group is employed to deal with the question about effects of consumption changes.

Greg Norris pointed out that there are two parameters for the dynamic modelling: average/marginal and linearity. The models closest to reality might be marginal and non-linear, but taking into account that the traditional approach is average and linear, the scientific standard is improved significantly by moving to linear, marginal modelling.

15.5 NEED FOR FURTHER INITIATIVES?

Anders Schmidt pointed out that for practical use it was necessary to have a clear method for how little data was necessary to reach a reasonable certainty of the study. Thus a quantification of the uncertainties by speed of conversion per sector (or per input) is needed. Bo Weidema suggested to this end that Treloars’ method should be tested and developed in a practical case study with Danish data.

Manfred Lenzen was curious about the audience´s reasons to show up. In response to this, Arne Egelund, Technical University of Denmark, said that he had hoped for an easy method to make traditional LCAs more complete.

Greg Norris launched the vision of a computer program for environmental assessments with a default IO-database as fallback, still offering the opportunity to insert process-data. Tapio Pento and Sangwon Suh pointed to the program KCL ECO, which uses the IO-relevant inverted matrix calculation.

Bo Weidema asked what plans Statistics Denmark had for producing IO-tables with physical units. Ole Gravgård Pedersen answered that the NAMEA work continues, but that there are no present decisions on whether the work on complete physical input-output tables will be continued. He pointed out that degree of external demand would be taken into account before work continues.

15.6 REFERENCES

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Treloar, G.J. (1997). Extracting embodied energy paths from input-output tables: Towards an input-output-based hybrid energy analysis method. Economic Systems Research, vol.9, no.4.

16 Report from expert meeting

16.1 INTRODUCTION

This chapter summarizes the discussion at the expert meeting held on Saturday the 30th of September - the day after the workshop. The participants were:

- Tapio Pento, University of Jyväskylä, Finland,
- Ole Gravgård Pedersen, Statistics Denmark, Denmark,
- Greg Norris, Harvard University, USA,
- Manfred Lenzen, University of Sydney, Australia,
- Sangwon Suh, Leiden University, The Netherlands,

and hosts were:
Bo Weidema and Anne Merete Nielsen, 2.-0 LCA Consultants, Denmark

The debate was structured around the following issues:

2 Presentation of participants and their current work
3 Other current work of interest
4 Dynamics and modelling
5 Applying I/O-A in LCA

16.2 PRESENTATION OF PARTICIPANTS AND THEIR CURRENT WORK

Tapio Pento, Professor at the University of Jyväskylä, Finland, has been working for a decade with material flows, mainly in the paper sector. He mentioned having constructed a hybrid model in 1993. He has currently 9 Ph.D. students working on different topics within this field:

- Two work on a 65 by 65 input/output satellite account for the forest products sector for Finland (both tons and monetary units).
- One studies dynamic industry-level emission data.
- Two work on large forest sector LCA based on 2200 by 2200 product to product matrices for Finland and Germany, made with the KCL-ECO software with modifications, based on data from 1991 and 1997. The functional unit is the FAO forecasts of the market demands of products, and the analysis covers changes in investment, technology, recovery rate and re-use patterns.
- Two work on quasi-dynamic market based hybrid models for the forest sector in the Nordic countries and UK (environment, money and employment).
- One prepares a regional LCA-hybrid of energy and main material flows.

Tapio Pento presented a number of slides that analysed the relationship between pollutant emission and scale of plant in the pulp and paper industry as an example of large potential uncertainties of using the linearity assumption in I/O based LCA. Tapio Pento also described it as challenging to obtain the “off-diagonal” data which links a satellite model to the original model. With further discussion it became clear that the challenge focuses on linking outputs from the satellite system to users elsewhere, and that these challenges are surmountable with data from the companies involved.

Ole Gravgård Pedersen described his NAMEA and physical I/O work at Statistics Denmark. He indicated that most European countries had constructed NAMEAs by now. Denmark has published annual I/O tables since 1966. The air emissions factors for Denmark's NAMEA are based on fuel consumption data together with emissions factors (kg/energy unit) for groups of industries, published by the Environmental Research Agency. Also measured emissions and some non-energy-related emissions are included.

Greg Norris described his work on making LCA-tools integrating NAMEAs (see http://www.sylvatica.com/tools.htm).

Manfred Lenzen gave a quick review of the extensive work he has completed to date. Among other work, he mentioned a paper including the rebound effects from changes to disposable income. He mentioned that 1st order rebound effects could be significant, 2nd order effects were not investigated. He mentioned a paper in the US looking at the impacts on CO_2 emissions of cutting the defence budget and how it depended on what was done with the money. He also mentioned research to strengthen the upstream component of Rees and Wackernagel's work, and work by CSIRO using satellite imagery to bring land disturbance impacts into I/O-LCA (Graetz et al. 1995).

Sangwon Suh has 4 years of funding to complete his PhD at Leiden University (CML), working on a multi-national I/O-LCA model, which captures the bulk (i.e. 80%) of world economic activity. He also presented a hybrid LCA model in which a process based foreground matrix is linked to an I/O background system. CML is working on modification of CMLCA software (http://www.leidenuniv.nl/interfac/cml/ssp/cmlca.html), which will allows users to apply this hybrid modelling technique. Sangwon reported looking for some application fields, such as:

- Materials flow analysis,
- CO2 budgets for nations and regions with a focus on consumption-driven allocation rather than activity-driven inventories,
- Extending Leontief's "factor content approach" which looks at upstream capital intensity versus labour intensity.

16.3 OTHER CURRENT WORK OF INTEREST

It was suggested that the resolution of GTAP (http://www.agecon.purdue.edu/gtap/) was very coarse, suited to strategic, long-term policy questions at a world level, but not to LCA. Evidently this level of modelling has lead to two articles using coarse global I/O-models to look at sustainability questions; one by Imura & Moriguchi (1995) and one by Proops et al. (1999).

The "London Group" (http://ww2.statcan.ca/citygrp/london/london.htm) is meeting to revise the 1993 UN guidance document entitled "Integrated Environmental and Economic Accounting." (This older report is UN report number ST/ESA/STAT/SER.F/61). Ole Gravgård Pedersen cautioned that the focus of this group is more on general environmental accounting and not on pollutant releases only.

Harald Florin, IKP in Stuttgart, Germany (http://www.ikpgabi.uni-stuttgart.de/) is the German point of contact in connection with the multi-regional project of CML. Their research interests include searches for "zero emission" scenarios of waste-to-feedstock conversion in the economy.

The IPPS system of the World Bank (http://www.worldbank.org/nipr/polmod.htm) was also mentioned. It has taken US emissions factors from the US to offer developing nations an ability to estimate the total upstream environmental implications of development options.

The MARKAL-MATTER model (http://www.ecn.nl/unit_bs/etsap/markal/matter/) was also mentioned. Dolf Gielen was a key person in the development of this model, and he is now working with Yuichi Moriguchi, who is a key contact person for IOA/LCA-work in Japan.

The work of Treloar (1997) was also mentioned as an important contribution (see below).

16.4 DYNAMICS AND MODELLING

The problems regarding the import assumption (that imported goods are treated with the same production functions as domestic goods) appear to be well taken care of through the multi-regional modelling undertaken by Sangwon Suh.

The problem of structural change could be investigated through time series of I/O data. Greg Norris indicated that he planned to work on this issue.

There was considerable discussion of marginal versus average impacts of consumption changes. It was first concluded that for “allocation of guilt”, average models are adequate. For what-if (prospective) decision support, marginal models are more accurate. The question becomes: which plants will increase or decrease output, (or leave production entirely) as a result of the predicted demand changes?

The importance of using marginal production functions and emissions coefficients increases with the variability/heterogeneity of the plants in a sector. It also depends upon economic considerations and constraints specific to each sector.

For modelling of materials with recycled content, I/O matrices include implicitly the average recycled content for products of the sector as a whole. Bo Weidema pointed out that in growing markets, it is most accurate to model material inputs as coming entirely from virgin inputs, since in this situation the recycled content is generally constrained by the supply of recyclable material.

It was concluded that there is a need to create a modified, marginal I/O matrix for dealing with prospective questions. Bo Weidema and Greg Norris indicated that they plan to write an initial paper on this issue.

The impacts of re-spending (the “rebound effect”) have been studied by Manfred Lenzen. It is obvious that the impact of re-spending is an issue that can only be treated adequately by marginal modelling.

16.5 APPLYING I/O-A IN LCA

The potential sources of error in developing sector pollutant intensities were discussed at length. Greg Norris exemplified this with respect to the use of the Toxic Release Inventory. These sources of error were summarized as follows:

- Classification mis-match between reporting sectors (e.g., SICs) and I/O Sectors. The challenge arises in part because the I/O sectors are constructed by separating the production of diverse products (sometimes by the same reporting establishment) into different sectors. The problem also arises when a given SIC has been mapped to more than one I/O sector.

- Sector non-reporting: not all sectors of the US economy, for example, are required to report toxic releases as part of the US EPA's Toxic Release Inventory (TRI).
- Establishment non-reporting: not all establishments within reporting sectors are required to report their toxic releases. For example, establishments with fewer than 10 full-time-equivalent employees are exempt from reporting.
- Chemical non-reporting: not all chemical releases are reported by reporting establishments. For example, chemicals for which annual usage is less than 10,000 lbs per year are exempt from reporting.
- Reporting/measurement/estimation error: TRI releases are not required to be measured, but are often reported based on mass-balance calculations, the use of published emissions factors, or "other approaches."

Sangwon Suh indicated that it is part of his current work to seek to limit these sources of error.

A need was identified to inform those responsible for collecting statistics (both environmental and economic) about the requirements from the side of environmental product assessment.

The work of Graham Treloar (1997) was discussed at length. The idea of identifying critical energy paths was recognized as fundamental to further work in this field. It was suggested that uncertainty (and possibly the idea of speed of convergence, see Chapter 9) should be integrated into the approach. Sangwon Suh and Bo Weidema pointed out that Treloar implicitly assumed every value to have the same uncertainty, while a process analysis typically would include processes with a large uncertainty, such as "industrial chemicals", even though the process on average contributes only little to the overall result. Regarding uncertainty, Manfred Lenzen referred to a forthcoming article of his. Important issues mentioned for further research were to test the homogeneity assumption, to investigate correlations in the I/O data, and to investigate allocation procedures based on economic value versus physical quantities.

The development of software for hybrid LCAs was discussed. It was suggested that coordination would be useful between the CML-LCA software, Greg Norris' LCNetBase and possible future advancements of PRé's SimaPro software. Greg Norris volunteered to gather the relevant stakeholders for a dialogue.

16.6 REFERENCES

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