

# **Data Frameworks in Monetary, Physical and Time Units for Quantitative Sustainable Consumption Research**

**Jan Christoph Minx**

**PhD in Environmental Economics and  
Environmental Management**

**University of York**

**Environment Department**

**March 2007**

# Abstract

The overriding aim of this thesis is to establish how integrated input-output data frameworks in monetary, physical and time units can contribute to a better understanding of the environmental pressures generated by a given final demand including the underlying economic, social and demographic driving forces. The thesis mainly focuses on environmental input-output analysis and related methods and evaluates the opportunities provided by recent data developments at the Federal Statistical Office. In particular, physical input-output tables and social accounting extensions published as part of the “socio-economic reporting system” are used for improving the specification and conceptualisation of production technology and lifestyles.

The first part of the thesis contributes to the recent discussion on monetary and physical input-output analysis. In particular, it looks at how the representation of production technology can be improved through the availability of information from physical input-output tables (PIOT) to allow for a more robust allocation of environmental pressures to final consumption/demand. The conceptual discussion highlights a whole range of misperceptions in the debate associated with the construction of the German PIOT and highlights the shared conceptual basis between monetary input-output tables (MIOT) and PIOTs to the extent to which product flows are concerned.

However, a detailed empirical comparison of production structures in monetary and physical units using the graph theoretical toolkit provided by qualitative input-output analysis highlights fundamental differences in their representation of technologies due to the particular scope of monetary and physical measurement: 45% of all intermediate product flows in MIOT and PIOT are fundamentally different in that they have a positive record in one table and a zero record in the other.

As expected, most of these are ‘weightless’ immaterial service flows. However, the thesis highlights that such fundamental differences in the production structures associated with intermediate service flows are not only relevant in tertiary sectors, but are prominent throughout the economy: in fact, for some manufacturing sectors of capital goods with a high service component immaterial service flows can make up to 90% of all intermediate outputs, highlighting the importance of an endogenisation of capital investment for an adequate attribution of environmental pressures to final demands.

Remaining differences are explained by unpriced, material flows in environmental service sectors (recycling, waste treatment), where PIOTs provide a more comprehensive coverage. The first part of this thesis concludes by highlighting that production technology in environmental input-output models will usually be most appropriately specified in hybrid units. An outline of some of the main avenues for future research is provided.

The second part of the thesis uses detailed SAM-type extensions to better understand the environmental pressures associated with lifestyles in their socio-demographic context. Initially, an expenditure based lifestyle definition is deployed to analyse the social and demographic driving forces behind changes in GHG emissions associated with consumption patterns of 45 lifestyle groups in Germany between 1990 and 2002. A structural decomposition analysis confirms previous studies in that most technologically induced reductions in GHG emissions have been “eaten-up” by additional emissions from growth in final consumption. However, results highlight that important demographic trends are at work at the same time counteracting GHG emission savings. These pressures need to be considered in climate change policy formation, if climate change targets are to be delivered,

Results from the environmental input-output model are further analysed using a panel regression approach in order to highlight the influence of individual social, economic and demographic determinants of GHG emissions. The time-specific effects capture the slowing progress in GHG emission reductions after the re-unification in Germany. Group specific effects highlight the dominance of household size and the belongingness to a particular social group for differences in GHG emissions from consumption patterns of different lifestyle groups.

The analysis is concluded by highlighting the importance of adding social and demographic information into standard environmental input-output frameworks to better understand global environmental pressures generated by the consumption patterns of different lifestyle groups. However, the top-down classification of lifestyles as commonly applied in national accounting based on only a few socio-demographic descriptors such as income, occupancy and household size is seen to limit the analysis. Of at least equal importance with people’s social and demographic characteristics are the local conditions within which they are acting: general neighbourhood characteristics, the accessibility of private and public services and building properties (size, type, age, insulation etc.). Geo-

demographic lifestyle classifications, as commonly applied by marketing practitioners, are proposed as a spatially-specific alternative raising hopes to overcome the “one size fits all”-type policy recommendations which are commonly derived from environmental input-output models.

Finally, the commonly applied expenditure based lifestyle definition is fundamentally challenged. It is argued that a lifestyle definition should be based on what people do rather than on what they spend. Following the economic household production function literature, this activity focus in the empirical description of lifestyles can be achieved through the introduction of time-use data. The usefulness of the approach is demonstrated in an empirical example using data from the input-output tables in time units provided by the Federal Statistical Office of Germany.

In the Appendix of this thesis, an initial analysis of the social and economic determinants of CO<sub>2</sub> emissions based on geo-demographic lifestyle data is provided. Furthermore, different ways of dealing with environmental pressures from imported products based on single region and multi-regional input-output models are discussed and a methodology for estimating Ecological Footprints based on input-output analysis is proposed.

# Contents

<b>Abstract.....</b>	<b>2</b>
<b>Contents.....</b>	<b>5</b>
<b>List of Tables.....</b>	<b>10</b>
<b>List of Figures.....</b>	<b>13</b>
<b>List of Boxes.....</b>	<b>15</b>
<b>Acknowledgements.....</b>	<b>16</b>
<b>Author's Declaration.....</b>	<b>18</b>
<b>Dedication.....</b>	<b>19</b>
<b>Chapter 1 Introduction.....</b>	<b>20</b>
1.1 Sustainable consumption – Background.....	21
1.2 Conceptual roots.....	22
1.2.1 The literature on resource consumption.....	22
1.2.2 The literature on economic consumption.....	23
1.2.3 Implications for the debate.....	27
1.3 Modelling Sustainable Consumption.....	28
1.3.1 Conceptualising Sustainable Consumption	28
1.3.2 Using environmental input-output analysis for quantitative Sustainable Consumption research.....	30
1.3.2.1 Basic input-output economics.....	31
1.3.2.2 Generalised environmental input-output analysis and hybrid unit models.....	33
1.3.2.3 Representing domestic technology: Monetary vs. physical input-output analysis.....	36
1.3.2.4 Representing consumer behaviour and lifestyles.....	38
1.3.2.5 Representing foreign technology and accounting for global trade: Multi-regional input-output analysis.....	41
1.4 Aims and outline of thesis.....	44
<b>Chapter 2 On Flaws and Features of Physical Input-Output Tables: A Comment on the Physical Input-Output Debate and Some Analysis.....</b>	<b>48</b>
2.1 Introduction.....	49
2.2 On the construction of the German physical input-output tables..	50
2.2.1 The case of agriculture and forestry output.....	51
2.2.2 The case of service outputs.....	52

2.2.3	The table layout.....	53
2.2.4	On the construction of physical input-output tables.....	54
2.3	Revisiting the unit price argument.....	55
2.3.1	A generalised unit price model.....	55
2.3.2	On the existence of positive unit prices.....	57
2.3.3	On the representation of services in single unit physical input-output tables.....	58
2.3.4	Implications for environmental input-output modelling.....	60
2.4	Towards an empirical discourse on the empirical differences between monetary and physical input-output analysis.....	62
2.4.1	Methodology and data description.....	62
2.4.2	Some empirical results.....	64
2.5	Conclusion.....	68
<b>Chapter 3</b>	<b>Seeing the Forest for the Trees? Using Qualitative Information to Reveal Structural Features in Production Systems in Alternative Measurement Units.....</b>	<b>70</b>
3.1	Introduction.....	71
3.2	Literature review.....	74
3.2.1	Monetary and physical input-output analysis.....	74
3.2.2	Qualitative methods and physical input-output tables.....	78
3.3	Methodology.....	83
3.3.1	Revealing a production structure in monetary and physical units using qualitative input-output analysis.....	84
3.3.2	A simple method for revealing the nature of product flows.....	86
3.4	Data Description.....	87
3.5	Results.....	91
3.5.1	Visualising product production structures in monetary and physical measurement units.....	91
3.5.2	On the nature of product flows.....	103
3.6	Conclusion.....	109
<b>Chapter 4</b>	<b>The Impact of Lifestyle and Socio-Economic Factors on Greenhouse Gas Emissions in Post-Unification Germany.....</b>	<b>112</b>
4.1	Introduction.....	113
4.2	On the consumer lifestyle approach for analysing energy use and GHG emissions.....	117
4.2.1	The impact of lifestyles and socio-economic factors.....	117
4.2.2	Input-output based analyses of lifestyles.....	119
4.2.2.1	Advantages of input-output based approaches to lifestyle analysis.....	120
4.2.2.2	Methodological challenges.....	121
4.3	Input-output methodology and Data.....	123
4.3.1	Estimating the energy demands and climate change impacts of lifestyle cohorts.....	123
4.3.2	Structural decomposition analysis: Identifying driving forces behind changes in GHG emissions.....	127
4.3.3	Data description.....	130
4.4	Results and policy implications.....	133

4.4.1	On the climate change impacts of household consumption.....	133
4.4.2	Driving forces behind structural changes in GHG emissions from household consumption.....	141
4.5	Panel regression approach.....	144
4.5.1	Data Preparation.....	144
4.5.2	Model outline.....	146
4.5.3	Specification testing.....	147
4.5.4	Result discussion.....	147
4.5	Conclusion.....	152
<b>Chapter 5</b>	<b>Time and Sustainability? An Input-Output Approach in Mixed Units.....</b>	<b>155</b>
5.1	Introduction.....	156
5.2	Time-use data for sustainability research.....	157
5.3	Towards a Basic Data Framework for Comprehensive Sustainability Research.....	160
5.4	Integrating time-use data into the analysis of household activities.....	161
5.5	The data set – a “Magic Triangle of Input-Output Tables”.....	166
5.6	Some descriptive statistics – an input-output based indicator framework.....	169
5.7	Model.....	173
5.8	Results.....	175
5.8.1	Model estimations.....	175
5.8.2	Some further extensions of the consumer lifestyle approach.....	179
5.9	Conclusion.....	183
<b>Chapter 6</b>	<b>Discussion and Conclusion.....</b>	<b>184</b>
6.1	Introduction.....	184
6.2	Monetary and physical input-output analysis.....	184
6.3	Lifestyle analysis.....	188
6.4	Broadening the view.....	190
<b>References</b>	<b>.....</b>	<b>192</b>
<b>Appendix</b>		
<b>A</b>	<b>Allocating Ecological Footprints to Final Consumption Categories with Input-Output Analysis.....</b>	<b>204</b>
A.1	Introduction.....	205
A.1.1	The need for a combined footprint approach.....	205
A.1.1.1	Current Ecological Footprint accounting and some of its deficiencies.....	205
A.1.1.2	The combined approach.....	207
A.1.2	Input-output analysis and the Ecological Footprint – a short review.....	209

A.2	Methodological approach.....	212
A.3	Results and discussion.....	221
A.3.1	Results from the allocation of Ecological Footprints to detailed consumption categories.....	221
A.3.2	Assumptions and limitations.....	227
A.4	Conclusions.....	231
A.5	References.....	233
<b>B</b>	<b>The Impact of Social Factors and Consumer Behaviour on the Environment.....</b>	<b>238</b>
B.1	Introduction.....	239
B.2	Literature review.....	240
B.3	CO <sub>2</sub> emissions of lifestyle groups.....	245
B.3.1	Input-output model.....	245
B.3.2	Input-output data.....	246
B.3.3	Results.....	248
B.4	Impacts of socio-economic factors on emissions.....	252
B.4.1	Emission determinants.....	252
B.4.2	Panel regression methodology and estimation.....	254
B.4.3	Result discussion.....	255
B.5	Conclusion.....	257
B.6	References.....	258
<b>C</b>	<b>Models of National CO<sub>2</sub> Accounting.....</b>	<b>260</b>
C.1	Introduction.....	261
C.2	Responsibility and IO models.....	262
C.3	Literature review.....	265
C.3.1	Producer responsibility models.....	265
C.3.2	Consumer responsibility models.....	266
C.4	Model description.....	268
C.4.1	Producer responsibility models.....	269
C.4.1.1	Direct emissions from production.....	269
C.4.1.2	Direct and indirect emissions from production.....	270
C.4.2	Consumer responsibility models.....	270
C.4.2.1	Single region approach.....	271
C.4.2.1.1	Direct emissions in a single region model.....	271
C.4.2.1.2	Direct and indirect emissions in a single region model.....	271
C.4.2.2	Multi-region approach.....	273
C.4.2.2.1	Direct emissions in multi-region models.....	273
C.4.2.2.2	Direct and indirect emissions in a uni-lateral model.....	273
C.4.2.2.3	Direct and indirect emissions in a multi-directional trade model.	274
C.5	Data description.....	275
C.6	Results and discussion.....	277
C.7	Model applications for policy analysis.....	282
C.8	Conclusion.....	286
C.9	References.....	288



<b>D</b>	<b>Influence of Trade on National CO<sub>2</sub> Emissions.....</b>	<b>291</b>
D.1	Introduction.....	292
D.2	CO <sub>2</sub> accounting and responsibility.....	293
D.3	Model approaches.....	295
D.4	Examples of using single region models.....	297
D.5	Examples of using multi-region models.....	299
D.6	Model comparison.....	301
D.7	Conclusion.....	302
D.8	References.....	304

# List of Tables

## Chapter 2

Table 2.1	Model Results.....	67
-----------	--------------------	----

## Chapter 3

Table 3.1	Hypothetical Physical Input-Output Table.....	80
Table 3.2	Hypothetical Waste adjusted Input-Output Table.....	81
Table 3.3	Sectoral breakdown of German 1995 input output data at 58 sector level.....	89
Table 3.4	Sectoral breakdown of German 1995 input output data at 14 sector level.....	90
Table 3.5	Sectoral breakdown for comparison between German and Danish data.....	90
Table 3.6	Minimal number of intermediate output deliveries required for provision of a certain output proportion.....	97
Table 3.7	Unilateral and Bilateral Connections at variable filter levels in the MIOT.....	102
Table 3.8	Unilateral and Bilateral Connections at variable filter levels in the PIOTnw.....	102
Table 3.9	Unilateral and Bilateral Connections at variable filter levels in the PIOT.....	102
Table 3.10	Type of product flows in the economy.....	104

## Chapter 4

Table 4.1	Development of Greenhouse Gas Emission in the EU-15 1990-2003 (European Environment Agency, 2005).....	115
Table 4.2	Household Consumption Categories Distinguished in Study.....	132
Table 4.3	Households Groups and Household Sizes Distinguished in this Study.....	133
Table 4.4	Development of Greenhouse Gas Emissions 1991-2002 by Final Demand Category.....	135
Table 4.5	Development of Greenhouse Gas Emissions by Functional Final Consumption Category.....	136
Table 4.6	Development of Greenhouse Gas Emissions per € spent on Final Consumption by Functional Category.....	137
Table 4.7	Greenhouse Gas Emissions by Household Group.....	140
Table 4.8	Results Structural Decomposition Analysis.....	143
Table 4.9	Variable included in the regression model.....	144
Table 4.10	Descriptive statistics.....	146
Table 4.11	Results from different regression models.....	150

## Chapter 5

Table 5.1	Basic information content of time-use Data.....	158
Table 5.2	Household activities distinguished in study.....	167
Table 5.3	Socio-demographic groups distinguished in study.....	168
Table 5.4	Socio-economic and environmental key indicators.....	170
Table 5.5	What do people do? Activity patterns across socio-economic groups.....	172
Table 5.6	Household consumption by sector and activity.....	172
Table 5.7	Money, time and resource flows by household activities.....	177
Table 5.8	Resource Intensities by Household Activities.....	177
Table 5.9	Subjective enjoyment ratings for the four main activities.....	180
Table 5.10	Enjoyment associated with activity patterns of different socio-economic groups.....	181

## Appendix A

Table A.1	Overview – supply and use framework.....	213
Table A.2	Summary National Footprint account; UK, 2000.....	214
Table A.3	Ecological Footprint broken down by final demand category; UK, 2000.....	222
Table A.4	Expenditure and Ecological Footprint of household consumption; UK, 2000.....	223
Table A.5	Expenditure and Ecological Footprint of capital investment; UK, 2000.....	225

## Appendix B

Table B.1	Main COICOP categories.....	247
Table B.2	Household classification: 17 ACORN groups.....	248
Table B.3	Total CO <sub>2</sub> emissions in the UK by final demand categories.....	249
Table B.4	Consumption expenditure and CO <sub>2</sub> emissions by COICOP category.....	250
Table B.5	Description of regression variables.....	252
Table B.6	Descriptive statistics.....	253
Table B.7	Correlation between determinants.....	253
Table B.8	Panel regression results: best regression.....	256

## Appendix C

Table C.1	Data sources and features.....	276
Table C.2	Producer responsibility CO <sub>2</sub> account for Denmark 1997.....	278
Table C.3	Consumer responsibility CO <sub>2</sub> account for Denmark 1997: single region model.....	279
Table C.4	Consumer responsibility CO <sub>2</sub> account for Denmark 1997: Uni-directional trade model.....	280
Table C.5	Consumer responsibility CO <sub>2</sub> account for Denmark 1997: Multi-directional trade model.....	281

## Appendix D

Table D.1	CO <sub>2</sub> multipliers in five regions.....	300
Table D.2	Comparison of 1997 Danish CO <sub>2</sub> trade balances from input-output models with varying degree of interaction.....	301

# List of Figures

## Chapter 1

Figure 1.1	Sustainable Consumption I.....	29
Figure 1.2	Sustainable Consumption II.....	29

## Chapter 3

Figure 3.1	Matrix plot (log) of intermediate flow matrix of MIOT.....	92
Figure 3.2	Matrix plot (log) of intermediate flow matrix of PIOT.....	93
Figure 3.3	Matrix plot (log) of intermediate flow matrix.....	93
Figure 3.4a	Network representation of 32 largest intersectoral product flows in MIOT without considerations of flow size.....	95
Figure 3.4b	Network representation of 32 largest intersectoral product deliveries in MIOT with flow size represented by thickness of arcs.....	95
Figure 3.5a	Network representation of 32 largest intersectoral product flows in PIOTw without considerations of flow size.....	95
Figure 3.5b	Network representation of 32 largest intersectoral product deliveries in PIOTw with flow size represented by thickness of arcs.....	95
Figure 3.6a	Network representation of 32 largest intersectoral product flows in PIOTnw without considerations of flow size.....	95
Figure 3.6b	Network representation of 32 largest intersectoral product deliveries in PIOTnw with flow size represented by thickness of arcs.....	95
Figure 3.7	Lorenz intermediate flow concentration curve (level).....	98
Figure 3.8	Lorenz intermediate flow concentration curve (natural log).....	98
Figure 3.9	Graph of uni- and bi-lateral connections (MIOT).....	100
Figure 3.10	Graph of uni- and bilateral connections (PIOTw).....	100
Figure 3.11	Graph of uni- and bilateral connections (PIOTnw).....	100
Figure 3.12	The Nature of Product Flows in the German Production Structure at a 58 sector aggregation level.....	103
Figure 3.13	The Nature of Product Flows in the German Production Structure at a 26 sector aggregation level.....	108
Figure 3.14	The Nature of Product Flows in the Danish Production Structure at a 26 sector aggregation level.....	108

## Chapter 4

Figure 4.1	Periodic Effects.....	148
Figure 4.2	Household Type specific effects.....	149

## **Chapter 5**

Figure 5.1	Relationship between monetary and time use data for the representation of human activities.....	158
Figure 5.2	A Magic Triangle for Quantitative Sustainability Research.	160
Figure 5.3	Two Distinct Views of Household Consumption (adapted from Hawrylyshyn, 1977).....	162
Figure 5.4	Interrelationships across four categories of time (adapted from Robinson and Godbey, 1997).....	167
Figure 5.5	Interrelation between expenditure, time and resource use by activity field.....	178

## **Appendix A**

Figure A.1	Correlation (elasticity) between Ecological Footprint (EF) and per capita expenditure of socio-economic types.....	230
------------	--	-----

## **Appendix B**

Figure B.1	Pie chart: Total CO <sub>2</sub> emissions in the UK by final demand category.....	249
Figure B.2	Matrix plot: CO <sub>2</sub> by COICOP consumption category and socio-economic group.....	251

## **Appendix C**

Figure C.1	Producer vs. consumer responsibility.....	263
Figure C.2	Classification of CO <sub>2</sub> accounting models.....	265

## **Appendix D**

Figure D.1	Schematic overview of three trade scenarios.....	297
Figure D.2	Danish CO <sub>2</sub> trade balance.....	298
Figure D.3	CO <sub>2</sub> intensities for 10 Danish industries.....	302

# List of Boxes

## Chapter 1

Box 1.1	Max-Neef's threshold hypothesis.....	24
Box 1.2	Income and happiness.....	26p.

# Acknowledgements

First of all, I would like to thank Giovanni Baiocchi for taking on the role as my supervisor informally from the start of the project, but above all for being a great and inspiring friend. Equally, I would like to express my gratitude to John Barrett for making this PhD possible by providing the required co-funding for my PhD scholarship: John, I hope you think that the money was well spent. John has also been an invaluable source of advice in the various TAC meetings and a great teacher during the last year, where I worked with him as part of the Future Sustainability Group at Stockholm Environment Institute York.

Many thanks also to Carsten Stahmer, who has inspired most of the work in this thesis and has always been there to patiently answer my questions about PIOTs, MIOTs and SIOTs. It is great that it was possible for me to meet you and that based on our shared interest also a friendship could grow.

Many other people have helped in this PhD project. Thanks to Riccardo Scarpa for taking the formal role as my supervisor, Jesper Munksgaard for inviting me to Denmark and supervising me during my stay at AKF, Klaus Hubacek for hosting me in Leeds and being always there for advice, Joachim Merz for giving me the opportunity to spend some time researching at the University of Lüneburg, and Thomas Wiedmann for the good collaboration. Thanks to Charles Perrings for chairing my TAC and providing valuable advice and all other members of the Environment department for creating a warm and open study atmosphere. I am also grateful to Lucy Welsh, Liz Cover-Crump, Anne Owen and Leon van den Bergh for providing floor-space or sofa-beds during my research stay at Leeds University. The help of Mark Bulling and Leendert Plug particularly during the last tough days before submission are greatly appreciated and will never be forgotten.

There are many other people, who have made my life much fuller during the last years, and contributed in one way or the other to my personal development: Julia Schumacher, Virgilio Valente, Alessandro Antimiani, Dan Vecciato, the Bridge Farm Possie, John, Yuan Zhao, Wanyu Lin, and all other people I was able to share some bits of my life in York with. Equally, I would like to thank my good friends in Cologne and at home.



I am grateful to Tim Crabtree, Ewan Fisher and Matthew James for celebrating the beauty of music with me and adding another important dimension to my life, which also strengthened, inspired and sometimes slowed-down my academic progress. I do not want to miss a single second of this. Matt, I greatly miss our drum'n'bass sessions. Tim and Ewan, thanks for being so close friends: I can hear your beautiful souls in every song you write.

There are some other people, who just contributed to this PhD project, because I can feel their presence every day, namely, Axel Biegert, Ande Eckermann and Holger Hust. In a way, it cannot be explained why I want to add Jochen Merkel – but that's beautiful as well in its own way.

Satoshi Kojima and Toyonobu Fujii have been great teachers and friends to me: you both showed me how to look at things differently and that most barriers only exist in our heads. Many of the ideas, which motivated this thesis developed from our daily discussions. Satoshi, thank you both for always being there when I felt stuck and for the passionate discussions about sustainable development. I admire the rigour of your thoughts. You both greatly contributed to this thesis. York was not the same anymore for me after the two of you had left.

Thanks to Michele for helping me through the last three month and being with me since. You are a wonderful woman. Let the "Dorfchronik" continue in Berlin.

Finally, thanks to my family for their love, trust and patience. It is great to know that there is always a home in Roxheim. Mia and Nele, after finishing this project, we will finally have time to catch a pony together in Cumbria. Sorry for the delay.

# Author's Declaration

Chapter 2 benefited from helpful suggestions by Giovanni Baiocchi, Klaus Hubacek and Carsten Stahmer. Ole Gravgard Pedersen, Angela Heinze, Carsten Stahmer provided information about the statistics used, Klaus Hubacek commented on an old version of one part and Giovanni Baiocchi helped developing the “Lorenz Curve” argument in Chapter 3. An altered version of Chapter 3 has recently been submitted to *Ecological Economics*. Support in the estimation and writing of the regression analysis part in Chapter 4 was provided by Giovanni Baiocchi, who also commented on Chapter 5. Chapter 5 is published in the *Handbook for Input-output Methods in Industrial Ecology*.

Appendix A was mainly written by Thomas Wiedmann. My own contribution is limited to the development of the input-output model and the writing of the technical Sections. Appendix A is published in *Ecological Economics*. In Appendix B the panel regression analysis was undertaken by Giovanni Baiocchi. An earlier version of Appendix B was presented at the Input-output conference in Istanbul. Some of the later Sections of Appendix C were written by Jesper Munksgaard. The model estimations were carried out by Line Christoffersen and Lise-Lotte Pade. Appendix C is published in the *Handbook for Input-output Methods in Industrial Ecology*. I further assisted Jesper Munksgaard in the writing of Appendix D with most model estimation carried out by Manfred Lenzen. Appendix D is published in the *International Journal of Global Energy Issues*. With these exceptions, I declare that the work contained in this thesis is my own and has not admitted for any other degree or award.



Jan Minx

# Dedication

*To*

*Carsten for making this thesis possible*

*and my parents for their love*

# **1 INTRODUCTION**

## 1.1 BACKGROUND

Sustainable Consumption (SC) is a recent concept, which was coined in chapter 4 of Agenda 21 at the 1992 Earth Summit in Rio de Janeiro. It emerged as a “how to” or “toolset” debate on Sustainable Development (SD), concerned with unsustainable patterns of consumption and production (Charkiewicz et al., 2001). Chapter 4 set a landmark in environmental policy-making for breaking with the tradition of defining global environmental problems almost fully in terms of population growth and therefore allocating the main responsibility to the poor and powerless South (Cohen and Murphy, 2001). This was inspired by the ideas previously put forward in the Brundtland Report (WCED, 1987).

The “[...] major cause of the continued deterioration of the global environment [...]” was identified in “[...] the unsustainable patterns of consumption and production, particularly in industrialized countries [...]” (UNCED, 1992, paragraph 4.3). In order to avoid serious detrimental effects of these wasteful resource use patterns, chapter 4 encouraged to challenge the inefficient ways of producing goods and services, but also highlighted the important role of changes in (economic) consumption, consumer behaviour and lifestyles (see Jackson and Michaelis, 2003). It therefore provided a potentially far-reaching mandate to fundamentally rethink current ways of doing business and to develop “new models of wealth and prosperity which allow for higher standards of living through changes in lifestyles and are less dependent on the Earth’s finite resources” (UNCED, 1992). In this sense SC emerged as a fundamentally “green discourse” with a central focus on developed countries discussing the issues of consumption and lifestyle in the larger context of environment and development (Manoochehri, 2003; 2005), guided by more general considerations about current and future human well-being.

## 1.2 CONCEPTUAL ROOTS

Much of the conceptual roots might be seen in the two distinct notions of consumption, chapter 4 of Agenda 21 referred to (Minx, 2002; Jackson, 2003; Manoochehri, 2003). Economic consumption refers to the purchase and use of goods and services. Resource consumption denotes the physical use of natural resources in all human (production and consumption) activities. Both concepts themselves have a long-standing tradition in dealing with some of the most important issues highlighted in the Rio mandate. In this sense SC should not be seen as a new discourse initiated at the Earth Summit, but as a continuation and integration of a variety of wider discussions with a pedigree in environmentalism and consumer culture.

### 1.2.1 The literature on resource consumption

The literature on resource consumption, in the widest sense, deals with the environmental limitations of current lifestyles. It is concerned with the over-consumption of natural resources in the light of limited source and sink capacities of the natural environment, and its detrimental effects on human well-being (Boulding, 1966; Georgescu-Roegen, 1971; Perrings, 1987; Daly, 1992; Princen, 1999; Cohen and Murphy, 2001; Princen et al., 2002). Whilst concerns about over-consumption date back at least to the ancient Greeks, the roots of the modern debate can be seen in the discussion surrounding the publication of the Limits to Growth report (Meadows, 1972), which has been framed in most textbooks as one of environmental sustainability (e.g. Atkinson, 1997; Pearce, 1998).

Alongside the question of existence and relevance of environmental limitations (see Perrings, 1987; Cleveland and Ruth, 1997) and their operationalisation through concepts such as Carrying Capacity (e.g. Osborn, 1953, Wackernagel and Rees, 1996), Resilience (e.g. Holling, 1986, Perrings and Walker, 1997) or Safe Minimum Standards (Ciriacy-Wantrup, 1952) among others, authors have usually tried to identify driving forces behind resource consumption patterns, and to identify and design less material intensive ways of organising society (e.g. Weizsäcker et al., 1995; Jackson, 1996). Major determinants of the nature of such policy responses are the authors' definition of environmental sustainability<sup>1</sup>, the associated perceptions of human ingenuity and belief in

---

<sup>1</sup> Most importantly the literature distinguishes between weak and strong sustainability.

technological potential to solve problems associated with overconsumption of natural resources both on the source and sink side of the economy (Ekins, 1993; Minx, 2002) as well as the perception of the stability of eco-systems and their potential for adaptation (Perrings and Walker, 1997).

## 1.2.2 The literature on economic consumption

However, there is also a second strand of literature related to the concept of economic consumption. It is domiciled in the various social sciences and tries to understand consumerist choices - often framed in a larger welfare context. This vast and heterogeneous body of research stretches from classical and modern philosophy (Schmid, 1998), through consumer psychology and motivation research, to critical social theory, social anthropology, consumer theory and national accounting (see Jackson, 2004).

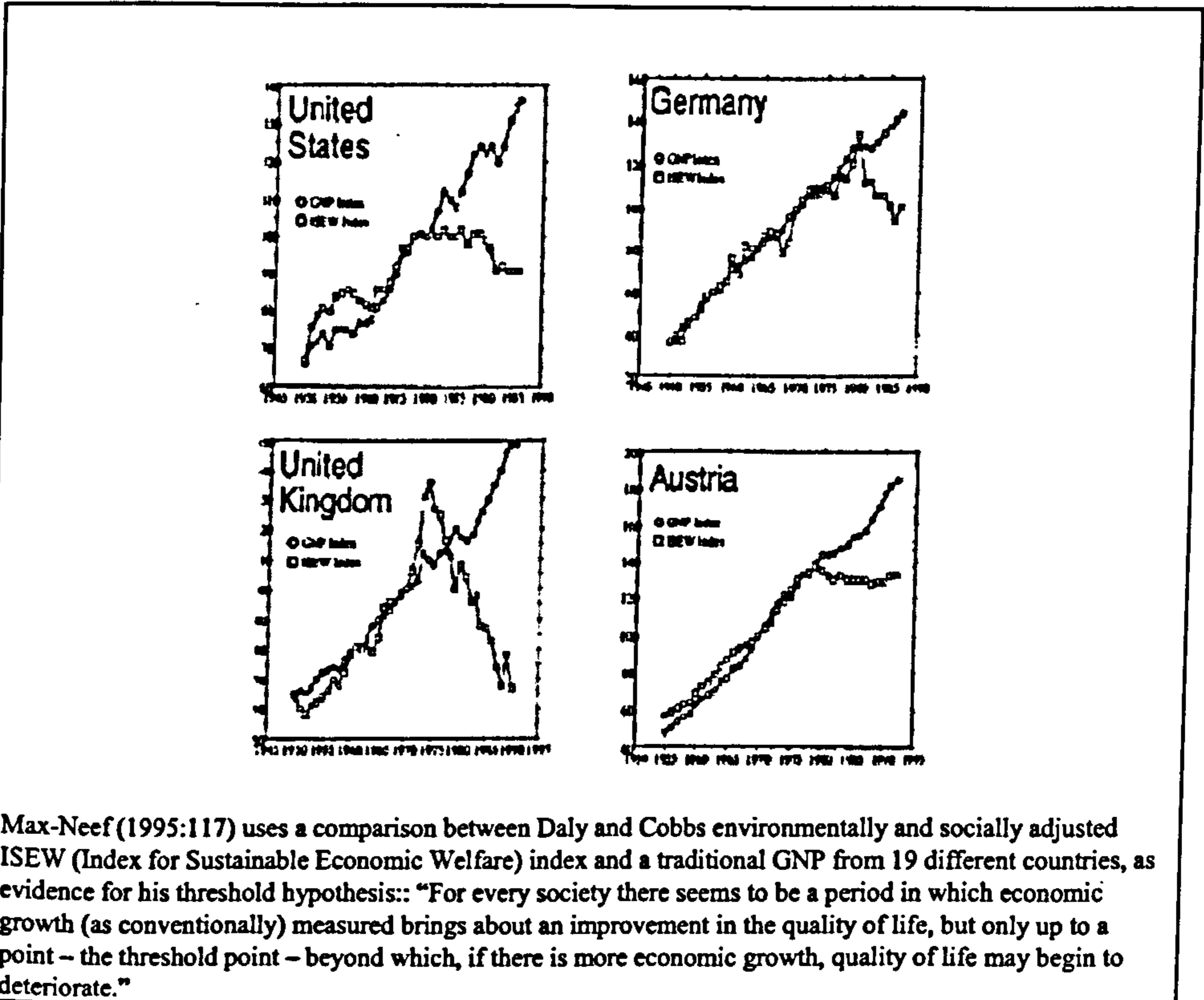
A considerable part of this literature deals with the welfare implications of consumers' choices on the individual (micro) as well as societal (macro) level. It developed as a social critique of today's dominant welfare paradigm of "more is better" consumerist choices shaped by modern economics.

In this context authors have very often identified or referred to some sort of social limitations to economic consumption limiting or reversing the positive welfare effects of additional consumption once basic material requirements for everyday life are widely met (e.g. Scitovsky, 1976; Hirsch, 1977; Dodds, 1997; Lintott, 1997; Jackson and Marks, 1999; Jackson et al., 2004; Segal, J.M., 2004).<sup>2</sup> Thus, these critiques all share the opinion that apart from environmental impacts, the consumer society is adrift in its attempts to

---

<sup>2</sup> The classic argument highlighting the increasing importance of the relative aspects of consumption with rising average income has been provided by Hirsch (1977) and taken further by various authors since (e.g. Wachtel, 1983, Lintott, 1998). Based on a distinction between private and positional goods, Hirsch argues that an increasing proportion of consumption takes on a social aspect, because the social - as the natural environment - has a restricted capacity of extending use without quality deterioration. It is therefore increasingly the relative position in the socio-economic hierarchy, which determines an individual's well-being leading to an "adding-up problem" between individual and social welfare. Other authors have started from need theories (e.g. Ekins, 1992; Jackson and Marks, 1999; Jackson and Stagl, 2004). Using Max-Neef's universal human needs approach, Jackson and Marks (1999), for example, argue that with rising income the satisfaction of non-material needs such as idleness, identity or understanding gain in importance. Peoples' attempts to satisfy these needs as frequently done in consumer societies often fail, because of the limited suitability of material goods to address these needs. Finally, some authors draw from motivational theories (e.g. Scitovsky, 1977; Dodds, 1997). Using insights from physiological psychology Scitovsky in his classical argument distinguishes between pleasure and comfort with some kind of balance necessary between the two for optimum welfare. Because discomfort is a prerequisite for pleasure, social and technological advance enable more comfortable lives, but make pleasure more difficult to obtain.

deliver human well-being. A lifestyle based on reduced economic consumption would not necessarily lead to smaller life enjoyment, but might instead open-up new doorways towards an increased quality of life (see Jackson, 2004).



**Box 1.1 – Max-Neef's Threshold Hypothesis**

Evidence to support such arguments has been provided throughout the social sciences based on a variety of different data sources. Some authors have, for example, adjusted standard economic indicators to better reflect environmental and social externalities (Daly, 1989; Stahmer, 1991) suggesting the existence of some sort of threshold after which the direct relationship between consumption and welfare breaks (see Box 1.1).

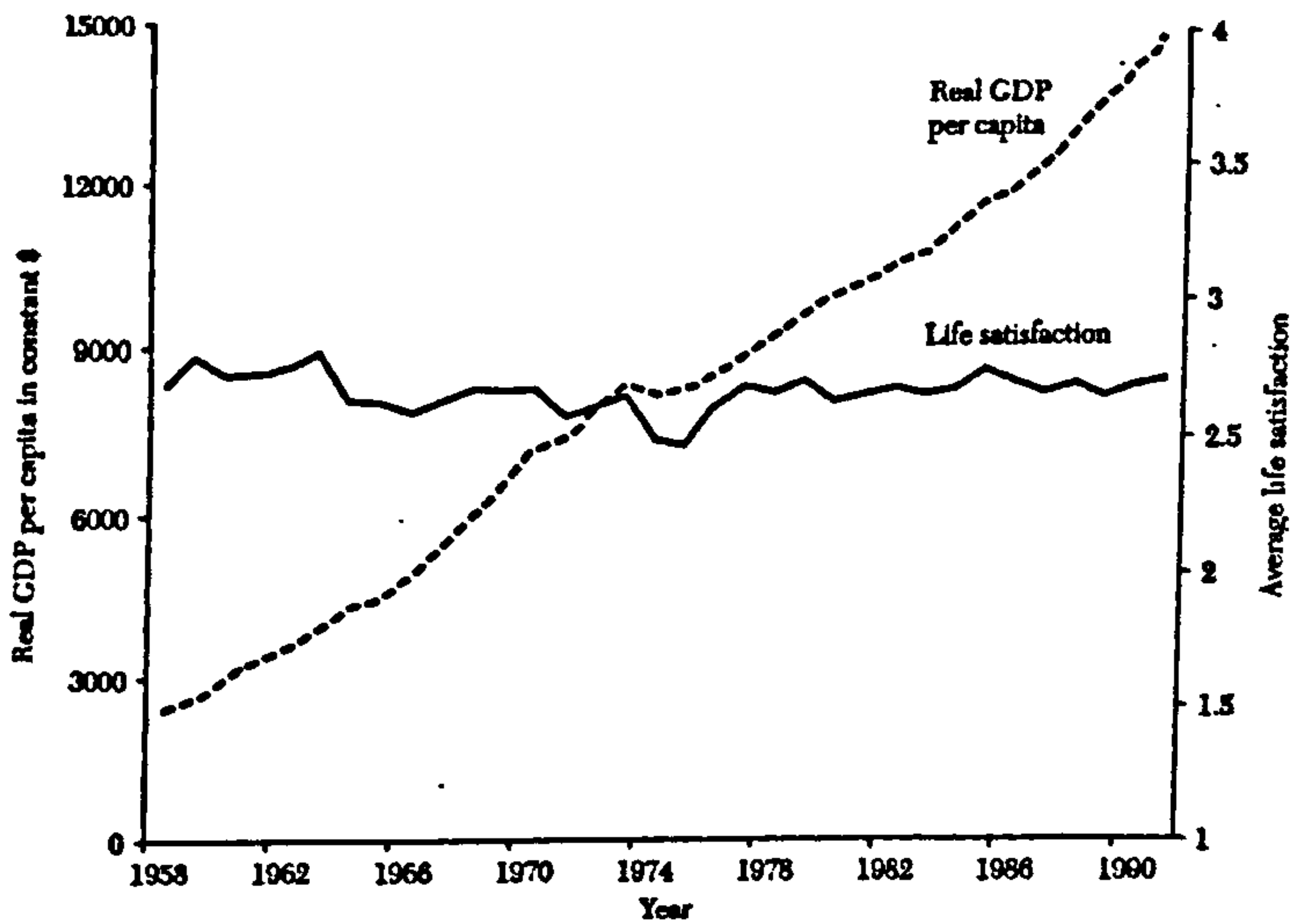
Another line of authors in sociology, economics and psychology have used results from studies on self-reported happiness (e.g. Easterlin, 1974; Frank, 1997; Oswald, 1997; Easterlin, 2001; Frey and Stutzer, 2002) and argued that it is the relative, not the absolute level of consumption, which determines peoples' perceived well-being



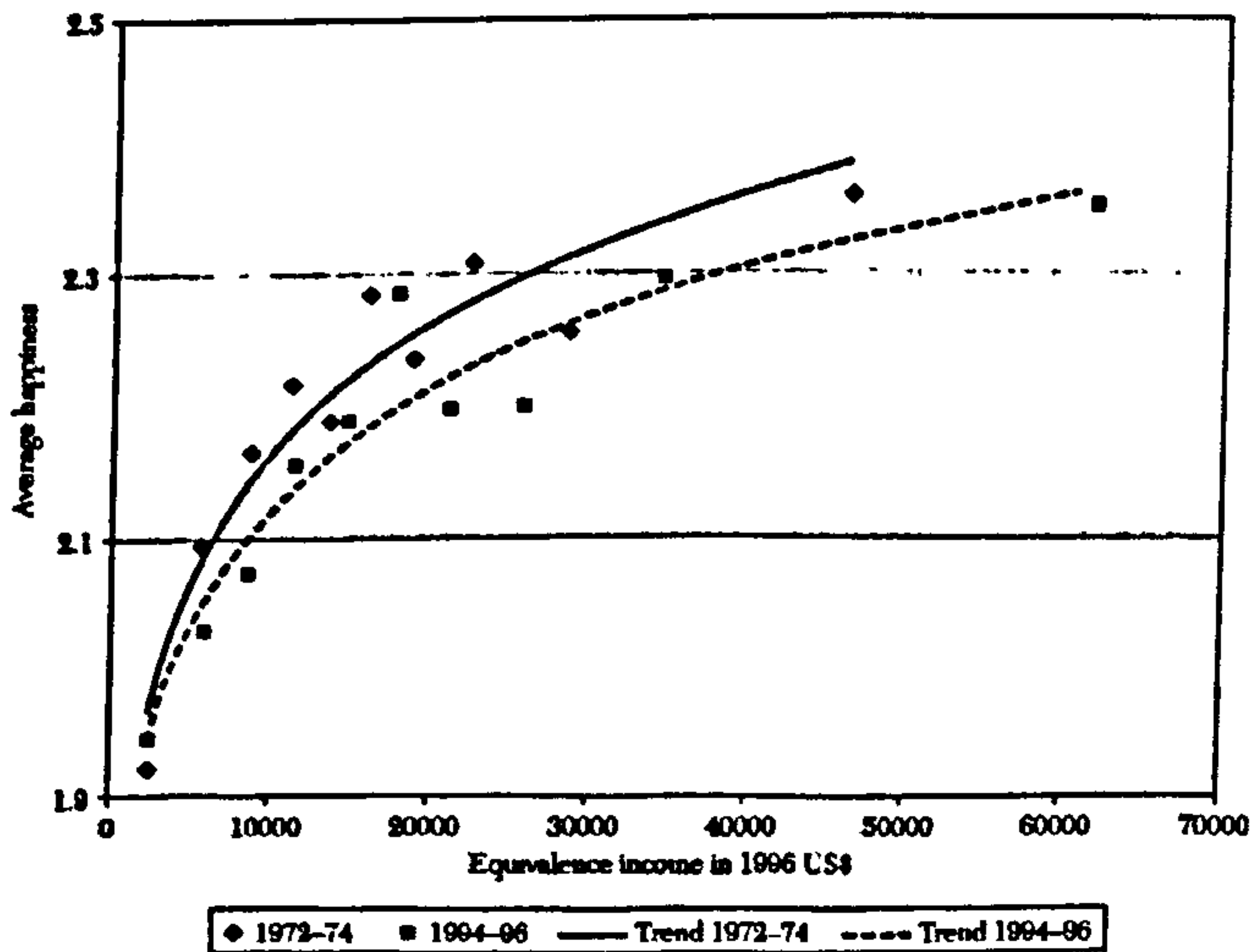
(see Box 1.2). Thus, they argue that raising everybody's income does not increase everybody's happiness, because in comparison to others, income has not improved (Frey and Stutzer, 2002). These findings are supported by laboratory experiments (e.g. Smith et al., 1989; Tversky and Griffin, 1991). Moreover, other non-monetary variables such as employment and health status have a much stronger influence on happiness than income and consumption (see Oswald, 1997; Easterlin, 2001).

Other parts of the literature have tried to understand consumption as a desire, in its role for social positioning, for the creation of individual and public identity, to communicate with others and to generate meaning in peoples' lives. Several excellent and comprehensive reviews of the literature have been provided by Tim Jackson (2004; 2005) addressing reasons for people consuming the way they do, their expected gains from consumption, the drivers of these expectations and the success in meeting them.

Hence, at the broadest Sustainable Consumption (SC) brings together a social discourse on modern consumerism with an environmental critique of the wasteful resource consumption habits attached to these consumerist lifestyles. This is not a novelty as the two avenues outlined above did not emerge in isolation. There are very obvious synergies in arguments within the context of affluence as probably most strikingly spelled out by Schumacher (1973) and Hirsch (1977). Therefore, it is not surprising that authors from both avenues have frequently touched the subject of the other and blended some of these arguments in a wider socio-environmental critique (e.g. Packard, 1960; Elgin, 1993; Schor, 1998a; Hayden, 1999; Schaffer and Stahmer, 2005; Schor, 2005). However, more fundamentally, both strands are inextricably linked with each other as the particular view on the relationship between economic growth, consumption and welfare generation are other important variables determining the range of policy options available to tackle resource consumption.

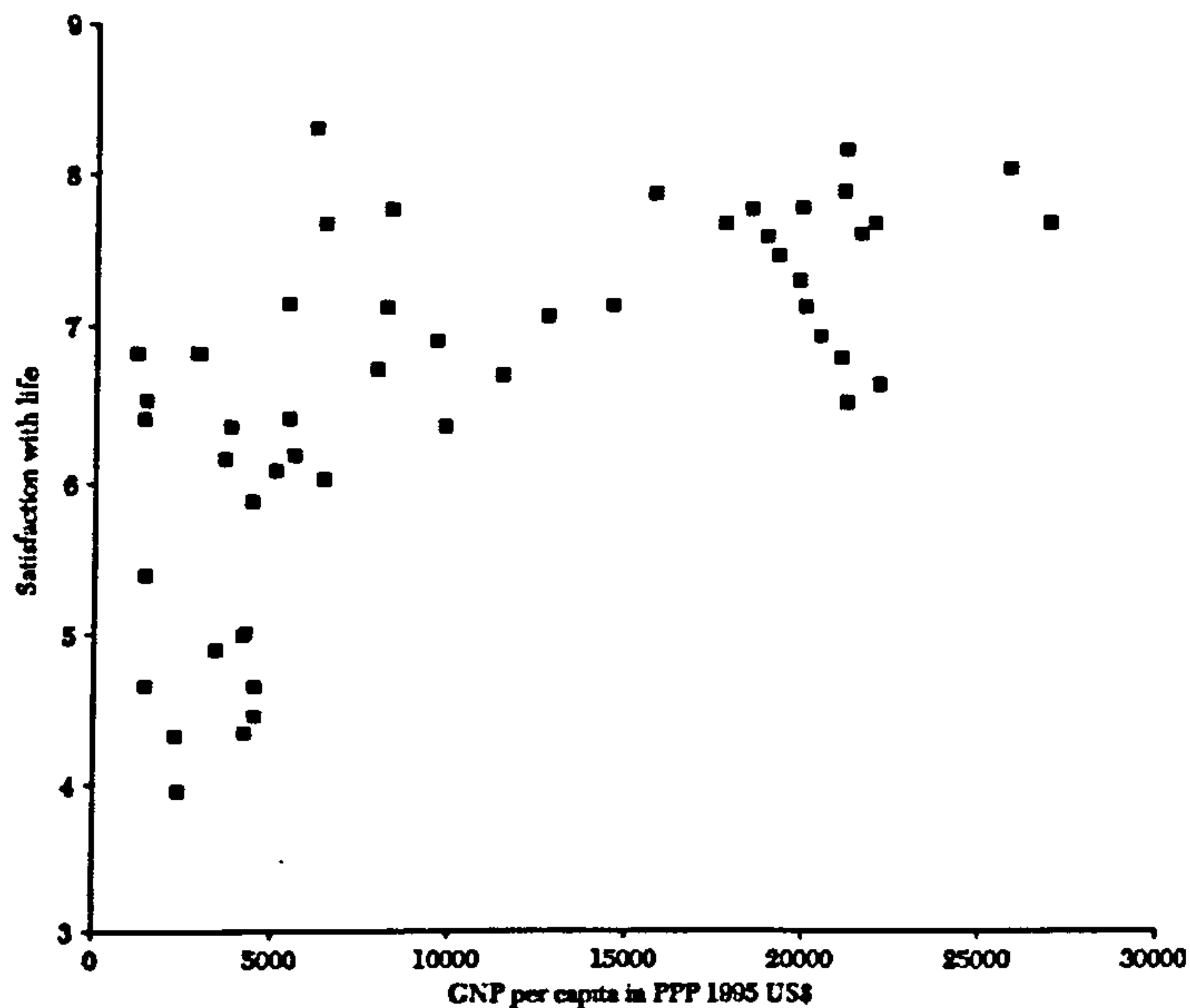


**Happiness-Income Relationship over time:** Several scholars have found that in different industrialised countries like the United States, the United Kingdom and Japan, the average happiness has stayed virtually constant or even declined. The above graph shows a spectacular growth in per capita income in post World War II Japan. However, the associated increase in material well-being reflected in almost all households having an indoor toilet, a washing machine, a telephone, a colour TV and a car in 1990, was not accompanied by an increase in average life satisfaction. Aspiration level theory provides one important avenue to explain why the satisfaction from increased material wealth might wear-off (see Easterlin, 2001).



**Happiness-Income Relationship across Income Groups:** It has been found as a robust result that richer people in a particular point in time and place (country), on average, report higher well-being. However, there is diminishing marginal happiness with a unit rise in absolute income, and income also explains only a low proportion of the differences in happiness among people. Other economic and non-economic indicators exert strong influences beyond their indirect influences on income. Importantly individuals who prize material goods more highly than other values in life tend to be substantially less happy (Sirgy, 1997). Similarly, those who define their values by themselves, tend to be happier than those with extrinsic goals (Kasser and Ryan, 2001).

Box 1.2a – Income and Happiness (Frey and Stutzer, 2002, including graphs)



Results from comparison of the relationship between happiness and income across countries show that people in richer countries tend to be happier. However, once country specific effects are controlled for, the effect of per capita GNP on reported life satisfaction is very small and diminishing (see Helliwell, 2001). However, the literature shows that the hypothesis that people in poor countries enjoy life more due to less stressful and more natural conditions than people in richer countries can be confidently rejected.

Box 1.2b – Income and Happiness (Frey and Stutzer, 2002, including all graphs)

### 1.2.3 Implications for the debate

On the international political level such a clear mandate to review affluent consumption patterns of industrialised countries was unheard of before<sup>3</sup> and marks a fundamental change in the policy landscape (Cohen and Murphy, 2001). Even though Agenda 21 puts a strong emphasis on reducing the lifecycle environmental impacts of economic consumption, it highlights the importance of a fundamental re-think of the way we consume in the light of individual, national and global well-being when we try to meet this challenge. This can be seen as an acknowledgement that purely technologically driven approaches to meet global environmental challenges might be insufficient to meet the SC challenge. However, even if a purely technological solution of the problems is striven for, some consideration of consumer behaviour is indispensable. The rebound effect is a prominent and well documented example of behavioural responses to

<sup>3</sup> This means in the context of global environmental negotiation processes.

technological efficiency improvements partially or fully off-setting the gains (see Hertwich, 2005).

Within this larger context, SC seems to raise a whole range of opportunities. Re-arranging the institutional setting to promote durability and quality rather than systems of in-built obsolescence remains crucial on the way towards sustainable patterns of production and consumption (Packard, 1960). Equally important, this way requires a rethink of the institutional arrangements of post-fordism, where success mainly depends on the ability to control time and space, to produce faster and to manage globalised production and consumption chains (Charkiewicz et al., 2001).

Downshifting work-spent cycles driven by skyrocketing consumer credit, translating efficiency improvements into “more leisure” rather than “higher wage”-decisions (Schor, 1998; Hayden, 1999; Schaffer and Stahmer, 2005; Schor, 2005) and transforming the strong affinity for ownership into enthusiasm for systems of sharing and renting seem to be other necessary steps (Weizäcker et al., 1995). As important, however, is to explain to people the implied lifestyle changes and their positive effects on human well-being (Charkiewicz et al., 2001). The SC literature raises hopes that, in fact, taking the Rio mandate seriously might indeed provide people in industrialised countries with a “double-dividend”: a better life based on less consumption (Jackson, 2004).

## **1.3 MODELLING SUSTAINABLE CONSUMPTION**

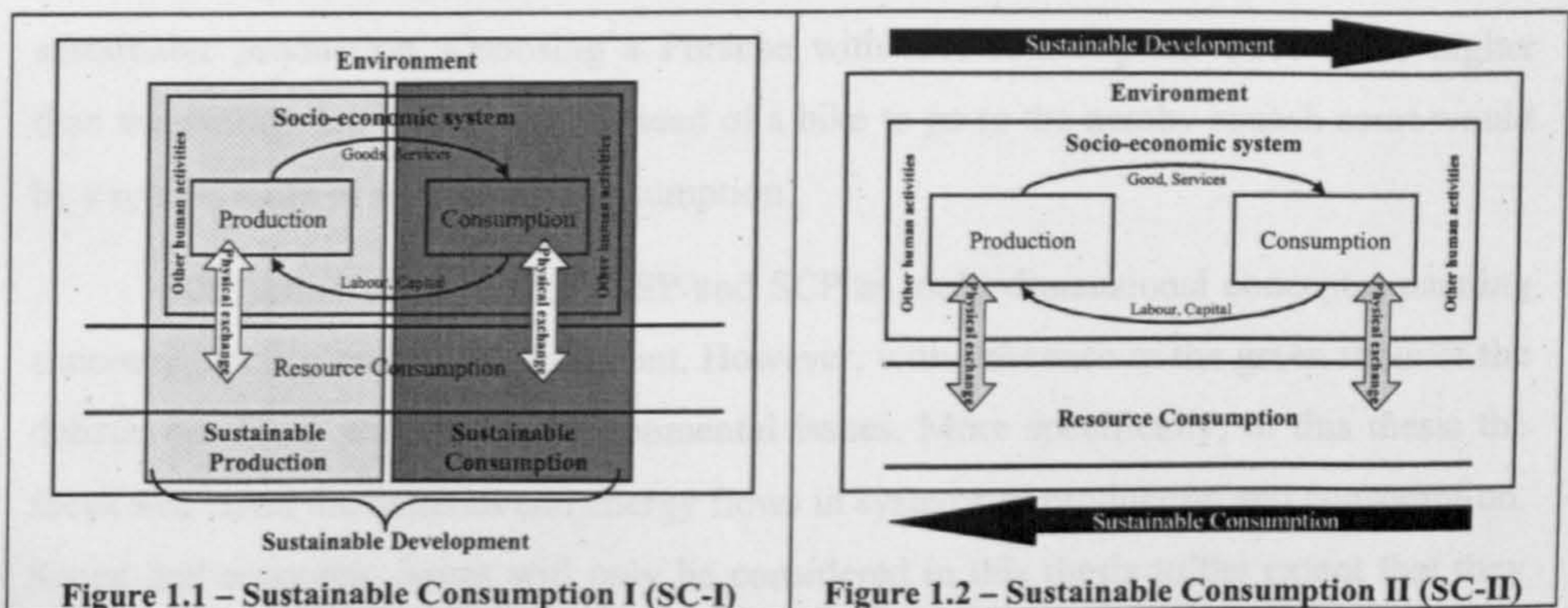
### **1.3.1 Conceptualising Sustainable Consumption**

In terms of its conceptualisation Sustainable Consumption (SC) has meant different things to different people. Even though authors have frequently referred to a definition provided by the United Nations (2003:12), there is no commonly accepted key statement and no consensus regarding what SC is exactly about. However, in order to model SC in this thesis, clarification is required.

The confusion surrounding the definition of SC is rooted in the fact that the term simultaneously deals with two different consumption concepts – economic and resource consumption as outlined in Section 1.2 – which refer to different system boundaries: Resource consumption refers to the use of resources in *all* human activities or within the

*whole* socio-economic system. Economic consumption refers only to a *part* of the socio-economic system. This is the part which is concerned, in the broadest sense, with the “use” of goods and services - final demand. Because a SC definition must decide on either the system boundaries of economic or resource consumption, two broad groups of SC definitions have emerged from the debate.

By choosing the system boundaries of economic consumption, SC (SC-I) deals with our manifold decisions spread over the whole economic consumption *process*. It assesses the environmental implications of “choosing and using” goods and services forming a necessary complement to Sustainable Production (SP). The latter involves an understanding of different impacts of decision chains involved in the processes of economic production. Both cannot be seen in isolation. They both contribute to a broader concept of “Sustainable Consumption and Production” (SCP). Such a choice of system boundaries corresponds with our traditional understanding of those different sustainability concepts and fits in the text of Chapter 4 of Agenda 21. Such a view of SC is used predominantly in the scientific debate by authors from the social sciences who wish to start the discussion from common grounds.



By choosing the system boundaries of resource consumption, SC (SC-II) refers to the “using up” of resources within all human activities. The whole economic process is re-defined from a consumption perspective and analysed step-by-step from a lifecycle perspective for its environmental, economic and social consequences. “Raw material extraction and manufacturing, for example, represent not just production and value-added, but also consumption and value-*subtracted*. Producers are consumers; Production is consumption” (Princen, Maniates et al. 2002). Subscribers to such a concept have often described SC as an alternative or complement to Sustainable Development (SD). UNEP

(2001), for example, describe it as the “inverse” of SD taking a specific view from the demand side. Other authors like Princen (2002) clearly see it as a new approach to sustainability completely detached from SD.

However, what both approaches have in common is an emphasis on the importance of addressing all human activities in a systems approach, i.e. SC as a green discourse must address all relevant resource flows (and associated pollution patterns) throughout the economy. Even in the case of SC-I it would be impossible to assess the resource implications of final consumption in isolation from production. The environmental implications of choosing a particular product are directly dependent on the way it is produced. One can say that production and consumption are systemically linked through the life cycle of a product. Life-cycle thinking and a systems-view must therefore be guiding principles of this thesis.

Hence, from such a systemic perspective it is not important how SC is conceptualised (i.e. as SC-I or SC-II). In the course of this thesis we understand SC with reference to economic consumption (SC-I) as part of a wider discourse on SCP consistent with the terminology established in Agenda 21. Minimising carbon emissions in car manufacturing or designing more fuel efficient cars would be framed as an issue of sustainable production. Choosing a Porsche with fuel consumption three times higher than the average car and using it instead of a bike to go to the nearby squash court would be a typical issue of sustainable consumption.

We further understand SC, SP and SCP as multi-dimensional concepts spanning economy, society and the environment. However, with reference to the green roots of the debate, our focus will be on environmental issues. More specifically, in this thesis the focus will be on the material and energy flows in systems of production and consumption. Social and economic issues will only be considered in this thesis to the extent that they help to develop a better understanding of these material and energy flows.

### **1.3.2 Environmental input-output analysis for quantitative Sustainable Consumption Research**

This thesis is concerned with the use of environmental input-output analysis for modelling material and energy flows. Material flows comprise all physical transactions within a given accounting period regardless of their position in the economic transformation process: raw material inputs, products and residual outputs. Strictly

speaking, energy flows are therefore included in the definition of materials. However, taking into account the particular history of the discourse, we will continue to refer to material and energy flow analysis (see Suh, 2004b).

Environmental input-output models have become popular in quantitative SC research as they link production and consumption systemically together through a comprehensive description of product flows throughout the economy. By doing so they can provide a life cycle perspective on the environmental implications of final consumption – fully accounting for technological factors as well as lifestyle factors as expressed in the spending behaviour of households.

Environmental input-output models and their variants have been used to analyse the environmental pressures associated with products (see Suh and Huppes, 2005; Tukker et al., 2006), to benchmark the performance of sectors (e.g. Foran et al., 2005a; Foran et al., 2005b); to analyse the global environmental pressures caused by consumption activities of a particular society (Lenzen et al., 2004; Wiedmann et al., 2007b, Peters, 2007); to identify hotspots in the domestic or international supply chain with regard to the build-up of environmental pressures (Lenzen, 2003; Peters and Hertwich, 2006); to analyse drivers behind changes in environmental pressures (e.g. Munksgaard et al., 2000; Dietzenbacher and Stage, 2006) and many other applications.

All these various input-output based approaches for analysing environmental pressures of some sort make particular assumptions in their analysis of the environmental pressures caused by material and energy flows. In this Section we will introduce the general input-output calculus and investigate its various underlying assumptions. Therefore, it is not the aim to provide yet another complete introduction to environmental input-output analysis, but rather to focus on issues on the production and consumption side, which are most important to the analysis of material and energy flows.

### **1.3.2.1 Basic Input-output economics**

At the heart of input-output analysis are input-output tables. They provide a detailed, but coherent and complete overview of economic interrelationships between sectors – usually recorded in monetary terms (e.g. million €). Input-output tables are accounting devices for which the sum of the outputs from a productive sector must equal the sum of the inputs to this productive sector.

In the rows of input-output tables the use of outputs from production sectors are typically recorded. Two different kinds of outputs can be distinguished: *First*, outputs to intermediate demands, i.e. intermediate products purchased by one sector from another. *Second*, outputs to final demands, i.e. final products consumed by domestic final demand entities such as households and government or products exported to the rest of the world. Let  $z_{ij}$  be the elements of a  $n \times n$  matrix  $Z$  of intermediate demands of the  $j^{\text{th}}$  sector (for  $j=1,2,\dots,n$ ) from the  $i^{\text{th}}$  sector (for  $i=1,2,\dots,n$ ) and  $y_i$  be an element of a  $n \times 1$  vector  $y$  of final demands from the  $i^{\text{th}}$  sector. Total output  $x_i$  of the  $i^{\text{th}}$  sector can be written as

$$x_i = \sum_j z_{ij} + y_i \quad (1.1)$$

Also the inputs can be of two different kinds. *First*, (primary) inputs of non-produced factors and capital summarised under the heading of value added. *Second*, inputs from other productive sectors corresponding to the intermediate demand. Let  $v_i$  be an element of the  $n \times 1$  vector  $v$  of value added. As total inputs and outputs of a production sector must be equal, total inputs  $x_i$  of the  $i^{\text{th}}$  sector can be written as,

$$x_i = \sum_j z_{ji} + v_i \quad (1.2)$$

Let  $A$  be a matrix of direct requirements or technological coefficients with elements  $a_{ij}$ , which relates the total output of sector  $j$  to its inputs from sector  $i$  by

$$a_{ij} = \frac{z_{ji}}{x_j} \quad (1.3)$$

In particular, each element  $a_{ij}$  gives the amount of inputs required from sector  $i$  to produce one unit of output of sector  $j$ . Using (1.3), Equation (1.1) can be re-written in matrix notation as

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \quad (1.4)$$

Solving this system of linear equations for  $x$  yields the standard demand-side Leontief model, that is



$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} = \mathbf{L} \mathbf{y} \quad (1.5)$$

where  $\mathbf{I}$  is the  $n \times n$  identity matrix and  $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$  the Leontief Inverse (or direct and indirect requirement matrix). Each element  $l_{ij}$  of the Leontief Inverse indicates the amount of total output required directly and indirectly from sector  $i$  to provide one unit of output to final demand in sector  $j$ . A unique solution of (1.5) exists, if and only if the determinant of  $(\mathbf{I} - \mathbf{A})$  is non-zero  $|(\mathbf{I} - \mathbf{A})| \neq 0$ .

This Leontief system is built on a variety of assumptions, which have been widely discussed in the debate (Miller and Blair, 1985). Most importantly, input-output models as represented in Equation (1.5) assume that economic sectors are homogenous, i.e. that a sector can be represented by its principal product. Moreover, the assumed Leontief production function is completely inelastic and implies constant returns to scale. Finally, the input-output model assumes that the economy is completely driven by demand. This requires under-utilised production capacity in all sectors to allow for an immediate response to increases in final demand. Therefore, it also has to be assumed that there are no inflationary effects caused by these demand pressures. While it is important to highlight these assumptions, it is equally important to stress that most are only relevant, if policy analysis is of concern. Following Sections focus on those assumptions, which are restricting the analysis of material and energy flows and resulting environmental pressures.

### 1.3.2.2 Generalised environmental input-output analysis and hybrid unit models

Already in the late 1960s and early 1970s Leontief himself and others proposed environmental extensions to input-output analysis. Different models with different purposes were proposed – some focussing on modelling sectoral abatement activities (Leontief, 1970), complete description of the interactions between the environment and the economy (Daly, 1968) or simply the generalisation of input-output calculus for environmental flows (Leontief and Ford, 1971).

This thesis will mainly focus on the last of the three options, i.e. the use of environmentally extended input-output models for tracing the use of resources and the

release of pollution in the economy. The author has provided a comprehensive review of material and energy flow methodologies in Wiedmann et al. (2006b).

The simplest way of generalising the basic economic Leontief model is through inclusion of a matrix (vector) of direct sectoral material and energy intensities. Let  $\mathbf{R}$  be a  $n \times m$  matrix of  $k$  different energy and material flows (for  $k=1,2,\dots,m$ ) in the  $n$  different sectors of the economy. A  $n \times m$  matrix of direct material and energy intensities  $\mathbf{Q}$  with elements  $q_{ki}$  can be derived by dividing the total material or energy output of each sector in physical terms (e.g. tonnes, BTU etc.) by its total economic output in value terms, that is

$$q_{ki} = \frac{r_{ki}}{x_i} \quad (1.6)$$

Each element  $q_{ki}$  gives the amount of the  $k^{\text{th}}$  material or energy flow required to produce one unit of the  $i^{\text{th}}$  sector's monetary output. Using Equation (1.6), the input-output model outlined in Equation (1.5) can be generalised by

$$\mathbf{p} = \mathbf{Q}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{\Omega}\mathbf{y} \quad (1.7)$$

where  $\mathbf{p}$  is the  $k \times 1$  vector of the  $k$  different energy and material flows triggered by a given final demand  $\mathbf{y}$ . As each direct and indirect multiplier  $\Omega_{kj}$  gives the direct and indirect material and energy flows required throughout the (domestic and/or international) supply chain to produce one unit of monetary final demand in sector  $j$ , it is not surprising that environmental input-output analysis has been used to assess the direct and indirect environmental pressures generated throughout the supply chain by a certain final demand. It is equally intuitive that life cycle assessment practitioners would have used environmental input output analysis for assessing the system wide environmental pressures generated by a particular final product (or product group) – at least from cradle to gate (see, Hendrickson et al., 1998; Minx et al., 2008).

The use of environmental input-output analysis for such assessments of material and energy flows and related environmental pressures rests on one crucial assumption: that the provision of each unit of economic output triggers the same amount of material and energy flows. However, this assumption can be challenged on various grounds:

Sectoral outputs are not homogenous, but rather reflect baskets of goods. The mix of this product basket will be different for deliveries to different sectors. Therefore, the distribution of environmental pressures should differ accordingly. Clearly, the associated error will be bigger at higher the aggregation levels and as sector definitions become less homogenous.

The appropriate attribution of material and energy flows (and resulting environmental pressures) based on monetary production structures might be further restricted by the responsiveness of monetary product flow measures to real world conditions/issues such as price differentiation and price fluctuation (see Suh, 2004; Weisz and Duchin, 2006; Minx et al., 2007). Hence, the value of product flows as represented in monetary input-output tables might not always be a good approximation of the physical size of the flows, and this may further distort the estimations in environmental input-output models.

However, it has been established in the energy economic literature that these problems can be partially overcome through use of hybrid models. These models are superior for tracing (material and) energy flows throughout the economy and allocating them to final demands as they replace (or augment) monetary structures by their physical counterparts in key sectors.

Let the superscripts  $m$  and  $p$  indicate data in monetary and physical units. A hybrid model alternative of equation (1.1) in matrix notation can be written as

$$\begin{pmatrix} \mathbf{x}^m \\ \mathbf{p}^p \end{pmatrix} = \begin{pmatrix} \mathbf{Z}^m \mathbf{1} \\ \mathbf{Z}^p \mathbf{1} \end{pmatrix} + \begin{pmatrix} \mathbf{y}^m \\ \mathbf{y}^p \end{pmatrix} = \mathbf{Z}^* \mathbf{1} + \mathbf{y}^* \quad (1.8)$$

where  $\mathbf{1}$  is a vector of ones of adequate size and the superscript “\*” indicates the hybrid (or mixed unit) nature of a given matrix or vector. The direct requirement matrix in hybrid units can then be derived by

$$\mathbf{A}^* = \begin{pmatrix} \mathbf{Z}^m \\ \mathbf{Z}^p \end{pmatrix} \begin{pmatrix} \hat{\mathbf{x}}^m & \mathbf{O} \\ \mathbf{O} & \hat{\mathbf{p}}^p \end{pmatrix}^{-1} = \mathbf{Z}^* (\hat{\mathbf{x}}^*)^{-1} \quad (1.9)$$

where the hat symbol “^” indicates diagonalisation. The basic demand side Leontief model in a hybrid unit formulation can then be written as,

$$\mathbf{x}^* = (\mathbf{I} - \mathbf{A}^*)^{-1} \mathbf{y}^* \quad (1.10)$$

### 1.3.2.3 Representing domestic technology: Monetary versus physical input-output analysis

So far, environmental input-output analysis – in whatever formulation - has mainly built upon input-output tables in value terms. However, almost 40 years ago Leontief himself already pointed towards the advantages of physical measurement by expressing most of his practical examples in physical terms (e.g. Leontief, 1970). Recently, new opportunities have arisen for a more comprehensive physical description of the economy through the availability of physical input-output tables. Physical input-output tables (PIOTs) are macro-economic activity-based material flow accounts measured in physical units (predominantly in tonnes), which establish a formal link between standard economic and energy and material flow accounting. In this thesis only single unit PIOTs measured in tonnes of weight will be dealt with in detail (Stahmer et al., 1998). However, it is clear that for many applications PIOTs in multiple units might be more appropriate (see Chapter 3).

There are important differences between monetary and physical input-output tables. To the extent that product flows are concerned PIOTs and MIOTs are conceptually congruent. However, PIOTs go beyond the scope of MIOTs in that they include the environment (natural assets) as a source of raw materials and as a sink for residuals. Therefore, PIOTs also slightly differ in the way they way they are constructed. The implications of these differences for environmental input-output modelling have been discussed in detail by Hubacek and Giljum (2003), Suh (2004), Giljum and Hubacek (2004), Dietzenbacher (2005), Giljum and Hubacek (2008) and Dietzenbacher et al. (2008).

The most immediate problem for constructing an environmental input-output model based on a production structure in physical units is that goods and bads are juxtaposed as parts of final demand: namely in the products consumed as well as the residual outputs discharged into the environment. This can provide problems in conducting meaningful analysis as residual outputs themselves are the result of economic transformation processes. Therefore, it is often necessary to remove residual outputs from final demand and treat them as negative primary inputs (see Suh, 2004; Dietzenbacher,

2005) in environmental input-output models based on purely physical production structures.

Let  $Z^p$  denote an  $n \times n$  intermediate flow matrix in physical units,  $y^p$  denote the  $n \times 1$  final demand for products expressed in physical units,  $w^p$  denote a  $n \times 1$  vector of waste or residual outputs released into the environment and  $x^p$  the  $n \times 1$  total material output vector including both product and residual outputs, that is

$$x^p = Z^p \iota + y^p + w^p \quad (1.11)$$

where  $\iota$  is a vector of ones of adequate size. Removing residual outputs from final demand and treating them as a negative input yields a  $n \times 1$  vector of total output of products in physical units denoted as  $\bar{x}^p$ , that is

$$\bar{x}^p = Z^p \iota + y^p \quad (1.12)$$

Conceptually, vector  $\bar{x}^p$  can then be seen as the physical counterpart of the monetary total output vector  $x^m$ . A direct requirement matrix  $\bar{A}^p$  can be derived by

$$\bar{A}^p = Z^p (\bar{x}^p)^{-1} \quad (1.13)$$

An input-output model based on a purely physical production structure, which is conceptually comparable with models based on monetary production structures as shown in Equation (1.5), can be written as

$$\bar{x}^p = (I - \bar{A}^p) y^p \quad (1.14)$$

It can be shown that models (1.5) and (1.14) lead to exactly the same results given the existence of a vector of unique sectoral unit prices (Weisz and Duchin, 2006; see Chapters 2 and 3 of this thesis). In such a case there would be no need to compile physical input-output tables for material and energy flow analysis, because environmental input-output models based on monetary and physical production structures would provide the same answers to policy questions.

However, there are a variety of reasons why such a unit price assumption will not hold. These include aggregation level (Hubacek and Giljum, 2003; Dietzenbacher, 2005), real world conditions such as price differentiation and price fluctuations (Suh, 2004) as well as the different scope of monetary and physical measurements (Minx et al., 2007). Therefore, one of the key questions is how information from PIOTs can be used to improve the representation of the technological component in environmental input-output models. This is one of the main issues, which will be addressed in this PhD thesis.

#### **1.3.2.4 Representing consumer behaviour and lifestyles**

Apart from the question of how to best specify the production structure in environmental input-output models for the analysis of energy and material flows and the resulting environmental pressures, there has been great interest in the question how lifestyles and related socio-economic driving forces might be comprehensively introduced. This literature has usually started by assessing the direct and indirect material and energy flows associated with final household consumption, which is at the root of the majority of environmental pressures generated by a particular society. In this context, household expenditure patterns are usually seen as a manifestation of a particular lifestyle. Importantly, to account fully for the environmental pressures associated with a particular lifestyle it is crucial to cover domestically produced and imported products to the same level of detail.

A large array of studies has tried to inform policies about the environmental pressures associated with household consumption by identifying the most material-intensive product groups, or those ones with the largest potential for environmental saving. For example, a detailed literature review in a recent European study (see Tukker et al., 2006; Hertwich, 2006) found that most environmental pressures across different environmental themes including global warming, acidification, ozone layer depletion, toxicity or waste are associated with the lifecycle of a relatively small number of products/consumption categories: most importantly food, housing and travel. This has highlighted these consumption categories as priority areas for integrated product policy to reduce the environmental impacts associated with the final consumption of products across the life cycle. Equally, authors have interpreted results from such studies in the context of wider human needs theories in order to motivate changes in households'

consumption patterns towards reduced material consumption and low impact products (Lenzen, 1998; Jackson and Marks, 1999; Minx, 2001).

However, insights from such studies concerning the environmental pressures associated with household consumption and lifestyles are limited unless they are connected to a broader set of social, economic and demographic statistics. Such information could be of vital importance for the design of effective policies, which also take into account the social and economic make-up of society as well as relevant demographic trends. Where input-output tables sit in such a wider socio-economic reporting system is described in the literature on social accounting and social accounting matrices (e.g. Keuning, 1994; Keuning, 2000). An excellent review with a particular focus on the contributions of Nobel Prize winner Sir Richard Stone can be found in Stahmer (2002).

The most immediate concern for environmental input-output modelling is to differentiate between the household consumption expenditure patterns of different socio-economic (household) groups. Two competing approaches to stratifying households have been discussed in the literature (see Duchin, 1998; Duchin and Hubacek, 2003), which will both be discussed in this thesis. For this introduction it is sufficient to deal with the most general case.

Let  $A_m^{tot}$  denote the  $n \times n$  direct requirement matrix in monetary terms relating domestic and imported intermediate inputs provided from sector  $i$  to sector  $j$  per unit of domestic output of sector  $j$  (for  $i, j = 1, 2, \dots, n$ ). Moreover,  $y_{hh,tot}^m$  is the  $n \times 1$  final household demand vector in monetary terms for domestically produced and imported products of the  $i^{th}$  production sector. Through further decomposition we can express the environmental pressure exerted by the  $l^{th}$  socio-economic household group (for  $l = 1, 2, \dots, s$ ) as

$$p^{soc} = Q'(I - A_m^{tot})^{-1} Y_{hh,coicop}^{m,prop} Y_{hh,soc}^{m,prop} \bar{y}_{hh,tot}^{m,cap} d_{hh,soc}^{prop} d_{tot}^{prop} \quad (1.15)$$

where:

- $Y_{hh,fcf}^{m,prop} = Y_{hh,fcf}^m (\hat{y}_{hh,fcf}^m)^{-1}$  is the proportional spending of households on final products of the  $i^{th}$  production sector in the  $h^{th}$  functional spending category (for  $h = 1, 2, \dots, r$ ): with  $y_{hh,fcf}^m = Y_{hh,fcf}^m \mathbf{1}$  and  $\mathbf{1}$  being a vector of ones of adequate size;

- $\mathbf{Y}_{hh,soc}^{m,prop} = \mathbf{Y}_{hh,soc}^m (\hat{\mathbf{y}}_{hh,soc}^m)^{-1}$  is the proportional spending of the  $l^{th}$  socio-economic groups across the  $r$  functional spending categories: with  $\hat{\mathbf{y}}_{hh,soc}^m = \mathbf{Y}_{hh,soc}^m \mathbf{1}$  and  $\mathbf{1}$  being a vector of ones of adequate size;
- $\hat{\mathbf{y}}_{hh,tot}^{m,cap}$  is a vector of the total per capita spending of the  $l^{th}$  socio-economic group on final products;
- $d_{tot}$  is the total population;
- $\mathbf{d}_{hh,soc}^{prop} = \mathbf{d}_{hh,soc} / d_{tot}$  is the population structure with  $\mathbf{d}_{hh,soc}$  being the number of people in  $l^{th}$  socio-economic group;

Note that the relationship  $\mathbf{y}_{hh,tot}^m = \mathbf{Y}_{hh,coicop}^{m,prop} \mathbf{Y}_{hh,soc}^{m,prop} \hat{\mathbf{y}}_{hh,tot}^{m,cap} \mathbf{d}_{hh,soc}^{prop} d_{tot}$  must hold. To calculate the full environmental pressures generated by the lifestyle of different socio-economic groups as highlighted previously, it is assumed that imported products are produced in exactly the same way abroad than at home. The implications of this single region assumption are dealt with further in the next Section. This further disaggregation of final demand does not only allow for a better understanding of the environmental pressures associated with different lifestyle groups, but also provides links to other social, economic and demographic statistics, which can be used for further analysis (see Chapter 4).

However, the environmental pressures generated by particular lifestyle groups is not only determined by their particular socio-demographic make-up, but the immediate physical environment people are living in (infrastructure) is of at least equal importance: neighbourhood characteristics such as the accessibility of shops, schools or other private and public services (buses, recycling etc.), the features of the particular dwelling people live-in including the age, size and energy-efficiency of the buildings (type of insulation, type of windows, on-site renewables etc.) or more general characteristics of the wider area such as the degree of ruralness, population density and many others. There is a wealth of local area statistics available in many countries, which could be used to gain a better understanding of how the local environment in an area might influence environmental pressures from consumption of the people living in that area (SEI, 2007). Are there particular physical barriers to reducing environmental pressures from consumption? What are the opportunities to reduce these environmental pressures?



Even though this is a very promising and policy relevant field, it has received little attention so far. Once the socio-demographic make-up of a certain spatial area  $\gamma$  (for  $\gamma=1,2,\dots,t$ ) is known, environmental pressures caused by its residents can be imputed, that is

$$\mathbf{p}^{area} = \mathbf{Q}'(\mathbf{I} - \mathbf{A}_{tot}^m)^{-1} \mathbf{Y}_{hh,coicop}^{m,prop} \mathbf{Y}_{hh,soc}^{m,prop} \hat{\mathbf{y}}_{hh,tot}^{m,cap} \mathbf{d}_{tot}^{soc,area} \quad (1.16)$$

Usually such models assume that the consumer behaviour of members of a particular socio-demographic lifestyle group  $l$  (for  $l=1,2,\dots,s$ ) does not differ in different spatial areas of the economic system under consideration. To relax this assumption, spending data can be further regionalised. However, ultimately this “regionalisation” of household expenditure is limited by the sample size of the underlying survey data.

This thesis uses a variety of different data sources to understand the direct and indirect material and energy flows associated with different lifestyles. However, by doing so it also addresses the fundamental question concerning the conceptualisation of lifestyles for empirical purposes in general as well as in a particular input-output context. As a result, ways of introducing social, economic and demographic information into input-output frameworks are highlighted.

### 1.3.2.5 Representing foreign technology and accounting for global trade: Multi-regional input-output analysis

Even though the previous Section has already dealt with imported goods based on a single region model assumption, trade has not been considered explicitly in these introductory remarks. Environmental input-output models can deal with trade related emissions in very different ways depending on data availability. A good review of the literature can be found in Lenzen et al. (2004), Wiedmann et al. (2006), Wiedmann et al. (2008) and Munksgaard et al. (2008: see Appendix C of this thesis). For adequately modelling material and energy flows in an environmental input-output context, the way in which foreign production/technology is treated is crucial.

As mentioned above, most authors use a simple short-cut to assess the import-related environmental pressures by assuming that goods and services are produced with exactly the same technology at home and abroad. Let  $\mathbf{A}_{m,dom}$  be a  $n \times n$  domestic direct requirement matrix as calculated in Equation (1.3) and  $\mathbf{A}_{m,imp}$  be a  $n \times n$  direct requirement

matrix for imported intermediate products giving the amount of intermediate imports provided by sector  $i$  and consumed by sector  $j$  per unit of domestic product output of sector  $j$ . Finally,  $y_{m,dom}$  identifies the final demand for domestically produced products and  $y_{m,imp}$  final demand for imported products. We can then rewrite the basic demand side Leontief model as

$$\begin{aligned} \mathbf{p}_{SR} &= \mathbf{Q}'(\mathbf{I} - \mathbf{A}_{tot})\mathbf{y}_{tot} = \\ &= \mathbf{Q}'(\mathbf{I} - \mathbf{A}_{dom})^{-1}\mathbf{y}_{dom} + \mathbf{Q}'\left((\mathbf{I} - \mathbf{A}_{tot})^{-1} - (\mathbf{I} - \mathbf{A}_{dom})^{-1}\right)\mathbf{y}_{dom} \\ &\quad + \mathbf{Q}'(\mathbf{I} - \mathbf{A}_{tot})^{-1}\mathbf{y}_{imp} \end{aligned} \quad (1.17)$$

where  $\mathbf{A}_{tot} = \mathbf{A}_{dom} + \mathbf{A}_{imp}$  and  $\mathbf{y}_{tot} = \mathbf{y}_{dom} + \mathbf{y}_{imp}$ . Clearly, it is brave to assume that production technologies and their resource intensities are the same throughout the world. Therefore, particularly over the past five years, multi-regional input-output models have been increasingly developed in the research community to better represent and account for differences in technologies across countries or larger regions of the world (e.g. Lenzen et al., 2004; Munksgard et al., 2005; Hertwich and Peters, 2006; Wiedmann et al., 2007).

Uni-directional multi-regional input-output models focus on one country and its trade links to other regions. Production technologies of these other regions are taken into account as well as their material and energy intensities. However, the trade between these regions is neglected. This means that not all feedback effects can be taken into account in the input-output system (see Lenzen, 2004).

Let us assume that we can divide up the world into  $r$  different regions (*for*  $k=1,2,\dots,r$ ). Let the first superscript of a matrix or vector identify the exporting region (from) and the second superscript the receiving region. We can then express a uni-directional environmental input-output model focussing on the environmental pressures associated with imports and exports of country 1 by,

$$\begin{pmatrix} \mathbf{p}^{11} \\ \mathbf{p}^{21} \\ \vdots \\ \mathbf{p}^{r1} \end{pmatrix} = \begin{pmatrix} \mathbf{Q}^1 & \mathbf{O} & \dots & \mathbf{O} \\ \mathbf{O} & \mathbf{Q}^2 & & \mathbf{O} \\ \vdots & & \ddots & \vdots \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{Q}^r \end{pmatrix} \begin{pmatrix} \mathbf{I} & \mathbf{O} & \dots & \mathbf{O} \\ \mathbf{O} & \mathbf{I} & & \mathbf{O} \\ \vdots & & \ddots & \vdots \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{11} & \mathbf{O} & \dots & \mathbf{O} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & & \mathbf{O} \\ \vdots & & \ddots & \vdots \\ \mathbf{A}^{r1} & \mathbf{O} & \dots & \mathbf{A}^{rr} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y}^{11} \\ \mathbf{y}^{21} \\ \vdots \\ \mathbf{y}^{r1} \end{pmatrix} \quad (1.18)$$

Note that  $p^{11}$  then holds all emissions produced in region 1 to satisfy all final demands in region 1 and  $p^{21}$  gives all emissions produced in region 2 to produce all final demands in region 1.

As mentioned earlier such a uni-directional model neglects all feedback effects occurring in the international supply chain. While evidence suggests that these feedback loops might not be so important for the robustness of trade-related emission accounts (see Lenzen et al., 2004), a large number of applications such as the analysis of global supply chains and global trade flows, input-output based life cycle assessment or their hybrid counterparts require such a fully integrated, multi-regional input-output model. Such a model can be expressed in matrix notations as follows

$$\begin{pmatrix} p^{11} & p^{12} & \dots & p^{1r} \\ p^{21} & p^{22} & & p^{2r} \\ \vdots & & \ddots & \vdots \\ p^{r1} & p^{r2} & \dots & p^{rr} \end{pmatrix} = \begin{pmatrix} Q^1 & O & \dots & O \\ O & Q^2 & & O \\ \vdots & & \ddots & \vdots \\ O & O & \dots & Q^r \end{pmatrix} \begin{pmatrix} I & O & \dots & O \\ O & I & & O \\ \vdots & & \ddots & \vdots \\ O & O & \dots & I \end{pmatrix} - \begin{pmatrix} A^{11} & A^{12} & \dots & A^{1r} \\ A^{21} & A^{22} & & A^{2r} \\ \vdots & & \ddots & \vdots \\ A^{r1} & A^{r2} & \dots & A^{rr} \end{pmatrix}^{-1} \begin{pmatrix} y^{11} & y^{12} & \dots & y^{1r} \\ y^{21} & y^{22} & & y^{2r} \\ \vdots & & \ddots & \vdots \\ y^{r1} & y^{r2} & \dots & y^{rr} \end{pmatrix} \quad (1.19)$$

The Appendix to this thesis therefore deals in detail with trade related aspects of environmental input-output based material and energy flow analysis.

## **1.4 AIMS AND OUTLINE OF THESIS**

The overriding aim of this thesis is to establish how integrated input-output data frameworks in monetary, physical and time units can contribute to a better understanding of the environmental pressures generated by a given final demand including the underlying economic, social and demographic driving forces. The thesis mainly focuses on environmental input-output analysis and related methods and evaluates the opportunities provided by recent data developments at the Federal Statistical Office. In particular, physical input-output tables and social accounting extensions published as part of the “socio-economic reporting system” are used for improving the specification and conceptualisation of production technology and lifestyles. By doing so, it attempts to discuss the value of integrated data systems in monetary, physical and time units for SC research as prominently introduced by Stahmer (2000). Moreover, it tries to bridge a gap between accounting and modelling: the compilation of statistics and their application by practitioners to answer policy questions.

To strike a good balance in dealing with issues on both the production and consumption sides of the economy, the four main chapters of this PhD thesis have been equally divided between the two. Chapters 2 and 3 are devoted to examining the production side, and are mainly concerned with monetary and physical representations of technology in environmental input-output models. Chapters 4 and 5 deal with consumption-related issues of lifestyle and behaviour, and their representation in monetary and time-units. By doing so, they increasingly shift the attention from environmental-economic aspects towards social aspects in quantitative SC research.

From a data perspective, Chapters 2 and 3 focus on physical input-output tables and their value for the environmental input-output models commonly encountered in quantitative SC research (e.g. Hertwich, 2006). Environmental input-output models assume that each unit of a sector’s commodity output triggers the same amount of a particular environmental factor (natural resource input or pollution output). The question in the discussion surrounding physical input-output analysis therefore becomes whether the monetary or physical structure (or parts of it) is a better approximation of the flow of a particular environmental factor. In such a case physical input-output tables (PIOT) can be used to improve the quality of the specification of the technological component in environmental input-output models and therefore also improve the quality of the quantitative results provided to inform SC policy.

The literature on physical input-output analysis has started addressing this question. In a recent article, Weisz and Duchin (2006) set out to better understand the difference between monetary and physical input-output analysis. Chapter 2 is an extended comment on this article. In the first part, it highlights some serious flaws in the argument concerning the construction of the German PIOT. The second part shows how important insights can be gained through a rigorous application of a conceptual model describing the relationship between monetary and physical input-output analysis proposed by Weisz and Duchin (2006). The final part stresses the neglected empirical dimension of the question “Physical and monetary input-output analysis – what makes the difference?”, and presents the first detailed results from environmental input-output models based on production structures in monetary, physical and hybrid units.

Chapter 3 provides a first detailed empirical comparison of monetary and physical representations of production structures as provided by a monetary input-output table (MIOT) and its corresponding PIOT. Due to the lack of empirical work so far on the issue, it argues that visualisation methods are a valuable way of obtaining an initial understanding of basic structural features and to examine differences between the different representations of the production structure. This provides the main theme for the Chapter: “Seeing the Forest for the Trees”. The first part uses the graph-theoretical facilities provided by qualitative input-output analysis to reveal core patterns of inter-sectoral connectedness. The second part proposes a simple qualitative methodology for identifying the nature of product flows, which is at the core of some of the most fundamental differences between monetary and physical input-output tables. It is shown that both issues have direct implications for the specification of environmental input-output models and the scoping of future research.

Chapters 4 and 5 focus on the consumption side and lifestyle analysis, as frequently carried out in the environmental input-output literature. From a data perspective, attention is drawn towards some of the rather recent data developments provided by the Federal Statistical Office of Germany’s “Socio-economic reporting system”. These developments are an acknowledgement of the importance of social and behavioural issues in the context of sustainable development (and therefore SC), and the lack of comprehensive socio-demographic statistics consistent with the other economic and environmental account data. The general question in the context of this thesis therefore is how some of these data developments can contribute to introduce social and behavioural issues in quantitative models. To limit the scope of this undertaking, a strong

focus is put on environmental input-output methods, though Chapter 5 will broaden the discussion.

Chapter 4 uses detailed data on income, expenditure, employment and demographics to add social information in the form of a Social Accounting Matrix (SAM) - type extension to the environmental input-output model. It provides a comprehensive analysis of the development in greenhouse gas (GHG) emissions of 41 different socio-economic groups in Germany between 1991-2002. Structural decomposition and panel regression analyses are used to obtain a better understanding of the influence of different socio-economic determinants. The value of this lifestyle analysis is critically discussed in terms of its value for informing climate change policy.

Chapter 5 argues that conventional environmental input-output models will remain very limited in their treatment of social issues due to the limitations of their expenditure-based conceptualisation of lifestyles. Instead it is argued that lifestyles are reflected in what people do rather than in what they spend. Therefore, a lifestyle concept based on human activity patterns is developed. Due to full complete coverage, time-use data are introduced as an appropriate way of representing human activities and as the adequate basis for the empirical lifestyle conceptualisation. The idea of integrated data frameworks in monetary, physical and time units as a basis for SC research is outlined. Using the data from the 'Magic Triangle' dataset of the socio-economic reporting system, an environmental input-output model in monetary, physical and time units is used as an empirical foundation for a discussion of the merits and pitfalls of such data frameworks.

Some further general remarks should be made about this thesis. It is highlighted from the beginning that the thesis is of 'cumulative' nature; each chapter is the basis of at least one article, which has been or will be shortly submitted to an academic journal. This structure does not provide the same level of coherence in arguments across chapters as traditional theses. However, the separate strands of the argument will be connected in the discussion section (Chapter 6). Moreover, note in this context that most of the time, the current chapter is referred to as 'this article' rather than 'this chapter'.

Finally, it should be mentioned that the main chapters only represent the most recent work-stream coming out of this PhD project associated with the German data. Other work has included multi-regional input-output analysis, input-output based Ecological Footprint analysis as well as lifestyle analysis using commercial marketing data. These, mostly published, articles or book chapters are appended. A book chapter on land-use accounting in a socio-economic input-output context in German language has

been left out, but will be briefly summarised in the discussion. It was decided not to include these articles in the main body of this thesis for two main reasons:

- these articles did not fit the intended focus on the new data developments in Germany;
- co-authors have been more heavily involved in writing and empirical estimation for these articles even though in each case a significant contribution was made by the PhD candidate.

However, above all, these articles remain as a valid part of this PhD project and they will be brought into the picture in the discussion provided in Chapter 6.

## **2      On Flaws and Features of Physical Input- Output Tables**

### **A Comment on the physical input- output debate and some analysis**

**Abstract:** This article comments on a recent paper by Weisz and Duchin (2006) on the relationship between monetary and physical input-output analysis. In the first part, it highlights some serious flaws in the argument associated with the construction of the German PIOT. The second part shows how important insights can be gained through a rigorous application of a conceptual model describing the relationship between monetary and physical input-output analysis proposed by Weisz and Duchin (2006). The final part stresses the neglected empirical dimension of the question “Physical and monetary input-output analysis – what makes the difference?” and presents the first detailed results from environmental input-output models based on production structures in monetary, physical and hybrid units.



## 2.1 INTRODUCTION<sup>1</sup>

Within the last four years a series of papers have been published on physical input-output analysis (Hubacek and Giljum, 2003; Giljum and Hubacek 2004; Giljum et al., 2004; Suh, 2004; Dietzenbacher, 2005; Hoekstra and Van den Bergh, 2006; Weisz and Duchin, 2006; Dietzenbacher et al., 2007). The debate has largely focussed on the appropriate treatment of wastes in environmental input-output models based on physical input-output tables (PIOT), while a discussion of their relationship to models with production structures solely defined in monetary terms has accompanied this main theme from the beginning. In a recent contribution Weisz and Duchin (2006) – henceforth referred to as WD - shift the question “Physical and Monetary Input-Output Analysis: What Makes the Difference?” to the centre of attention.

They start their discussion by presenting a conceptual model explaining the relationship between monetary and physical input-output analysis: static input-output models with coefficient matrices derived from input-output tables in monetary and physical units respectively provide exactly the same results given the existence of a vector of unique sectoral unit prices. In the remainder of their article WD discuss various reasons why the relationship between the German 3-sector monetary input-output table (MIOT) and PIOT used in the debate on physical input-output analysis is described by a price matrix rather than a vector of homogenous sectoral unit prices and provide two main reasons:

- *First*, due to the faulty construction of the German PIOT, the monetary and physical models are not comparable.
- *Second*, the real world conditions are at odds with the axiomatic structure of input-output analysis. In particular, the standard input-output assumptions of homogenous prices is too restrictive and needs to be challenged.

In this article we review the arguments brought forward by WD. We argue that WD are misled in several of their findings in particular with respect to the construction of the German PIOT driven by a superficial knowledge of the data. They overlook other important arguments in the context of their unit price discussion and fail to live-up to the empirical dimension of their remarks.

---

<sup>1</sup> We are grateful to Carsten Stahmer for his remarks on a previous version of this article. However, all mistakes remain the full responsibility of the author.

We continue by pointing towards the strong empirical nature of the question of the difference between monetary and physical input-output analysis and the urgent need to start such a discussion to further advance the debate on physical input-output analysis. Only learning about these differences will allow the appropriate specification of production structures with the available data for answering policy questions. Model estimates are provided using the German 1995 data in order to illustrate this point. Therefore, we highlight the hybrid nature of the article. While it is largely organised and written like a comment, it goes beyond this scope by providing some analytical sections.

Section 2.2 reviews WD arguments. Section 2.3 demonstrates that additional insights can be gained from a conceptual analysis of the relationship between monetary and physical input-output models. In Section 2.4 the empirical analysis is provided before Section 2.5 concludes.

By doing so we hope to contribute to the discussion in at least two respects:

- By reviewing WD arguments we add to the understanding of the available PIOT data and its construction and further clarify the conceptual relationship between monetary and physical input-output analysis.
- We provide the first comparative analysis of different environmental input-output models based on production structures in purely monetary, purely physical and mixed units (at an aggregation level of empirical relevance).

## **2.2 ON THE CONSTRUCTION OF THE GERMAN PIOTs**

WD see one major reason for the absence of a homogenous vector of sectoral unit prices in the “faulty” construction of the German 3 sector PIOT used by Hubacek and Giljum (2003) – henceforth referred to as HG - in the original paper. Because no standardisation has taken place yet in the young history of PIOTs, they suggest that there might be no commensurability in the concepts and definitions applied in the compilation of monetary and physical tables – not only for the factor inputs but also the interindustry and final demand tables. From their discussion they conclude “that the PIOT used by Hubacek and Giljum (2003) fails to provide reliable physical values to quantify the flows of commodities (including services) among the sectors of the economy even after the correction for the treatment of waste” (Weisz and Duchin, 2006: 540).

In this Section we critically review WD's arguments associated with the construction of the German PIOT used by HG. We show that their conclusion is largely unsubstantiated and mainly caused by a limited understanding of the data under consideration. We proceed by discussing their arguments associated with the output of the agriculture and forestry sector before the service case will be reviewed. After some remarks on their arguments directed towards the table layout, we add relevant information associated with the construction of the tables.

### 2.2.1 The case of agriculture and forestry output

The output of the agriculture and forestry sector in the PIOT comprises not only the sector's commodity output like for example the harvest quantity, but the total biomass increase of cultivated plants and animals (Stahmer et al., 1998:16). WD argue that "the total biomass increase on agricultural land, managed forests and the total increase in livestock can hardly be interpreted as commodity output of the primary sector and therefore the derivation of a coefficient matrix from such PIOT will be grossly misleading" (WD, 2006: 539).

However, such a commodity output definition is consistent with the latest revision of the System of National Accounts (SNA92) (UN, 1992: 6.94-6.100) and therefore equally included in monetary accounts like input-output tables.<sup>2</sup> In fact, such commodity outputs are part of any GDP estimate to the extent agriculture and forestry output adds to final demand. This is highlighted in the System of Integrated Economic and Environmental Accounts (SEEA) (UN, 1993: par 173) "According to the SNA, the natural growth of biota in agriculture, forestry and fishery is treated as production if human cultivation is involved. Natural growth of non-cultivated biota is treated as other volume changes in assets which are not taken into account in the calculation of GDP."<sup>3</sup>

---

<sup>2</sup> In the UN Handbook of National Accounting (UN, 2003: 21) detailed information can be found how these monetary estimates should be derived.

<sup>3</sup> What might have caused the confusion is Stahmer et al.'s (1998:16) emphasis that the presentation of the agriculture and forestry sector "in the PIOT differs greatly from the concept of the monetary input-output tables in their *existing (unrevised)* form, but does, however, largely take account of the concepts of the *revised SNA*". However, this is a simple indication that Stahmer et al. in anticipation of the revision of the national accounts at the Federal Statistical Office, already used SNA93 instead of SNA68 concepts for some sectors. This was – like in the case of "agriculture and forestry" - extremely helpful for the PIOT compilation as it was one major concern in the design of SNA93 concepts to strengthen price-volume/quantity relationships (mainly to allow for more robust deflation of monetary accounts).

## 2.2.2 The case of service outputs

In their second argument WD turn the attention towards service sectors. The authors conclude from their discussion that “the coefficient matrix derived from PIOTs is misleading as a representation of the inputs and outputs of this large and growing part of the economy” (Weisz and Duchin, 2006: 539). They develop their argument along two lines. The first part highlights the limitations of accounting systems in mass units to represent (the largely) immaterial commodity outputs of service industries. The second part identifies deficiencies in the full representation of service outputs in the German PIOT associated with data shortages.

Let us deal with the latter issue first. The claims of deficiencies in the representation of *physical* outcomes in service sectors are rooted in Stahmer et al.’s (1998) remark that the service outputs in the original PIOT publication “represent only a subset (selected on the basis of data availability) associated with some services” (Weisz and Duchin, 2006). This, indeed, is an issue associated with the construction of the German PIOT and would adversely affect the commensurability between monetary and physical model outcomes. However, HG *do not use* the original PIOT, but a later extended and updated version, in which these deficiencies have been largely removed.

In fact only a brief glance at the publications would have been sufficient to detect these differences: neither name nor table layout of the data is the same. Hence, rather than deficiencies in the data, it is a lack of sufficient knowledge about the data under consideration and an appropriate use of the accompanying documentation, which is at the root of the claim that the representation of the physical flows associated with (intermediate and final) service deliveries is incomplete. Instead, from an accounting perspective the German PIOT represents the physical flows associated with service outputs with similar levels of confidence as MIOT represents the monetary ones (Stahmer, 2006).

Because consistent accounting based on the same definitions and concepts in MIOTs and PIOTs (incl. data availability) is a sufficient condition for commensurability between monetary and physical models, there must be a further confusion generated in the first part of the argument. It is a valid observation as previously highlighted by Stahmer (2000) and Dietzenbacher (2005) that physical accounting frameworks fail to capture immaterial service flows. It follows that these immaterial service flows do not have a unit price as long as they are strictly defined in mass units and that the ratio between corresponding entries in the monetary and physical intermediate flow matrices

usually do not measure the unit price of a commodity. However, this is due to the difference in coverage of data systems in monetary and physical units and has nothing to do with the commensurability between MIOTs and PIOTs. Because the same accounting concepts and definitions are applied in the construction of MIOT and PIOT, commensurability is safeguarded and model results obtained from monetary and physical input-output analysis are fully comparable.

It seems that the question WD want to answer is why *results* obtained from (commensurable) models with monetary and physical production structures respectively are different. However, this question is not adequately framed as an issue of *table construction*, but as a matter of *model specification*. Given their coverage do, the tables in monetary and physical units provide an adequate representation of the production structure for modelling purposes?

Hence, the PIOT underlying HG's model does not fail to provide reliable physical values nor does it seem to lack commensurability with the corresponding MIOT. The coefficient matrix, therefore, also does not present a misleading representation of physical inputs and outputs of the service sector. Instead it shows that the monetary and physical realities are strikingly different. However, it is correct that production structures specified purely in physical units are not suited for environmental input-output analysis, where an adequate representation of the interlinkages between all different economic activities is indispensable for robust model estimations. This has been previously highlighted by Dietzenbacher (2005). In this sense the physical coefficient matrix might be misleading for many *modelling exercises* without the PIOT being flawed in its construction.

### 2.2.3 The table layout

Finally, the authors identify “a third discrepancy in assumptions between the PIOT and the standard input-output practices introduced by HG (2003) and again in a later publication (Giljum and Hubacek, 2004), when they added the weight of waste to the weight of final demand [...]”. Again, not the construction of the PIOT is of relevance in this context. Instead, the debate on the appropriate treatment of waste has shown how fully comparable monetary and physical input-output models can be set-up (Hubacek and Giljum, 2003; Suh, 2004; Giljum et al., 2004; Dietzenbacher, 2005). As long as wastes and commodities are fully separable – as in the German tables – no problems associated with the table layout arise.

### 2.2.4 On the construction of PIOTs

While WD are so busy searching for differences in the construction between MIOTs and PIOTs contributing to an explanation why the assumption of homogenous sectoral unit prices cannot be observed in the available tables, they miss out one of the most crucial facts: that commodity flows in (the German) MIOTs and PIOTs *are* related by a unit price assumption in their construction – only on a very low aggregation level (see Stahmer et al., 1998; Gravgard Pedersen, 1998).<sup>4</sup> In particular, commodity output vectors (domestic production, imports) are distributed proportionally over mixed – physical and (mainly) monetary – use structures depending on the sector under consideration. In earlier German PIOT publications, for example, about 1500 products were distinguished in this process (see Stahmer et al., 1998), while later ones increased this even up to 3120 (see Statistisches Bundesamt, 2001). With monetary and physical tables directly related through a unit price assumption in the construction process, the relevance of the construction argument for explaining the existence of a price matrix can at most be a marginal one. Further corrections for price differentiation, price fluctuations and the like in this construction process, provide another argument why a “price matrix” might be observed even for fully commensurable monetary and physical tables (see WD, 2006: Section 4.2).

---

<sup>4</sup> The reader should be aware that this reference is still suitable for general methodological reference. The point made earlier was related to a data-related issue, which, of course, only holds for the data described in this publication.

## 2.3 REVISITING THE UNIT PRICE ARGUMENT

Hence, most of what WD discuss under the heading of ‘table construction’ has little to do with the issue. They could have shed much more light on to the question what makes the difference between monetary and physical input-output analysis, by exploiting their own conceptual model rigorously. This will be done in this Section.

### 2.3.1 A generalised unit price model

In this Section we would like to discuss input-output models derived from physical representations of the economy and consider their relationship to alternative monetary representations: For convenience we restrict our considerations to the case of a closed economy, which does not trade with the rest of the world, even though a generalisation to open systems would be straightforward.

Let  $Z$  denote a non-negative square matrix depicting the intermediate product exchanges between  $n$  different economic sectors and  $y$  a  $n \times 1$  vector of their final deliveries. Intermediate and final outputs of the  $i^{\text{th}}$  sector (for  $i=1,2,\dots,n$ ) represented in the  $k^{\text{th}}$  physical measurement unit (for  $k=1,2,\dots,m$ ) are denoted by elements  $z_{ij}^k$  and  $y_i^k$  respectively. Note that it is assumed that the output of each sector is homogenous and can be adequately represented in a single measurement unit. It follows that by definition the number of measurement units cannot exceed the number of sectors ( $m \leq n$ ). This allows the physical description of the (complete) structure of product inputs and outputs of each sector by a set of  $n$  linear equations:

$$\begin{aligned}
 z_{11}^1 + z_{12}^1 + z_{13}^1 + \dots + z_{1n}^1 + y_1^1 &= x_1^1 \\
 z_{21}^1 + z_{22}^1 + z_{23}^1 + \dots + z_{2n}^1 + y_2^1 &= x_2^1 \\
 z_{31}^2 + z_{32}^2 + z_{33}^2 + \dots + z_{3n}^2 + y_3^2 &= x_3^2 \\
 &\vdots \\
 z_{n1}^m + z_{n2}^m + z_{n3}^m + \dots + z_{nn}^m + y_n^m &= x_n^m
 \end{aligned} \tag{2.1}$$

Each element  $x_i^k$  of the total output vector  $x$  sized  $n \times 1$  gives the sum of all intermediate and final product deliveries of the  $i^{\text{th}}$  sector measured in the  $j^{\text{th}}$  measurement unit. Such physical representations of products outputs in multiple units have been

applied for explanatory purposes by Leontief himself (e.g. Leontief, 1965; Leontief, 1970; Leontief, 1972) and has been recommended in the System of National Accounts for the derivation of price-volume/quantity relationships (see UN, 1992: XIV).

Technical coefficients  $a_{ij}^{kl}$  in mixed units measuring the intermediate output of sector  $i$  measured in unit  $k$  (for  $k=1,2,\dots,m$ ) absorbed by sector  $j$ ,  $z_{ij}^k$ , per unit of its total output measured in unit  $l$  (for  $l=1,2,\dots,m$ ),  $x_j^l$ , can be derived by

$$a_{ij}^{kl} = \frac{z_{ij}^k}{x_j^l} \quad (2.2)$$

Using (2.2), the system of linear equations in (2.1) can be re-arranged to yield the basic equation input-output equation:

$$\begin{aligned} a_{11}^{11}x_1^1 + a_{12}^{11}x_2^1 + a_{13}^{12}x_3^2 + \dots + a_{1n}^{1m}x_n^m + y_1^1 &= x_1^1 \\ a_{21}^{11}x_1^1 + a_{22}^{11}x_2^1 + a_{23}^{12}x_3^2 + \dots + a_{2n}^{1m}x_n^m + y_2^1 &= x_2^1 \\ a_{31}^{21}x_1^1 + a_{32}^{21}x_2^1 + a_{33}^{22}x_3^2 + \dots + a_{3n}^{2m}x_n^m + y_3^2 &= x_3^2 \\ &\vdots \\ a_{n1}^{m1}x_1^1 + a_{n2}^{m1}x_2^1 + a_{n3}^{m2}x_3^2 + \dots + a_{nn}^{mm}x_n^m + y_n^m &= x_n^m \end{aligned} \quad (2.3)$$

These systems of linear equations can be summarised in matrix notation. Let  $A^{hybrid}$  denote the  $n \times n$  matrix of technical coefficients with  $m \times m$  partitions corresponding to the square of the numbers of different units in the linear system and  $y^{hybrid}$  and  $x^{hybrid}$  corresponding final demand and total output vectors with  $m$  partitions:

$$A^{hybrid} = \begin{pmatrix} A^{11} & A^{21} & \dots & A^{m1} \\ A^{21} & A^{22} & \dots & A^{m2} \\ & & \vdots & \\ A^{m1} & A^{m2} & \dots & A^{mm} \end{pmatrix}; \quad y^{hybrid} = \begin{pmatrix} y^1 \\ y^2 \\ \vdots \\ y^m \end{pmatrix}; \quad x^{hybrid} = \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} \quad (2.4)$$

We can rewrite Equations (2.3) by:

$$x^{hybrid} = A^{hybrid} x^{hybrid} + y^{hybrid} \quad (2.5)$$

and further manipulate:

$$(I - A^{hybrid}) x^{hybrid} = y^{hybrid} \quad (2.6)$$



Given the existence of a homogenous vector of sectoral unit prices, there exists a dual monetary model such that

$$(\hat{\mathbf{p}}^{hybrid})^{-1}[(\mathbf{I} - \bar{\mathbf{A}})\bar{\mathbf{x}}] - (\hat{\mathbf{p}}^{hybrid})^{-1}\bar{\mathbf{y}} = (\mathbf{I} - \mathbf{A}^{hybrid})\mathbf{x}^{hybrid} - \mathbf{y}^{hybrid} \quad (2.7)$$

where  $\mathbf{p}^{hybrid}$  is a  $n \times 1$  vector of unique sectoral unit prices with elements indicating the price of one unit of the  $i^{th}$  sector's output measured in the  $k^{th}$  measurement unit; the hat symbol “^” indicates diagonalisation; the bar symbol “—” identifies matrices and vectors exclusively defined in monetary units. Such a model set-up as shown in Equation (2.7) seems useful as it provides the most general case and easily allows to derive some conditions, which need to be met for a unit vector of sectoral unit prices to exist.

The literature so far has failed to point that this is only the case, if and only if, the total physical output vector  $\mathbf{x}^*$  is strictly positive. Moreover, Equation (2.7) will hold, if and only if, for any commodity flow (unless there is no!) in the economy there exists a positive unit price ( $p_i^k > 0$ ) and quantity component ( $z_{ij}^k > 0$  and  $y_i^k > 0$ ). Discussing how likely it is that these conditions will be met in the real world allows to reveal some general insights in the relationship between monetary and physical input-output tables and the specification of environmental input-output models.

### 2.3.2 On the Existence of Positive Unit Prices

Let us begin with the typical assumption made in the economic literature that there is a measurable physical quantity for any commodity flow (e.g. Sraffa, 1960; Pasinetti, 1977; Proops et al., 1992). This assumption seems valid as long as no restrictions are imposed on number and type of measurement units. In fact, since the last major revision, the System of National Accounts (SNA92) (UN, 1992: XVI) requires Statistical Offices to provide physical output indicators for all product flows included in the production boundary.<sup>5</sup>

---

<sup>5</sup> The decomposition of the value of a product flow into a price and a quantity component are seen as important for a robust deflation (and therefore construction of time series) of time series data and for a systematic and detailed analyses of inflation and economic growth and fluctuations.

We have already highlighted above that even in the case of a full physical coverage of all intermediate and final deliveries, Equation (2.7) will only be defined if all attached prices  $p_i^{hybrid}$  are strictly positive as well.<sup>6</sup> However, this is not likely to be the case for two reasons: *First*, conceptually economic commodities can have a zero price in national accounting as they are defined by type and not based on a price criterion as in the economic literature (see UN, 2003: 3.66). *Second*, the SNA boundary does not only comprise economic goods, but also residual materials to the extent that they are inputs or outputs of a economic transformation processes.

In fact, in the accounting literature environmental service activities such as recycling or waste treatment are commonly discussed under the notion of “*production ex nihilo*” (production out of nothing). Residual outputs are often provided to these sectors free of charge where they stimulate further economic transformation processes. In the case of waste treatment the delivering sector often has to pay for the service. Therefore, even though these intermediate flows are all conceptually included in the SNA production boundary, they do not manifest in the monetary representation of the input structure of environmental service sectors. In this sense, production seems to appear “out of the blue”.

For our discussion of the general relationship this already provides two interesting, interrelated findings: *First*, the existence of a unit price is a necessary, but not a sufficient condition for dual representations of the economy in monetary and physical units as outlined in Equation 7. In addition, all  $n$  different unit prices  $p^{hybrid}$  need to be strictly positive. However, as long as the standard SNA93 production boundaries are applied, this will not be the case as it also includes intermediate and final deliveries with zero (and negative) prices such as environmental service activities. *Second*, as a result traditional monetary input-output tables provide an incomplete coverage of production sphere as delineated in the SNA. This might be particularly relevant in the discussion of an appropriate specification of environmental input-output models.

### 2.3.3 On the representation of services in single unit PIOTs

However, PIOTs are usually represented purely in terms of the weight of product flows all measured in a single unit ( $k=1$ ). Such single-unit re-presentations have various advantages from an accounting perspective (see Stahmer et al., 1998; Giljum and

---

<sup>6</sup> Note that commodities are identified by type and not as often in the economic literature by a price criterion.

Hubacek, 2007; Minx et al., 2007b: chapter 3 of this thesis). However, they might fail to capture all commodity flows included within a defined production boundary as we, for example, have just discussed for environmental service activities and their incomplete representation in value terms.

With regard to Equation (2.7) and our unit price discussion, we might distinguish two cases: *First*, some unit prices  $p_i^k$  might not exist, because total commodity outputs  $x_i^k = \sum_{j=1}^n z_{ij}^k + y_i^k = 0$  might be zero for  $k=1$  (i.e. measurement exclusively defined in weight units in the context of the current debate) even though there exists another physical measurement unit  $l$  such that  $x_i^l = \sum_{j=1}^n z_{ij}^l + y_i^l > 0$ .<sup>7</sup> *Second*, a unit price might exist, but individual commodity flows might not be represented in a particular unit.<sup>8</sup> With regard to our conceptual model this means that  $z_{ij}^k = 0$  (or  $y_{ij}^k = 0$ ) (where  $k$  represents weight units), even though there exists another physical measurement unit  $l$  such that  $z_{ij}^l > 0$  (or  $y_{ij}^l > 0$ ). Also in this case, Equation (2.7) no longer holds.

Only the first case has been dealt with in the discussion of immaterial service output in tertiary sectors. However, services are also produced by establishments in primary and secondary sectors. The agricultural sector, for example, provides landscape gardening services, or the computer industry support services. As discussed in Minx et al. (2007: see Chapter 3 of this thesis) the relevance of services in these sectors will depend on the accounting concepts applied in the construction of the PIOT.

Hence from the discussion of single-unit PIOTs measured in weight several implications can be derived. *First*, in contrast to the measurement of physical output in  $m$  different units, PIOTs strictly defined in terms of the weight of commodities cannot describe all the economic transactions within the SNA production outputs due to their “blindness” for weightless services. Like MIOTs, PIOTs are therefore incomplete in their coverage. *Second*, the lack of coverage might not be restricted to tertiary sectors, but equally concern primary and secondary sectors.

<sup>7</sup> To be fully correct: we need to further assume non-negativity for  $y$ , which is not necessarily met for all elements due to stock changes.

<sup>8</sup> With regard to our conceptual model, this means that  $z_{ij}^k = 0$  (or  $y_{ij}^k = 0$ ) even though there exists a measurement unit  $l$  such that  $z_{ij}^l > 0$  (or  $y_{ij}^l > 0$ ).

However, the coverage of such a physical table purely specified in weight units is restricted to physical objects, i.e. immaterial service outputs lie outside the scope of physical accounting system strictly defined in weight terms. Restricting the meaning of physical measurement to weight units, the SEEA therefore highlights (UN, 2003: 2.58): “For industrialised economies, the monetary tables are dominated by the role of services; in physical terms, although services absorb products, in general they do not supply any because their output is weightless.” Immaterial service flows are therefore represented in such a PIOT only in terms of its residual outputs as previously mentioned.

### **2.3.4 Implications for Environmental Input-Output Modelling**

Finally we should discuss the implications of our findings for environmental input-output modelling. These models assume that each unit of a sector’s output triggers the same amount of a particular environmental factor. This assumption might be reasonable at the individual product level given that the size of the product flow is well represented in a particular measurement unit. If a unit price existed, there would be no need for practitioners to discuss the difference between monetary and physical input-output analysis as environmental input-output models based on monetary and physical production structures would arrive at the same results.

The discussion is associated with the hope that particular economic activities might be better described in physical units. There might be many reasons for this. For instance, mass is a fundamental unit, because it cannot be expressed in a simpler fashion. All other units are derived from these units. For example being fundamental units they are simpler to obtain and interpret, can be used more easily for comparisons, and are not subject to additional problems introduced by derived measurements of complex monetary values. The measurement of complex monetary values is associated with a whole range of problems as probably most strikingly manifested in the large accounting literature on price measurement: there are current, constant, basic, purchasers, producer, cif and fob prices (see SNA, 1993). The application of different price concepts will result in different monetary representations of the production structure and therefore a different attribution of environmental factors to final demands in environmental input-output models.

Equally physical measurement has its limitations. Physical data, for example, might be less readily available. Equally aggregate single unit representations might be error-prone when measurement units are converted in the compilation of PIOTs,

dominated by particular flows in the production boundary or arbitrary because some of the most heavy flows need to be excluded due to their dominance over all other flows (as for example water in the Danish table).

Therefore, particularly at the high level of input-output analysis it remains unclear whether monetary or physical representations of a sector's output structure better resembles the flows of a particular environmental factor. However, there is little reason to believe that the data provided in PIOTs cannot be usefully combined with information contained in monetary tables for a more appropriate representation of the production structure in environmental input-output models. Similarly to the energy-economic debate, where the case for using data in energy units is commonly accepted, we can argue that PIOT partitions are generally preferable to its monetary counterparts, where the coverage of physical measurement goes beyond the monetary one. As previously discussed, this is the case in the recycling and waste treatment sectors and can be seen as the dual to Dietzenbacher's (2005) argument for the general superiority of monetary data in representing service outputs in environmental input-output applications.

However, for all other primary and secondary product flows the case is less clear-cut. It seems that an appropriate specification will depend on a variety of factors such as the policy question or the type of pollutant under consideration. Another pre-condition is a sound understanding of the empirical differences between monetary and physical production structures. However, so far PIOT data has never been used at any aggregation level of empirical relevance stressing the urgent need for a shift of the debate to an empirical level. Only by setting-up models on an empirically relevant aggregation level based on the available monetary and physical data, comparing their results and analysing how differences in model estimates evolve throughout the supply chain of final commodities, will allow us to make informed decisions about the specification of production structures in the light of the availability of data from MIOT and PIOT and might also stimulate an important discussion on how PIOTs should be constructed in the future to be of most use for informing policy processes.

## 2.4 TOWARDS AN EMPIRICAL DISCOURSE ON THE DIFFERENCE BETWEEN MONETARY AND PHYSICAL INPUT-OUTPUT ANALYSIS

To highlight the value of such an empirical debate we briefly discuss results from environmental input-output models based on monetary, physical and hybrid production structures. In the next Section the model will be outlined and the data will be described, before Section 2.4.2 discusses the results.

### 2.4.1 Methodology and Data Description

In this Section the methodology is described. Because comparability between different environmental input-output models based on production structures in monetary, physical and hybrid units is of major importance, only appropriate waste adjusted model specifications were chosen as described in Dietzenbacher (2005) and Suh (2004) (also see Section 2.2.3).

Let  $Z^k$  be an  $n \times n$  domestic interindustry commodity flow table,  $y^k$  be a  $n \times 1$  vector of domestic final commodity demand,  $x^k$  a  $n \times 1$  vector of total domestic commodity output,  $\tilde{x}^{piot}$  a  $n \times 1$  vector of total domestic material output in physical units,  $w^{piot}$  a  $n \times 1$  vector of total physical residual output,  $r$  a  $n \times 1$  vector of an environmental factor input and  $I$  a  $n \times n$  identity matrix. Let the subscripts  $k=miot,piot,hyb$  further refer to matrices and vectors in monetary, physical and hybrid unit respectively. Based on these definitions we can set up an environmental input-output model with a production structure defined purely in monetary terms:

$$e^{miot} = (q^{miot})'(I - A^{miot})^{-1} \hat{y}^{miot}$$

with

$$q^{miot} = ((r\hat{x}^{miot})^{-1})' \quad \text{and} \quad A^{miot} = Z^{miot} (\hat{x}^{miot})^{-1} \tag{2.8}$$

where  $e^{miot}$  is a  $1 \times n$  vector of the direct and indirect factor requirements of the final demand  $y$  and the hat symbol '^' indicates the diagonalisation of a vector. Following Suh (2005) and Dietzenbacher (2005) the corresponding model results  $e^{piot}$  from a specification of the production structure in purely physical terms can be written as:

$$\mathbf{e}^{piot} = (\mathbf{q}^{piot})' (\mathbf{I} - \mathbf{A}^{piot})^{-1} \hat{\mathbf{y}}^{piot}$$

with

$$\mathbf{q}^{piot} = (\mathbf{r}(\hat{\mathbf{x}}^{piot})^{-1})' \quad \text{and} \quad \mathbf{A}^{piot} = \mathbf{Z}^{piot} (\hat{\mathbf{x}}^{piot})^{-1} \quad (2.9)$$

where  $\mathbf{x}^{piot} = \tilde{\mathbf{x}}^{piot} - \mathbf{w}^{piot}$  is the total commodity output vector in physical units.

Finally the production structure can also be defined in hybrid units, that is,

$$\mathbf{e}^{hybrid} = \begin{pmatrix} \mathbf{q}_1^{piot} \\ \mathbf{q}_2^{miot} \end{pmatrix}' \left[ \begin{pmatrix} \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}_{11}^{hybrid} & \mathbf{A}_{12}^{hybrid} \\ \mathbf{A}_{21}^{hybrid} & \mathbf{A}_{22}^{hybrid} \end{pmatrix} \right]^{-1} \begin{pmatrix} \hat{\mathbf{y}}_1^{piot} & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{y}}_2^{miot} \end{pmatrix}$$

with

$$\mathbf{q}^{hybrid} = (\mathbf{r}'(\hat{\mathbf{x}}^{hybrid})^{-1})' = \left( \mathbf{r}' \begin{pmatrix} \hat{\mathbf{x}}_1^{piot} & \mathbf{O} \\ \mathbf{O} & \hat{\mathbf{x}}_2^{miot} \end{pmatrix}^{-1} \right)' \quad (2.10)$$

and

$$\mathbf{A}^{hybrid} = \mathbf{Z}^{hybrid} (\hat{\mathbf{x}}^{hybrid})^{-1} = \begin{pmatrix} \mathbf{Z}_{11}^{piot} & \mathbf{Z}_{12}^{piot} \\ \mathbf{Z}_{21}^{miot} & \mathbf{Z}_{22}^{miot} \end{pmatrix} \begin{pmatrix} \hat{\mathbf{x}}_1^{piot} & \mathbf{O} \\ \mathbf{O} & \hat{\mathbf{x}}_2^{miot} \end{pmatrix}^{-1}$$

where the superscripts  $l=1,2$  refer to the respective matrix partition.

Estimations were based on the German PIOT and MIOT for the year 1995 (Federal Statistical Office, 2003). The PIOT is provided at a 59 sector level. The corresponding MIOT (Federal Statistical Office of Germany, 2006f) is published at a 71 sector level and was aggregated accordingly. In both publications the sector 'uranium mining' contained only zero elements in input and output structure and were removed.

Water flows made 83% of the total weight of intermediate flows in the PIOT. This dominance in the production structure suggests that other flows might not be well represented. It follows that the environmental input-output model will assign environmental factors to final demands mainly according to the water flows in the supply chain. However, this might only be useful for very particular policy questions. For many other policy applications it might be much more appropriate to remove these water flows. In fact, the Danish PIOT does not include water flows (see Gravgard Pedersen, 1998) and in the material flow accounting literature it is also common practise not to include them in the headline indicators and provide information about water flows only in separately. It therefore seemed important to remove water from the PIOT for some analysis. This was achieved by using the water supply and use tables contained in the PIOT data set. The resulting PIOT without water flows included will be referred to as PIOTnw. Finally,  $CO_2$

emissions were taken from another supplementary provided with the PIOT on air emissions. In the hybrid models, services were specified in monetary terms, energy sectors in energy units taken from the supplementary energy table of the PIOT publication and the remaining sectors were represented in physical units.

## 2.4.2 Some empirical results

Table 2.1 shows the results of the estimation. No results could be provided for the environmental input-output models based on the PIOT<sub>nw</sub> without water flows at the 58 sector aggregation level due to singularity problems. These are associated with the fact that service sectors do not provide any commodity outputs in the physical table, while receiving inputs from other sectors (see Chapter 3).<sup>9</sup> In contrast, the singularity problem does not surface in PIOT<sub>w</sub> with water flows included, because each service sector has (at least) one positive entry in the commodity partition from the deliveries of residuals to the waste treatment sector.

Moreover, condition numbers increased drastically, once the physical data was adjusted for wastes – also in the hybrid models. A high condition number means that a small change (error) in  $(I-A)$  can cause a relatively large change (error) in  $(I-A)^{-1}$  (Meyer, 2000) – the system becomes more ‘sensitive’ increasing the importance of an adequate model specification. Hence, once the detailed PIOT data is applied, important computational aspects once associated with the discussion of physical input-output analysis, which will need to be further addressed in the future.

Table 2.1 strikingly demonstrates the vast differences in results, which are obtained from comparable environmental input-output models with alternatively specified production structures. This raises the question which results are most appropriate for answering a certain policy question. Column 2 seems to confirm our earlier remark that models based on purely physical production structures do not provide sensible results due to their lack of coverage of immaterial service outputs.

In fact, for 24 of the 58 production sectors, no physical final demands are recorded being non-zero in monetary terms. Therefore, the input-output model does not assign any direct nor indirect CO<sub>2</sub> emissions to these sectors. Instead the total direct CO<sub>2</sub>

---

<sup>9</sup> However, it should also be noted that such a physical representation of service industries does not make any sense economically. These sectors solely take-up goods in order to produce residual outputs, which they deliver to the waste treatment sector.



emissions arising in production are distributed over the remaining 34 sectors with non-zero final demand. Because service industries with immaterial outputs are only evaluated in terms of their waste outflows in the intermediate flow table of the PIOT, their direct CO<sub>2</sub> is exclusively assigned to the final demands of the waste treatment sector. As a result its direct and indirect emissions are more than 60 times higher than estimated by the environmental input-output model with a purely monetary production structure. In some sectors the waste flows taken-up by the waste treatment sector consist only of water. Therefore, once water is excluded from the PIOT, the physical model even fails to assign the total CO<sub>2</sub> emissions arising in production across final demands due to the absence of any intermediate outputs of these sectors.

However, the physical measurement is not only limited in service sectors, but also in other parts of the economy. Energy is another well-discussed case in the literature. The negative entry in Column 2 of Table 2.1 immediately reminds us that weight is a very incomplete proxy for the energy sector's commodity output.<sup>10</sup> Equally we have shown in a recent paper (see Minx et al., 2006), that the intermediate flows of some producers (secondary sectors) of durable goods with a high service share, as for example the computer industry, almost entirely consist of immaterial service outputs.

Even if hybrid models<sup>11</sup> with a “complete” coverage of the product flows are chosen, large differences to the results from the model based on a purely monetary production structure remain. However, it is interesting that results from the hybrid model seem to become more similar to the one from the monetary one, once water is excluded from the production structure. The issue of the influence of water flows on the results might therefore need more detailed addressing in the future. It is not surprising that the hybrid models with the physical partitions assign more CO<sub>2</sub> to the final demands of sectors such as construction or waste treatment, which typically draw their inputs from “heavy” sectors or have “weighty/heavy” commodity input paths themselves.

Whether a monetary or a hybrid production structure should be used will ultimately depend on the environmental factor under consideration. The specification of

---

<sup>10</sup> The negative final demand underlying this result is triggered by a (relatively large) negative entry in the account for changes in produced natural assets representing a utilisation of pit gas (personal communication with German Statistical Office). Because (the view was taken that) nature plays a vital role in the formation of pit gas, it was regarded as a withdrawal from nature for energetic purposes and recorded as a negative entry in the changes in stock of produced natural assets.

<sup>11</sup> In these hybrid models primary and secondary sectors have been specified in physical terms with the exception of the energy sector, which was represented in energy units. Tertiary sectors were specified in monetary terms. The difference between the hybrid models lies in the inclusion of water, which is only part of the product flows in the first one (column 3).

the production structure will ultimately depend on some personal judgement of the input-output practitioner, i.e. whether the flows of a particular environmental factor might be more appropriately approximated by the structure of the monetary or physical intermediate deliveries of a certain sector. Hence, given the way how product flows are recorded, are the flows of a particular environmental factor in the supply chain associated with the deliveries of a certain (average) product to other sectors better approximated in terms of weight or value? This question needs to be answered for each production sector included in the analysis.

In primary and secondary sectors, heavy environmental flows such as flows of water, sand and gravel or timber, for example, might be much better assigned to “up-taking” sectors using the structure of physical intermediate product deliveries. In contrast, the flows of toxic materials might often correlate much better with the value of intermediate products. Ultimately, it would be desirable to develop simple statistical measures, which might help in the specification of input-output models (such as simple correlation coefficients). However, another pre-condition for an appropriate model specification is to learn more about the production structure of monetary and physical input-output tables and how differences are transmitted in corresponding monetary and physical models. A variety of methodologies are available to do so, just waiting to be applied in the context of monetary, physical and hybrid input-output models.

SIC	Sector Name	in million tonnes of CO <sub>2</sub>				
		MIOT	PIOT	hybrid: water	hybrid: no water	
		(1)	(2)	(3)	(4)	
1	01	Agriculture and hunting	19.82	37.54	40.70	35.31
2	02	Forestry, Fishing etc.	0.42	0.33	0.61	0.66
3	05	Forestry	0.06	0.00	0.01	0.07
4	10	Coal and Peat	0.79	0.50	0.26	0.19
5	11	Crude Petroleum and Natural Gas	0.31	0.47	0.22	0.21
6	13	Metal Ores	0.00	0.01	0.00	0.00
7	14	Other mining and quarrying	1.12	1.09	0.66	0.53
8	15	Food Products and Beverages	51.83	17.09	14.07	39.29
9	16	Tobacco Products	1.48	0.17	0.23	0.91
10	17	Textiles	5.63	0.09	0.15	3.03
11	18	Wearing Apparel	2.65	0.22	0.42	1.74
12	19	Leather and Leather Products	0.76	0.05	0.10	0.81
13	20	Wood and Wood Products	1.86	6.58	2.66	1.78
14	21	Paper and Paper Products	6.79	2.36	1.95	7.69
15	22	Publishing, Printing etc.	4.61	2.99	2.32	3.02
16	23	Manufacture of coke, refined petroleum etc.	15.53	11.07	23.73	29.39
17	24	Chemicals and chemical products	34.02	8.22	9.89	36.11
18	25	Rubber and plastic products	6.04	0.92	1.27	5.59
19	26	Manufacture of other non-mineral products	12.77	2.01	2.29	2.50
20	27	Manufacture of basic metals	32.58	22.98	16.33	23.31
21	28	Fabricated metal products	14.00	5.99	4.89	10.52
22	29	Machinery and equipment nec	28.48	5.98	6.09	20.87
23	30	Office, accounting and computing machinery	1.38	0.09	0.21	1.02
24	31	Electrical machinery and apparatus	7.63	0.71	0.98	6.57
25	32	Radio, television and communication equipment	5.17	0.30	0.23	2.17
26	33	Medical, precision and optical instruments, etc.	4.71	0.09	0.16	2.03
27	34	Motor vehicles, trailers and semi-trailers	36.30	7.30	7.33	24.81
28	35	Transport equipment	4.82	0.51	0.48	3.21
29	36	Furniture and manufacturing nec	7.72	4.42	3.90	6.97
30	37	Recycling	-	2.72	0.29	0.59
31	40	Electricity, gas, steam and hot water supply	147.42	-21.81	169.47	160.15
32	41	Collection, purification and distribution of water	1.76	2.59	1.73	1.16
33	45	Construction	61.09	481.88	163.89	95.29
34	50	Sale, maintenance and repair of motor vehicles etc	8.40	-	7.15	6.30
35	51	Wholesale trade and commission trade	11.23	-	10.70	10.63
36	52	Retail trade	27.66	-	25.51	25.35
37	55	Hotels and restaurants	17.54	-	14.30	15.30
38	60	Land transport	21.10	-	20.09	19.06
39	61	Water transport	1.81	-	4.77	4.58
40	62	Air transport	12.40	-	12.55	12.75
41	63	Auxiliary transport services	4.36	-	4.47	4.36
42	64	Post and telecommunications	2.05	-	1.76	1.63
43	65	Financial intermediation	1.83	-	1.73	1.53
44	66	Insurance and pension funding	3.11	-	3.02	2.70
45	67	Auxiliary financial services	0.05	-	0.04	0.04
46	70	Real estate activities	9.33	-	14.67	9.66
47	71	Renting of machinery and equipment	0.18	-	0.17	0.16
48	72	Computer and related activities	0.93	-	0.90	0.82
49	73	Research development	1.94	-	2.45	1.77
50	74	Other business activities	2.36	-	2.53	2.24
51	75	Public administration and defence	26.40	-	29.21	27.02
52	80	Education	13.03	-	16.20	11.99
53	85	Health and social work	25.77	-	30.38	23.97
54	90	Sewage and refuse disposal	1.83	114.60	27.62	3.55
55	91	Membership organisations nec	1.57	-	1.98	1.80
56	92	Recreational, cultural and sporting activities	3.30	-	7.16	3.65
57	93	Other service activities	2.36	-	3.20	1.75
58	95	Private households with employed persons	-	-	-	-
		Total	720.07	720.07	720.07	720.07

Table 2.1 - Model Results

## 2.5 CONCLUSION

In this article we have reviewed and clarified some of the arguments proposed by WD in a recent paper in this journal about the differences between monetary and physical input-output models and highlighted the need for an empirical debate. In this context, we provided the first set of detailed results from environmental input-output models with monetary, physical and hybrid production structures.

WD's major conclusion that the assumption of sectoral unit prices might be inappropriate is relevant and certainly deserves further addressing in the future. However, we also show that many of their other arguments are flawed, provided in a misleading context and incomplete:

- By highlighting some of key issues in the construction process of the German PIOT and its relationship to the MIOT, we argue that both tables are fully consistent and therefore comparable to the extent product flows are concerned. Neither do the commodity output definitions lack in congruence including the agriculture and forestry sector nor is the table ill-constructed. Instead, we show that for material products, MIOT and PIOT are related by a unit price assumption in their construction on a 6-8 digit level of the German Input-Output Classification. For these partitions in the use structure of MIOT and PIOT, the conceptual model proposed by WD therefore initially holds.
- However, many service flows do not have any physical product output. Therefore, they also lack a unit price as long as defined strictly defined in mass units. By using WD conceptual model it can be easily shown that input-output models based on monetary and physical production structures respectively will never lead to the same results even in the absence of aggregation or real world conditions such as price fluctuations or price differentiation. Ultimately, only the fact that models based on physical structures are fundamentally different due to the particular coverage of physical units motivates the whole discussion. It raises hopes that model specification can be improved through the availability of physical information as previously explored in the energy economic literature.
- It is further stressed that immaterial service outputs are not only provided by tertiary sectors, but also mixed together with material products in primary and

secondary industries. In the presence of aggregation this forbids a (average) commodity price interpretation of the ratio between a commodity flows in MIOT and PIOT and points towards the care required in the specification of input-output models in hybrid units drawing equally from MIOT and PIOT data as proposed in the debate.

The results from the various environmental input-output models with monetary, physical and hybrid production structures reconfirmed earlier findings that purely physical models are not suited for environmental input-output analysis. As changes in the specification of hybrid models lead to very different results, the importance of the issue of an appropriate specification was highlighted. The influence of water was highlighted and might need particular attention in the future.

We believe that what is most urgently required at the moment is an empirical debate on the differences between monetary and physical input-output analysis. A variety of different PIOTs are available, which can be applied in this context. This will be crucial for an adequate specification of hybrid models combining data from MIOT and PIOT in one production structure to answer different policy questions most appropriately. In this course particular attention will need to be directed towards these primary and secondary industries with a high service component.

One key to a successful empirical discourse might be a close collaboration between compilers and practitioners. Moreover, an integration of the on-going accounting debates would be equally desirable. The revised SNA93, for examples, requires Statistical Offices to construct physical indicators for immaterial service outputs in other than weight units. These indicators might allow the construction of hybrid PIOTs only multiple physical units, which might be more useful for modelling applications than their single unit counterparts discussed here. This empirical discussion might just come at the right moment in time when a new Danish PIOT is about to be published and the German Statistical Office is reviewing the compilation of a PIOT for the year 2000.

# 3 Seeing the Forest for the Trees?

## Using Qualitative Information to Reveal Structural Features of Production Systems in Alternative Measurement Units

**Abstract:** Starting with the contribution by Hubacek and Giljum (2003) there has been a continuing discussion on the application of physical input-output tables for the assessment of the economy-wide environmental consequences of a given final demand in input-output models. While there appears to be a wide consensus among researchers that hybrid unit models have considerable potential advantages over standard “pure” single unit approaches, little attention has been given so far to the practical question of how to best combine the available monetary and physical information for applied ecological economic analysis. We believe that the key to an appropriate specification of such models in hybrid units is a clear understanding of the structural differences between monetary (MIOT) and physical (PIOT) input-output tables.

This article provides the first empirical comparison of monetary and physical production structures using the full detail from MIOTs and PIOTs. Significant structural features are revealed through the application of established and newly proposed graph-theoretical tools from qualitative input-output techniques. Our analysis finds that 45% of the commodity flows in MIOT and PIOT are fundamentally different in that they have a positive record in one table and a zero record in the other. As expected, most of these are weightless immaterial service flows. However, we show that these differences are not only relevant in tertiary sectors, but throughout the economy: in fact, for some manufacturing sectors of capital goods with a high service component they can make up to 90% of all intermediate outputs. Remaining differences are explained by unpriced, material flows in environmental service sectors, where PIOTs provide a more comprehensive coverage.

We also find that, product flows are also much more concentrated in PIOTs than in MIOTs. This requires practitioners to control for the impact of physical partitions on results as a few individual exchanges might have a dominant effect. The graph-theoretical analysis presented in this article 1) directly informs the specification of environmental input-output models with mixed monetary and physical production structure; and 2) identifies key areas where further quantitative research and a discussion on the construction of physical input-output tables are required.

### 3.1 INTRODUCTION<sup>1</sup>

The debate about physical input-output tables (PIOT) and analysis (PIOA) is rather recent even though its roots can be traced back at least to the emergence of the environmental extensions of input-output analysis (e.g. Leontief, 1970; Victor, 1972). It was not until the 1990s that serious attempts were started to depict the flows within the economy as well as the flows between the economy and the environment fully in physical terms. Katterl and Kratena (1990) provided a first physical table for Austria even though it remained partial (see also Kratena et al., 1992). First complete PIOTs were established by Stahmer et al. (1998) for Germany and by Gravgard-Pedersen (1998) for Denmark. Since then tables have been provided for several other countries including Finland (Mäenpää and Muukonen, 2001), Austria (Weisz et al., 1999; Weisz, 2000), Italy (Nebbia, 2000), and New Zealand (McDonald et al., 2006) as well as for industrial sub-systems (e.g. Konijn et al., 1997; Bailey, 2000). While there is no established methodological framework yet, authors have usually tried to ensure consistency with the concept of the System of Integrated Environmental and Economic Accounts (SEEA) (United Nations, 2003).

The academic discussion on the application had an early “precursor” in Konijn et al.’s (1997) estimations of the material contents of final products based on a production structure specified in hybrid units, but did not seriously start until the contribution of Hubacek and Giljum (2003). They proposed PIOTs as the suitable basis for their estimations of the land appropriation of international trade activities. This triggered a lively debate (Suh, 2004; Giljum et al., 2004, Giljum and Hubacek, 2004; Dietzenbacher, 2005; Weisz and Duchin, 2006; Hoekstra and Van Den Bergh, 2006; Giljum and Hubacek, 2007; Dietzenbacher et al., 2007) which has (mainly) been concerned with the characteristics of and differences between MIOTs and PIOTs and their implications for environmental input-output modelling.

Some agreement has been reached in this discussion that best use is made of the information provided in MIOTs and PIOTs when these are combined in environmental input-output models with production structures specified in mixed monetary and physical

---

<sup>1</sup> We would like to thank Carsten Stahmer and Angela Heinze from the Federal Statistical Office of Germany and Ole Gravgard Pedersen from Denmark Statistics for comments and provision of unpublished background information associated with the compilation of physical input-output tables. However, all errors and misperceptions remain the full responsibility of the authors.

units (see Dietzenbacher, 2005; Weisz and Duchin, 2006; Dietzenbacher et al., 2007; Minx et al., 2007). Such models in hybrid units and their advantages are well established in the energy-economic literature (e.g. Bullard and Herendeen, 1974; Proops, 1977).

So far this discussion has remained purely on a conceptual level. Little light has been shed on the question of how information from MIOTs and PIOTs is best combined in such hybrid models in practice according to a particular policy. Agreement has only been reached that service outputs should be represented in monetary units due to the inability of physical measurement to capture immaterial service outputs (Stahmner, 2000; Dietzenbacher, 2005; Weisz and Duchin, 2006). Minx et al. (2007: see Chapter 2) have suggested that physical units have the same advantage over monetary ones in the representation of waste treatment and recycling activities. However, in general answering such specification questions requires an empirical discussion on structural differences in monetary and physical representations of the production structure as provided in MIOTs and PIOTs, and on how these empirical differences influence the results of environmental input-output models.

The general problem of comparing alternative representations (unit-wise) of the same production structure is new to the empirical input-output literature and has not been seriously addressed so far. However, there is a large arsenal of (input-output) methods available to analyse structural differences in production structures over time or across countries, which can be applied to the problem (see Heinz et al., 1997; Dietzenbacher and Lahr, 2001). These might be roughly divided into quantitative and qualitative input-output methodologies/tools.

Quantitative methodologies usually try to reveal structural features and differences by computing summary measures, rearranging the tables in a process of triangularisation and decomposing differences into a set of determinants, or by identifying a set of key sectors or product flows of ‘structural importance’. Qualitative input-output techniques have been popular for their capability to condense the large amount of information contained in standard input-output tables to (what is usually interpreted as) a ‘crucial minimum’ and to provide an intuitive visual understanding of these ‘core activities’ and their interlinkages in the supply chain using standard graph-theoretical tools.

Clearly both sets of tools will play an important role in developing an understanding of the structural characteristics of and differences between monetary and physical input-output tables. We have opted for qualitative methods here, because we



believe that the graph theoretical analysis of the ‘reduced input-output system’ will provide an intuitive way of revealing some of the key issues and differences at an early stage of the empirical debate. One could say that we hope to get a glance of the forest before looking at some important groups of trees. This qualitative analysis might be an important requisite for choosing and specifying subsequent quantitative models. Note that there is already on-going quantitative research building on the results presented in this article.

The next Section provides the background for our analysis by reviewing the relevant literature on physical input-output analysis and qualitative input-output analysis. Section 3.3 outlines the methodologies applied in this paper before Section 3.4 describes the data used in the analysis. Results will be discussed in Section 3.5 and Section 3.6 concludes.

We believe this article makes three unique contributions to the literature:

- To our knowledge this is the first detailed empirical analysis of a production structure of any PIOT published so far;
- Qualitative input-output methods have never been applied to production systems in purely physical units and for comparisons of representations of the same production system in alternative measurement units;
- A methodology for a combination of qualitative information from PIOT and MIOT is proposed for revealing the nature of products flows within the production system, which might be useful for the identification of potential conceptual inconsistencies between MIOTs and PIOTs as well as for the specification of environmental input-output models in hybrid units.

## 3.2 LITERATURE REVIEW

### 3.2.1 Monetary and physical input-output analysis

Physical input-output tables (PIOTs) are activity-based material flow accounts at the meso level usually measured in tons (see Stahmer et al., 1998). In PIOTs, the representation of material flows associated with human activities is not restricted to the exchange of commodities throughout the economy like in traditional monetary input-output tables (MIOTs). It also includes the natural environment (natural assets) as a source of raw materials inputs<sup>2</sup> and sink of residual outputs.<sup>3</sup> The compilation PIOTs have been associated with some unique benefits from an accounting and policy perspective (e.g. Stahmer et al., 1998; Giljum and Hubacek, 2007):

- PIOTs combine a large variety of environmental data sources consistently in one overall system. The balancing of physical inputs and outputs in the compilation of PIOTs on a sectoral level reveals any data gaps and inconsistencies in economic and environmental statistics, and can help to improve the quality of national and environmental account data. Moreover, the consistency of the overall system in a PIOT based on the material balance principle makes it considerably easier to estimate missing data on the relationship between economy and environment, which are not covered by basic statistical sources.
- PIOTs are the only physical accounting tool which provides a complete picture of the material transformation process associated with human economic activities in a well defined (production) system. This unique information can be directly applied in the policy process. The material efficiency indicators which can be derived, and the very detailed picture of sectoral water flows provided in the PIOT publication might be good illustrations.

The academic debate so far has focussed on the potential benefits of PIOTs for environmental input-output modelling framed into a discussion of the differences

---

<sup>2</sup> Note that raw material inputs in the German tables comprise both natural resources such as mineral or energy resources, water and biological resources as well as some ecosystem inputs such as the water and other natural inputs (e.g. nutrients, carbon dioxide) required by plants, animals and humans for growth, and the oxygen necessary for combustion.

<sup>3</sup> Some materials never enter the economy themselves as commodities; they are so called throughflow materials (see Eurostat, 1998; Eurostat, 2001).

between MIOTs and PIOTs in association with environmental input-output modelling (the notable exception is Hoekstra and Van den Bergh, 2006). A lively debate has emerged along two main lines:

- A discussion of the appropriate treatment of wastes in physical input-output models;
- A discussion of the differences between environmental input-output models with production structures specified in monetary and physical measurement units.

Most of the remarks so far have been directed towards the first question (Hubacek and Giljum, 2003; Giljum and Hubacek, 2004; Suh, 2004; Giljum et al., 2004; Dietzenbacher, 2005; Dietzenbacher et al., 2007). The necessity to direct attention towards the appropriate treatment of waste is rooted in the conceptual extensions of PIOTs to include all material flows associated with human (economic) activities. Final demands do not only comprise commodity outputs ('economic goods'), but also societally undesirable residual outputs ('economic bads').

Because residual flows are themselves a result of production processes aiming at the provision of final products, they cannot simply be treated as exogenous final demands in environmental input-output models (Hubacek and Giljum, 2003). It would be very difficult to provide a meaningful interpretation to results obtained from such models. Moreover, both a comparison of results from environmental input-output models based on a monetary production structure and the integration of monetary and physical information in models with mixed unit production structures would be cumbersome, if not impossible. To deal with these issues the final demand matrix of the PIOT needs to be reduced to its commodity partitions through a deduction of these waste/residual flow components from total material output (i.e. this is equivalent to booking the residual flows contained in final demand as negative primary inputs). Authors have proposed different ways of achieving this. Tables 3.1 and 3.2 in Section 3.2.2 might serve as an illustration. The interested reader is referred to Dietzenbacher (2005) and Dietzenbacher et al. (2007) for a comparison and evaluation of these different models.

While the debate about the appropriate treatment of wastes rather deals with the 'technicalities' of realising the potential benefits from applying physical data in quantitative representations of the production structure in environmental input-output models, the question itself has been dealt with in the accompanying discussion on the fundamental differences between monetary and physical input-output analysis. While

individual arguments have been proposed by various authors, it was not before Weisz and Duchin (2006) and Minx et al. (2007) that the issue received systematic treatment.

According to economic theory the value  $v$  of a single, homogenous product  $i$  is determined by multiplying its unit price  $p$  by the number of quantity units  $q$ :

$$v_i = p_i q_i \quad (3.1)$$

Similarly, input-output models tacitly assume the existence of a unique sectoral unit price for the homogenous output of each individual production sector (Sraffa, 1960; Pasinetti, 1977; Proops et al., 1992). As long as this assumption holds a monetary production structure can be easily converted into a physical one (and vice versa) and environmental input-output models derived from monetary and physical coefficient matrices will provide exactly the same results (see Weisz and Duchin, 2006; Minx et al., 2007: see Chapter 2).

However, there would be little value in discussing physical input-output analysis if this was correct.<sup>4</sup> Environmental input-output models attribute environmental factors (resource input or residual output) to final demands by assuming that each unit of sectoral output triggers the same amount of that factor. Given the observed differences in the production structures of the published tables (e.g. Hubacek and Giljum, 2003; Dietzenbacher, 2005; Weisz and Duchin, 2006; Dietzenbacher et al., 2007), the argument associated with the availability of physical information is that the flows of a specific environmental factor might sometimes be better approximated by the physical rather than the monetary structure of commodity flows in the (domestic) supply chain.

One important pre-condition for addressing the associated specification issue is to understand in a first instance what drives the differences in the published monetary and physical tables. Authors have provided at least three reasons for why this might be the case despite the fact that MIOTs and the commodity partitions of PIOTs are constructed on the basis of exactly the same accounting concepts and definitions:

- **Real world conditions:** Unique sectoral unit prices do not exist in the real world. Producers might charge buyers with different prices depending on the quantities they buy. Equally price levels change over time and depend on the

---

<sup>4</sup> In this case the advantage of physical over monetary input-output tables would be that they are measured in a fundamental measurement unit and would be easier to handle, for example, in time series analysis or cross-country comparisons (see UN, 1993: Chapter XVI).

point of measurement in the value chain (Suh, 2004). Therefore, the structure of a sector's quantity and value estimates will differ.<sup>5</sup> In fact, due to the 'volatile nature' of value estimates rooting in their price dependency, physical measurements have generally been regarded by national accountants as more suitable for representing the size of product flows. The last revision of the SNA92 therefore required Statistical Offices to develop physical output indicators for all products (see UN, 1992: XVI).

- **Aggregation level:** Input-output analysis assumes that the outputs of production sectors are homogenous. However, at the rather high level at which input-output tables are typically published, sectoral outputs do not represent individual, but baskets of products. All these different products grouped together will have different prices. Because it is unlikely that they are delivered to the various sectors in the supply chain in exactly the same proportion, unit prices will (usually) not be observable for the average output of a sector at higher aggregation levels (Hubacek and Giljum, 2003; Dietzenbacher, 2005).
- **Scope of monetary and physical measurement:** In national accounting, physical quantities of products can be of very different kind and are chosen as a matter of convenience. They range from discrete or integral units such as the counts of automobiles, microcomputers, or haircuts, to continuous units such as the weight, volume, duration or distance for products such as oil, electricity, sugar or transportation.

In the PIOTs applied in the debate on physical input-output analysis so far, the physical measurement is strictly defined in weight terms (tons).<sup>6</sup> Because a large share of product flows in modern economies like Germany consists of immaterial services, such a (physical) measurement is limited in its representation of exchange processes between sectors. However, also MIOTs are limited in their representation of some product flows included in the SNA92 production boundary, because the price of sectoral outputs can also

---

<sup>5</sup> For completeness it should be said that monetary and physical input-output tables are usually directly connected by a unit price assumption on a very low aggregation level, as highlighted in Chapter 2 of this thesis. In the further construction process corrections are made for price differentiation and price fluctuations, i.e. the unit assumption breaks.

<sup>6</sup> An hypothetical example for an alternative PIOT measured in land units is, for example, provided in the SEEA (UN, 2003).

be zero. The recycling sector, for example, re-formulates residual materials<sup>7</sup>, which are often provided by other sectors for free, into products.

Hence, both monetary and physical representations of product flows have strengths and weaknesses. Authors have therefore agreed on the potential value of PIOTs for environmental input-output applications and acknowledged the shortcomings of representations of the production structure purely in monetary or physical units. Based on the same rationale, which has been used by authors in the energy economic literature (Bullard and Herendeen, 1974; Proops, 1977; Beutel and Stahmer, 1982), consensus in the debate is that best use of the available monetary and physical information is made by combining them in environmental input-output models with a production specified in hybrid units (e.g. Stahmer, 2000; Dietzenbacher, 2005; Weisz and Duchin, 2006; Dietzenbacher et al., 2007; Minx et al., 2007).

However, apart from the suggestion that (most) tertiary sectors are best represented in monetary units due to the ‘blindness’ of weight units for immaterial service flows, while environmental service sectors might be best represented in physical units (see also Takase et al., 2005; Tukker et al., 2006), not many suggestions have been made of how such hybrid models might be best specified. Minx et al. (2007: see Chapter 2 of this thesis) have recently argued that addressing this specification issue comprehensively requires a detailed understanding of the characteristics of and differences between monetary and physical representations of the production structure. However, the required empirical discussion utilising the various available data sources is lacking so far. In this article an attempt is made to provide such a basic understanding of the data using the visualisation capabilities of qualitative input-output analysis and proposing a simple methodology for revealing the nature of product flows represented in monetary and physical tables.

### **3.2.2 Qualitative Input-Output Methods and Physical Input-Output Tables**

The origins of qualitative input-output analysis go back at least to an article by Yan and Ames (1965), who derived discrete order matrices from input-output tables in

---

<sup>7</sup> In order to avoid confusion, note that residuals are defined in national accounting not in terms of a price criterion, but in terms of a list of materials. Residual flows are/can be part of a commodity output definition: “In the SEEA, recycling, re-use and treatment of residuals are all regarded as taking place within the economic sphere” (see UN, 2003).

order to examine whether interrelatedness in the US economy had changed between the years 1919 and 1929. The term ‘qualitative input-output analysis’ itself was coined in Czayka’s (1972) contribution and subsequently presented to a wider (international) audience in various publications by Holub, Schnabl and Bon (e.g. Schnabl and Holub, 1979; Holub and Schnabl, 1985; Bon, 1989).

Qualitative input-output analysis might be seen as a family of graph theoretical approaches (e.g. Harary et al., 1965) which aim at identifying and comparing ‘core structures’ of production systems. At the root of the development of this methodology is the belief that hidden behind the vast amount of quantitative information contained in (quantitative) input-output tables there is important structural information on the interdependencies of sectors in the production system. This structure can be revealed by systematically reducing the information content of input-output tables.

The information reduction is achieved in a joint process of *selection* and *binarisation*. Only product deliveries from sector *i* to sector *j* which are larger or equal than a defined filter *F* are assumed to belong to the core production structure and qualify for further analysis. Once a product flow is part of this selected “core”, its size is rendered unimportant, and it is represented by a 1. All other flows are represented by a 0 and seen as “noise” obscuring a clear view of the structural features of the system. The resulting (binary) adjacency matrix might be seen as a digital shadow identifying the main contours of the production system and is a common starting point for graph theoretical analysis (see Harary et al., 1965).

It is not surprising that qualitative input-output analysis has been exposed to some severe criticism. Most importantly the arbitrariness of the choice of filter value (*F*) and the associated identification of the core production structure, the loss of potentially important information, and problems of transitivity and over-estimation of the indirect linkages between core production activities have been disputed (see Kleine and Meyer, 1981; Mesnard, 1995; Mesnard, 2001).

Substantial improvements in the methodology were made during the 1980s and 1990s (see Holub et al., 1985; Holub and Tappeiner, 1987; Holub and Tappeiner, 1988), leading to a diversification of qualitative input-output approaches (Aroche-Reyes, 1996; Schnabl, 2003) including minimal flow analysis (Schnabl, 1994; Schnabl, 1995; Weber and Schnabl, 1998; Schnabl, 2001), important coefficient analysis (Aroche-Reyes, 1996; Ghosh and Roy, 1998; Aroche-Reyes, 2003; Schnabl, 2003) as well as the direct flow intensity method (Torre, 1989; Bellet et al., 1989). Moreover, authors have combined

qualitative input-output analysis with quantitative tools (Dietzenbacher, 2005; Meister and Verspagen, 2006). This discussion has highlighted that it is possible to deal with most of the limitations of qualitative input-output analysis through methodological adjustments, even though the problem of arbitrariness in the choice of the correct filter cannot be unambiguously resolved (see Schnabl, 2000). While minimal flow analysis has responded most comprehensively to these various lines of criticism, there is potential for further improvements of each individual method (Minx, 2007).

However, implementing any of the suggested methodological adjustments is complicated by singularity problems associated with the ‘waste-adjusted’ input-output models obtained from most published PIOTs. The fact that this fundamental problem in the application of PIOTs has remained unnoticed in the debate is arguably the most striking demonstration of the lack of focus on empirical aspects of physical input-output analysis so far. The problem is rooted in the particular representation of service sectors in physical measurement units as demonstrated in the hypothetical PIOT provided in Tables 3.1 and 3.2. While receiving product inputs from other sectors, the only physical output service industries produce are wastes (see Table 3.1: row 3). This does not only cause difficulties in attaching a meaningful economic interpretation to such a representation.<sup>8</sup>

Once wastes are treated appropriately as negative inputs (see Table 3.2: row 5), no Leontief inverse exists in the associated waste adjusted input-output model, because the total primary inputs in some sectors become negative, whilst total output equals to zero. The basic theorem and proof for this statement have been provided by Takayama (1985) and are attached as an Appendix. This general input and output structure of service sectors as sketched in Tables 3.1 and 3.2 is representative for most of the published PIOTs.

	Intermediate Demand			Final Demand		Total Output
	Agriculture and Mining	Manufacturing	Services	Commodities	Waste	
Agriculture and Mining	70	10	30	90	500	700
Manufacturing	20	100	40	140	700	1000
Services	0	0	0	0	200	200
Natural Resource Inputs =	610	990	130			
Total primary inputs						
Total Material Inputs	700	1000	200			

**Table 3.1 – Hypothetical Physical Input-Output Table**

<sup>8</sup> This might be seen as the dual to the problem of ‘production ex nihilo’ (production out of nothing) in recycling and waste treatment sectors in the monetary tables.



	Intermediate Demand			Final Demand	Total Commodity Output
	Agriculture and Mining	Manufacturing	Services	Commodities	
Agriculture and Mining	70	10	30	90	200
Manufacturing	20	100	40	140	300
Services	0	0	0	0	0
Natural Resource Inputs	610	990	130		
Waste	-500	-700	-200		
Total (Net) Primary Input	110	290	-70		
Total Commodity Input	200	300	0		

Table 3.2 – Hypothetical Waste Adjusted Physical Input-Output Table

In the German PIOTs waste treatment is endogenised and service sectors therefore have at least one physical output in the commodity partitions. As a consequence the derivation of a Leontief Inverse is usually possible in these tables. However, it has been suggested by Stahmer himself (1998), and throughout the material flow literature (see Eurostat, 2001), that it is crucial to remove water from the tables for many policy applications, due to their dominance over all other commodity flows. In fact, 83% of the total weight of intermediate product flows is water. Because water comprises most of the residual outputs delivered to the waste treatment sector by services, the singularity problem surfaces in the German data as soon as water is removed.

This is not only a problem for applying the most appropriate qualitative model for comparing production structures, but also for complementary quantitative ones (Minx et al., 2007c). In the current context there are five strategies for resolving the problem:

- Replace the zero service partitions with monetary data and apply a waste-adjusted mixed unit input-output model. Weber and Schnabl (1998) have demonstrated that qualitative input-output algorithms can be equally applied to such mixed unit systems in their analysis of the structure of energy flows in Germany. However, for the analysis of the production structure itself, meaningful results can only be obtained when all commodity flows represented are specified in the same unit.
- Estimate physical input-output model with wastes as part of final demand. This allows the use of all available data sources and the choice of the most appropriate qualitative input-output methodology. However, it seriously

restricts the comparability between monetary and physical production structures, which are the main interest of the analysis intended here.

- Estimate waste-adjusted input-output model without aggregation. This restricts the analysis to the use of the German input-output tables with water flows included. However, as explained above comparing not only the production structure of a MIOT and PIOT, but also those of a PIOT with water and a PIOT without water might be crucial for a discussion of an appropriate use of PIOT data in environmental input-output applications, as well as for the development of the methodological debate associated with the construction of the tables.
- Estimate waste-adjusted input-output model and aggregate services sectors as much as required for the input-output model to be non-singular. In practice this means “sacrificing” almost all detail in the description of service industries, with some notable exceptions such as “construction”, “catering” and “environmental service” sectors. However, the monetary table would need to be adjusted accordingly. Since services have become the dominant feature in MIOTs (see UN, 2003: 2.58), aggregation would seriously limit the analysis of the role of service sectors in the supply chain.
- Use the original qualitative input-output algorithm as proposed by Czayka (1972) and Holub and Schnabl (1985). This allows for a comparison of the various PIOTs and MIOTs proposed. However, such an analysis would be more open to methodological criticism.

In the context of this article it seems most important to keep the full detail and secure the general applicability of all different data sources. We have therefore opted for the last strategy. Applying the original qualitative input-output algorithm regardless of all criticism seems to be justifiable for two main reasons. *First*, qualitative input-output is seen as an effective way of highlighting some of the structural differences between MIOTs and PIOTs. Among the various alternatives discussed using the original qualitative input-output analysis algorithm seemed least restricting and better than fully sacrificing the visual analysis intended. *Second*, the limitations of the original qualitative input-output algorithm are well-known. In the context of the current article only the estimation of the indirect pathways in higher production layers will be seriously restricted, but it still appears justifiable, if a careful interpretation of the resulting graph is provided. In fact, the qualitative input-output algorithm based on important coefficient

analysis, which has been frequently applied during the last ten years (Aroche-Reyes, 1996; Ghosh and Roy, 1998; Aroche-Reyes, 2002; Schnabl, 2003), suffers from similar problems (see Schnabl, 2003).

### **3.3 METHODOLOGY**

In this Section the methodologies applied in this article are presented. The first part focuses on the visualisation of structural interrelationships in the production system represented by MIOTs and PIOTs using the methodological toolkit provided by the original qualitative input-output analysis algorithm of Czayka (1972) and Holub and Schnabl (1985). While such an analysis might help to reveal some of the structural differences between monetary and physical representations of the production structure, it is limited for gaining an understanding of what drives these.

In Section 3.2.1 we have highlighted that besides aggregation level and statistical corrections for real world conditions in the compilation of PIOTs, it is the nature of intermediate product flows circulating in the economy which determines particular monetary and physical representations of the production structure. If fed into an input-output model the direct and indirect (environmental factor) requirements triggered by final demand sectors will depend on this structure. A sound understanding of the nature of product flows and the associated methodology for the construction of the tables are crucial for a sound specification of input-output models tailored to particular policy needs and for optimising compilation procedures according to research needs. The second part of this Section will therefore outline a simple qualitative procedure to determine the nature of these flows.

#### **3.3.1 Revealing a production structure in monetary and physical units using qualitative input-output analysis**

Consider an intermediate flow matrix of an input-output table  $Z$  with elements  $z_{ij}$  (for  $i, j = 1, 2, \dots, n$ ) representing the direct inter-sectoral input-output relationships between  $n$  industrial sectors. The  $k$  biggest flows in  $Z$  (for  $k=1, 2, \dots, n^2$ ) can be derived by comparing each element  $z_{ij}$  with an exogenously pre-defined filter value  $F$ :

$$V = (v_{ij}) = \begin{cases} z_{ij} & \text{if } z_{ij} > F; \text{ for } i \neq j \\ 0 & \text{otherwise} \end{cases} \quad (3.2)$$

We can derive a Boolean representation of  $V$  by setting all non-zero elements equal to 1.

$$W^1 = (w_{ij}) = \begin{cases} 1 & \text{if } v_{ij} > 0; \text{ for } i \neq j \\ 0 & \text{otherwise} \end{cases} \quad (3.3)$$

$W^l$  is the  $n \times n$  sized adjacency matrix or matrix of *direct* delivery routes of  $Z$ . This adjacency matrix can be represented as a directed graph  $G(V, A)$  consisting of a set of vertices  $V$  (sectors) and a set of arcs  $A$ . Indirect connections between two sectors  $i$  and  $j$  can be identified by taking into account the supply chain links in higher production layers. By taking the  $l^{\text{th}}$  power of the adjacency matrix, a matrix of delivery routes  $W^l$  of  $l$  distance units:

$$W^l = (w_{ij}^l) = W^1 W^{l-1} = W^{l-1} W^1 \quad \text{for } l=1,2,\dots,n-1 \quad (3.4)$$

In this context, we define a delivery route or a delivery path as the shortest distance between two sectors<sup>9</sup> and a distance unit as the numbers of sectors involved to deliver products from sector  $i$  to sector  $j$ . These matrices  $W^l$  can be condensed into a dependency matrix denoted by  $D$  and defined as :

$$D = (d_{ij}) = \sum_{l=1}^{n-1} \oplus W^l \quad (3.5)$$

where the 'or' operator ' $\oplus$ ' indicates Boolean summation. An element  $d_{ij}$  is 1, if a direct or indirect link between two sectors  $i$  and  $j$  exists, and 0 otherwise. Equations (3.4) and (3.5) can be seen as the binary equivalent of the power series expansion (or Eulerian series) frequently applied in quantitative input-output analysis to unravel the domestic supply chain in terms of the direct and indirect effects of the elements of final demand. However, there is an important difference between the two as correctly pointed

---

<sup>9</sup> Hence, this implies a maximal length of delivery routes between two sectors  $i$  and  $j$  of  $n-1$  distance units.

out by Kleine and Meyer (1981) and Mesnard (1995): while the result matrix of a Eulerian series of a direct requirement matrix in quantitative input-output converges towards the zero matrix  $O$  with increasing power, the values of the  $W^k$ 's tend to infinity. Ultimately,  $D$  might indicate an indirect link between two sectors even though there is none in the input-output table. Thus, great care is required in the interpretation of the dependency matrix  $D$ : each element  $d_{ij}$  indicates whether a direct or indirect connection between two sectors *potentially* exists, while more quantitative information would need to be added to identify its *actual* existence.

Finally a connectedness matrix  $H$  can be defined:

$$H = (h_{ij}) = \sum_{i,j} (d_{ij} + d_{ji}) \quad (3.6)$$

Entries  $h_{ij}$  can take 3 discrete values<sup>10</sup> indicating the strength of the relationship between two sectors  $i$  and  $j$ :

- **Isolation:** If a sector is isolated and has no relationship to any other sector in the economy,  $h_{ij}=0$ .
- **Unilateral connectedness:** If sector  $i$  delivers to sector  $j$ , but not vice versa,  $h_{ij}=1$ .
- **Strong or bilateral connectedness:** If sector  $i$  delivers to sector  $j$  and vice versa,  $h_{ij}=2$ .

---

<sup>10</sup> Note that in the original algorithm by Czyzka (1972) and Holub and Schnabl (1985) also identified weakly or quasi-connected flows. However, as outlined in detail by Schnabl (2000) the inclusion of these flows does not add additional value to the analysis.

### 3.3.2 A simple method for revealing the nature of product flows

Beside aggregation level and statistical corrections for real world conditions in the compilation of PIOTs, it is the nature of intermediate product flows circulating in the economy in terms of pricing and physicality which determines monetary and physical production structures respectively. If fed into an input-output model the direct and indirect (environmental factor) requirements triggered by final demand sectors will depend on these structures. A sound understanding of the nature of product flows and the associated methodology for the construction of the tables are crucial for a sound specification of input-output models tailored to particular policy needs and for optimising compilation procedures of PIOTs according to research needs.

Based on a set of assumptions this nature of product flows can be studied once MIOTs and PIOTs are jointly available. Let  $Z^{unit}$  be an intermediate flow matrix of size  $n \times n$  and let the superscript  $unit=M,P$  identify measurement in monetary or physical units respectively. Further, assume that the matrices  $Z^P$  and  $Z^M$  are fully comparable being based on exactly the same accounting concepts and definitions. With  $Z^{unit}$  being non-negative each intermediate product flow  $z_{ij}^{unit}$  can either be positive or zero. We can derive a Boolean representation of  $Z^{unit}$  in the spirit of qualitative input-output analysis setting all non-zero elements to 1. This is equivalent to choosing a filter value of 0 in Equations 3.1 and 3.2:

$$\Phi^{unit} = (\Phi_{ij}^{unit}) = \begin{cases} 1 & \text{if } z_{ij}^{unit} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (3.6)$$

Comparing corresponding elements  $\Phi_{ij}^P$  and  $\Phi_{ij}^M$ , the relationship between  $Z^P$  and  $Z^M$  can always be described in one of the following four ways:

$$\Omega = (\Omega_{ij}) = \begin{cases} -1 & \text{if } \Phi^P = 1 \text{ and } \Phi^M = 0 \\ 0 & \text{if } \Phi^P = 1 \text{ and } \Phi^M = 1 \\ 1 & \text{if } \Phi^P = 0 \text{ and } \Phi^M = 1 \\ 2 & \text{if } \Phi^P = 0 \text{ and } \Phi^M = 0 \end{cases} \quad (3.7)$$

These four different combinations can help us understanding the nature of the product flows circulating in the economy with regard to their price and physical

constitution. For example, finding a positive entry ( $z_{ij}^P > 0$ ) in the PIOT and a zero element ( $z_{ij}^M = 0$ ) in the MIOT means that the described products within a particular product group provided by one sector to another do not have prices given the full comparability of MIOT and PIOT.<sup>11</sup> Following this line of thinking we can interpret  $\Omega$  as a product identification matrix and attach the following interpretations to the four different values each entry  $\Omega_{ij}$  can take with regard to the nature of the product flow observed:

- $\Omega_{ij} = -1$ : unpriced physical product flow;
- $\Omega_{ij} = 0$ : priced physical product flow;
- $\Omega_{ij} = 1$ : (priced) immaterial service flow<sup>12</sup>;
- $\Omega_{ij} = 2$ : no product flow.

Note that  $\Omega_{ij} = -1$ ,  $\Omega_{ij} = 1$  and  $\Omega_{ij} = 2$  are homogenous in that all product outputs delivered from sector  $i$  to  $j$  share the same characteristics in terms of their price and physicality. This is different for  $\Omega_{ij} = 0$ . In this case some of the product outputs delivered from  $i$  to  $j$  could, for example, only have a price or only a weight. Our method would not be able to detect this in the aggregate input-output world as long as some products with both price and weight characteristics are part of the described sectoral output.

### 3.4 DATA DESCRIPTION

For the estimations monetary and physical input-output data for Germany 1995 and Denmark 1990 was used. While the Danish PIOT publication contains both the physical and the corresponding monetary table (Gravgaard Pedersen, 1998), only physical data is included in the German publication (Federal Statistical Office of Germany, 2001). The identification of the corresponding MIOT (Federal Statistical Office of Germany,

---

<sup>11</sup> With full comparability we mean that the tables are compiled for the same spatial entity and year applying the same accounting concepts and definitions. In Minx (2007) we argue that this is usually the case for available PIOTs and MIOTs.

<sup>12</sup> Conceptually, unpriced immaterial service flows do not play a role, because the reason for products not to have a prize usually is related to their nature as ‘bads’, which seem to require the physicality criterion. If they are not priced for other reasons – say, because they are produced and used in two establishments of the same enterprise – they are valued by the Statistical Office (by the market price of the product). However, in the absence of information about these flows due to the single unit nature of PIOTs, it might be most correct to refer to ‘priced and unpriced’ immaterial services flows.

2006f) is not obvious from the documentation and required a special request at the Federal Statistical Office (Heinze, 2007).

The German 1995 PIOT are provided at a 58 sector breakdown as detailed in Table 3.3. The monetary table was obtained at a 71 sector level and aggregated accordingly. The water input and output tables provided as part of the PIOT publication were used to exclude water from the German PIOT. In the following we use PIOT for general reference, and PIOTw and PIOTnw to refer to the physical tables with and without water respectively. The exclusion of water was not only important for matters of comparability with the Danish data (which does not include water unless embodied in products), but also to analyse the influence of water on physical representations of the production structure.

For the qualitative input-output analysis the tables were aggregated to the 14 sector level. This corresponds to the standard 12 sector breakdown applied by the Federal Statistical Office of Germany for official publications at higher aggregation levels and further separates environmental services (recycling and waste treatment). Descriptions and classification codes are provided in Table 3.4.

Finally, for the comparison of the German and Danish PIOT further aggregation was required. Since the Danish PIOTs are provided at a 27 sector level, the German table was aggregated accordingly. However, the German and Danish classification could not be easily linked. While the German tables are classified according to NACE Rev.1, the Danish PIOT follows the older NACE-CLIO classification. Transition tables for outputs and inputs from NACE-CLIO to Nace Rev.1 were courteously provided by Denmark statistics and used to improve and control for the quality of the match. The resulting tables show 26 sectors (see Table 3.5): two of them were the environmental service activities of the German PIOT publication. While the quality match between the classifications is not of major importance for the type of analysis carried out, it is indicated in Table 3.5 using a star system: the more stars, the worse the match and the more different the recorded flows for a particular sector in the German and Danish tables.



No	SIC	Description
1	01	Agriculture and hunting
2	02	Forestry, Fishing etc.
3	05	Forestry
4	10	Coal and Peat
5	11	Crude Petroleum and Natural Gas
6	13	Metal Ores
7	14	Other mining and quarrying
8	15	Food Products and Beverages
9	16	Tobacco Products
10	17	Textiles
11	18	Wearing Apparel
12	19	Leather and Leather Products
13	20	Wood and Wood Products
14	21	Paper and Paper Products
15	22	Publishing, Printing etc.
16	23	Manufacture of coke, refined petroleum etc.
17	24	Chemicals and chemical products
18	25	Rubber and plastic products
19	26	Manufacture of other non-mineral products
20	27	Manufacture of basic metals
21	28	Fabricated metal products
22	29	Machinery and equipment nec
23	30	Office, accounting and computing machinery
24	31	Electrical machinery and apparatus
25	32	Radio, television and communication equipment
26	33	Medical, precision and optical instruments, etc.
27	34	Motor vehicles, trailers and semi-trailers
28	35	Transport equipment
29	36	Furniture and manufacturing nec
30	37	Recycling
31	40	Electricity, gas, steam and hot water supply
32	41	Collection, purification and distribution of water
33	45	Construction
34	50	Sale, maintenance and repair of motor vehicles etc.
35	51	Wholesale trade and commission trade
36	52	Retail trade
37	55	Hotels and restaurants
38	60	Land transport
39	61	Water transport
40	62	Air transport
41	63	Auxiliary transport services
42	64	Post and telecommunications
43	65	Financial Intermediation
44	66	Insurance and pension funding
45	67	Auxiliary financial services
46	70	Real estate activities
47	71	Renting of machinery and equipment
48	72	Computer and related activities
49	73	Research development
50	74	Other business activities
51	75	Public administration and defence
52	80	Education
53	85	Health and social work
54	90	Sewage and refuse disposal
55	91	Membership organisations nec
56	92	Recreational, cultural and sporting activities
57	93	Other service activities
58	95	Private households with employed persons

Table 3.3 – Sectoral breakdown of German 1995 input output data at 58 sector level

No	SIC	Description
1	01-05	Agriculture, Forestry and Fishery
2	10-14	Mining and Quarrying
3	15-16	Food, Beverages and Tobacco Products
4	17-22	Textiles, Wearing Apparel, leather, wood and paper products
5	23-26	Refined petroleum products, chemicals, non-metallic minerals
6	27-28	Metals
7	29-36	Machinery, electrical and optical equipment, vehicles and transport equipment
8	40-41	Energy and water
9	45	Construction
10	50-64	Wholesale and retail trade, hotels and restaurants, transport, storage and communication
11	65-74	Financial intermediation, real estate business,
12	80-85	Education, health and social work
13	75, 91-95	Public Administration and defence, other social and personal service activities
14	37, 90	Environmental Services

Table 3.4 – Sectoral breakdown of German 1995 input output data at 14 sector level

No	NACE-CLIO	Description
1	11000	Agriculture, horticulture etc
2	12000	Forestry and logging
3	13000	Fishing
4	20000	Mining and quarrying
5	31000	Manuf. of food, beverages, tobacco*
6	32000	Textile, clothing, leather industry*
7	33000	Manuf. of wood products, incl. furnit**
8	34000	Manuf. of paper, printing, publishing*
9	35000	Chemical and petroleum industries*
10	36000	Non-metallic mineral products*
11	37000 and 38000	Basic metal industries and manufacturing of fabricated metal products*
12	39000	Other manufacturing industries**
13	40000	Electricity, gas and water
14	50000	Construction
15	60099^+63000	Wholesale and retail trade and hotels and catering*
16	71000	Transport and storage*
17	72000	Communication*
18	80099	Financing and insurance
19	83110	Dwellings*
20	83509	Business services*
21	93009	Market services of education, health*
22	94000	Recreational and cultural services*
23	95009	Household services, incl. auto repair**
24	95399	Other producers, excl. government**
25		Recycling***
26		Waste Treatment***

Table 3.5 – Sectoral breakdown for comparison between German and Danish data

## 3.5 RESULTS

### 3.5.1 Visualising production structures in monetary and physical measurement units

Let us start with a brief visual inspection of the production structure of the German economy in 1995. Figures 3.1-3.3 show matrix plots of the (natural) log-transformed intermediate flow matrices of the MIOT ( $Z^{miot}$ ) and the two PIOTs ( $Z^{piot}$ ) with and without water. The natural logarithm was only applied to non-zero flows. Product flows of size zero were included separately because of the non-definition of the natural log for zero values. The log transformation was necessary because of the large range in values particularly in the physical tables. In the matrix plot each intermediate delivery from sector  $i$  to sector  $j$  is represented by a square. The colour of the square reflects the size of the product flow – the larger the intermediate product flow represented, the lighter the square.

Figure 3.1 shows the matrix plot of the monetary intermediate flow table. Beside the pronounced principal diagonal, high levels of production activities in value terms cluster around the outputs of the manufacturing (approximately between sectors 13 and 27) and service sectors indicated by the two light patches in the plot. The large size of the “service-patch” seems to reinforce arguments made previously in the debate on physical input-output analysis, stressing the important (and growing) role of services outputs in (the production structure of) mature economies like Germany (see Stahmer, 2000; Weisz and Duchin, 2006; also UN, 2003).

These broad production clusters shift once production activities are defined in terms of the weight instead of the value of product outputs. While high levels of economic activities associated with manufacturing outputs are maintained in the physical representations as shown in Figures 3.2 and 3.3, most service activities are not captured at all leaving the physical production structures with much larger number of zero flows. Instead more emphasis is given to the weighty outputs of primary economic activities such as mining or quarrying. However, most prominent in these plots are the input and output flows of the water (sector 32) and waste treatment sectors (sector 54).<sup>13</sup>

---

<sup>13</sup> Comparing Figures 3.2 and 3.3 might also be a good visualisation of the singularity problem associated with the PIOT without water. The reason why the PIOT with water can be inverted is that each sector delivers at least some physical output to the waste treatment sector. Because most of these residual flows are water, this is no longer the case for many service sectors (as they also have zero commodity partitions in final demand).

Finally, there seem to be more lighter cells in the MIOT than in the two PIOTs, and more in the PIOT without water than in the PIOT with water. Considering that the plotting function used assigns the colour shadings in discrete intervals of equal size, a darker overall appearance of the plot is a first indication that the exchange of products among sectors are more concentrated. This might suggest that the physical production structures are dominated by a small number of large flows, while the monetary flows might be more evenly distributed across sectors – an issue which will be addressed later. Hence, just by plotting the intermediate flow matrices of MIOTs and PIOTs a rough impression of structural similarities and differences can be obtained.<sup>14</sup>

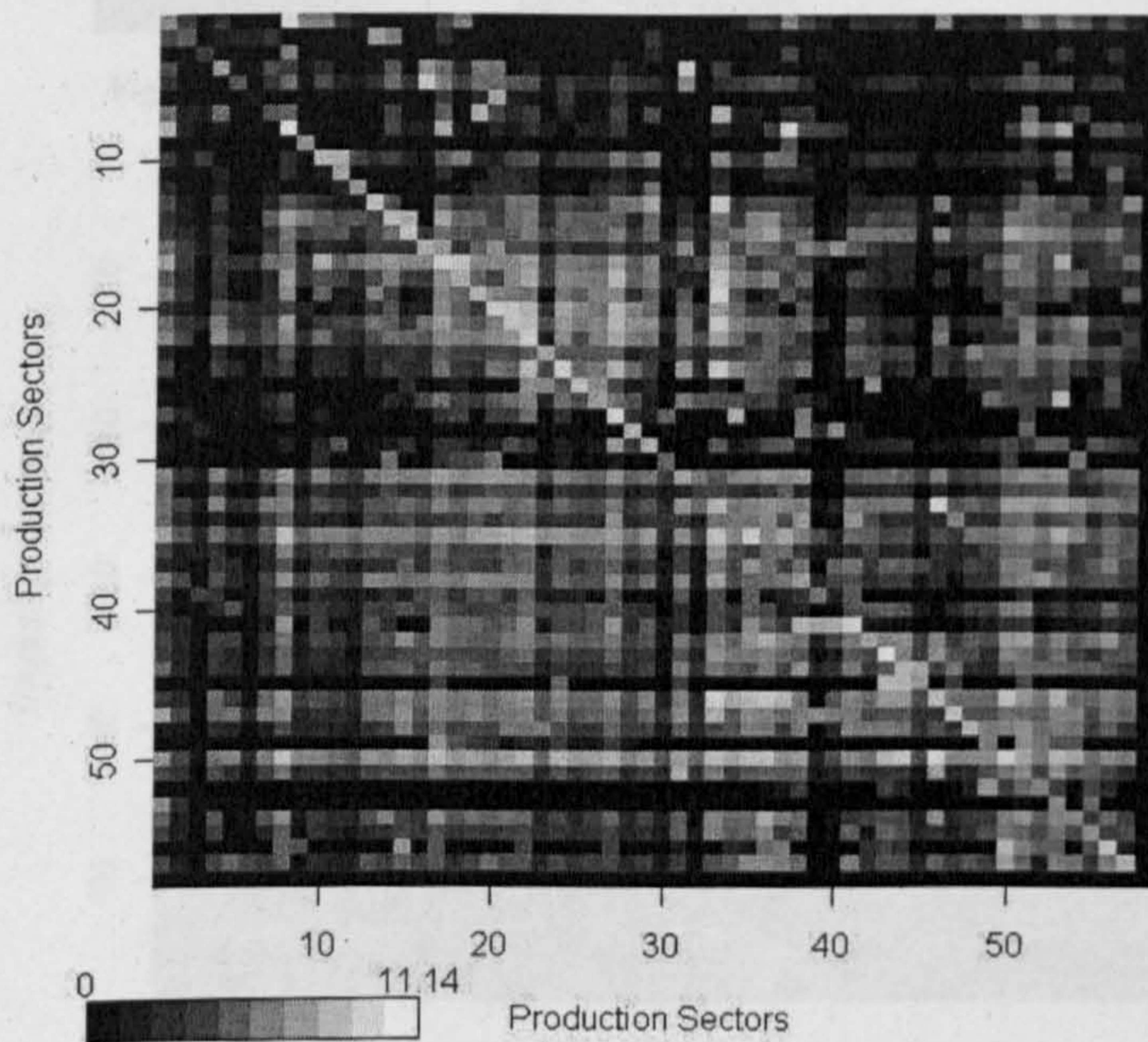


Figure 3.1 – Matrix plot (log) of intermediate flow matrix of MIOT

<sup>14</sup> Note that a very similar picture is obtained when the direct coefficient matrices are visualised.

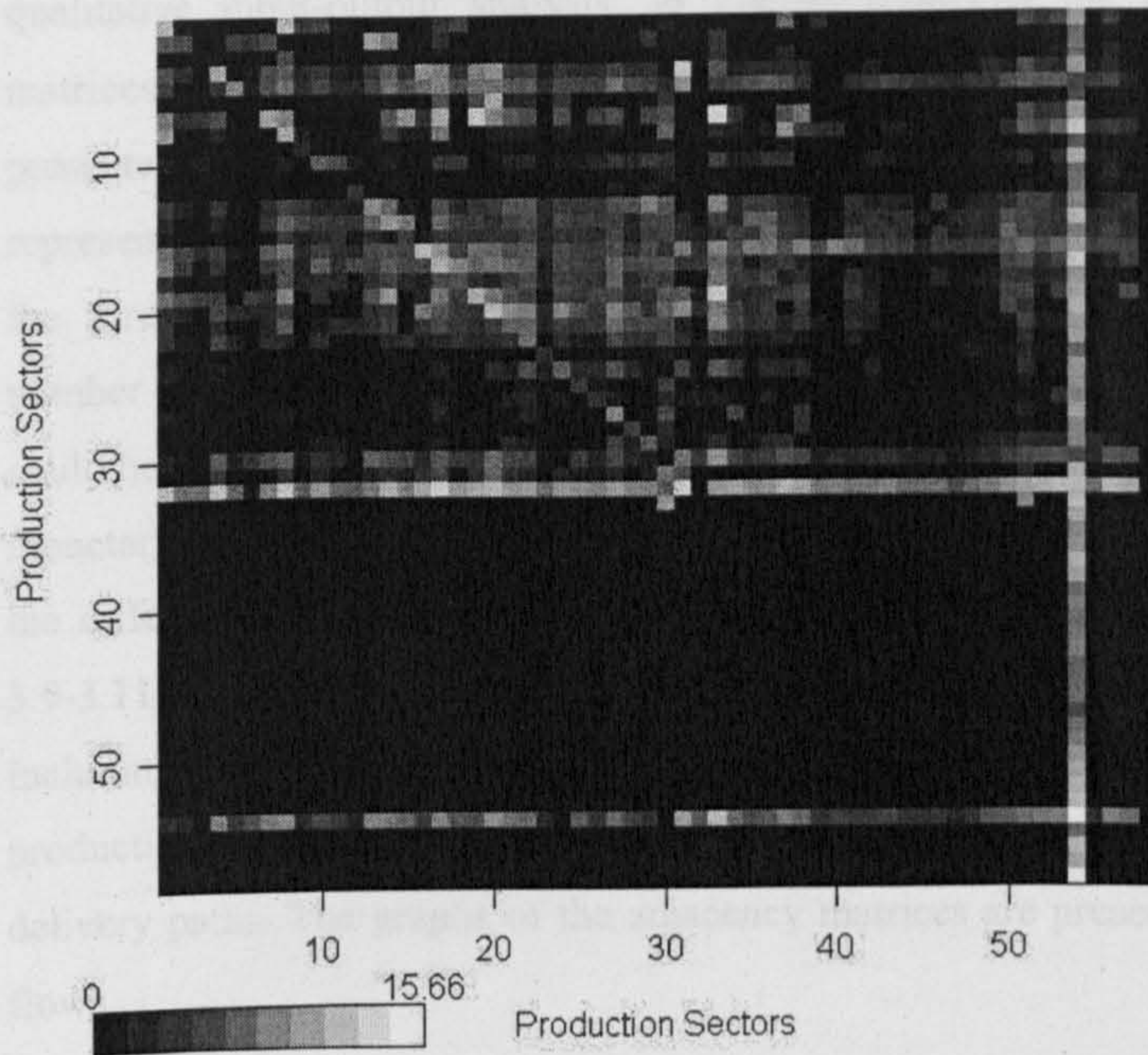


Figure 3.2 – Matrix plot (log) of intermediate flow matrix of PIOT

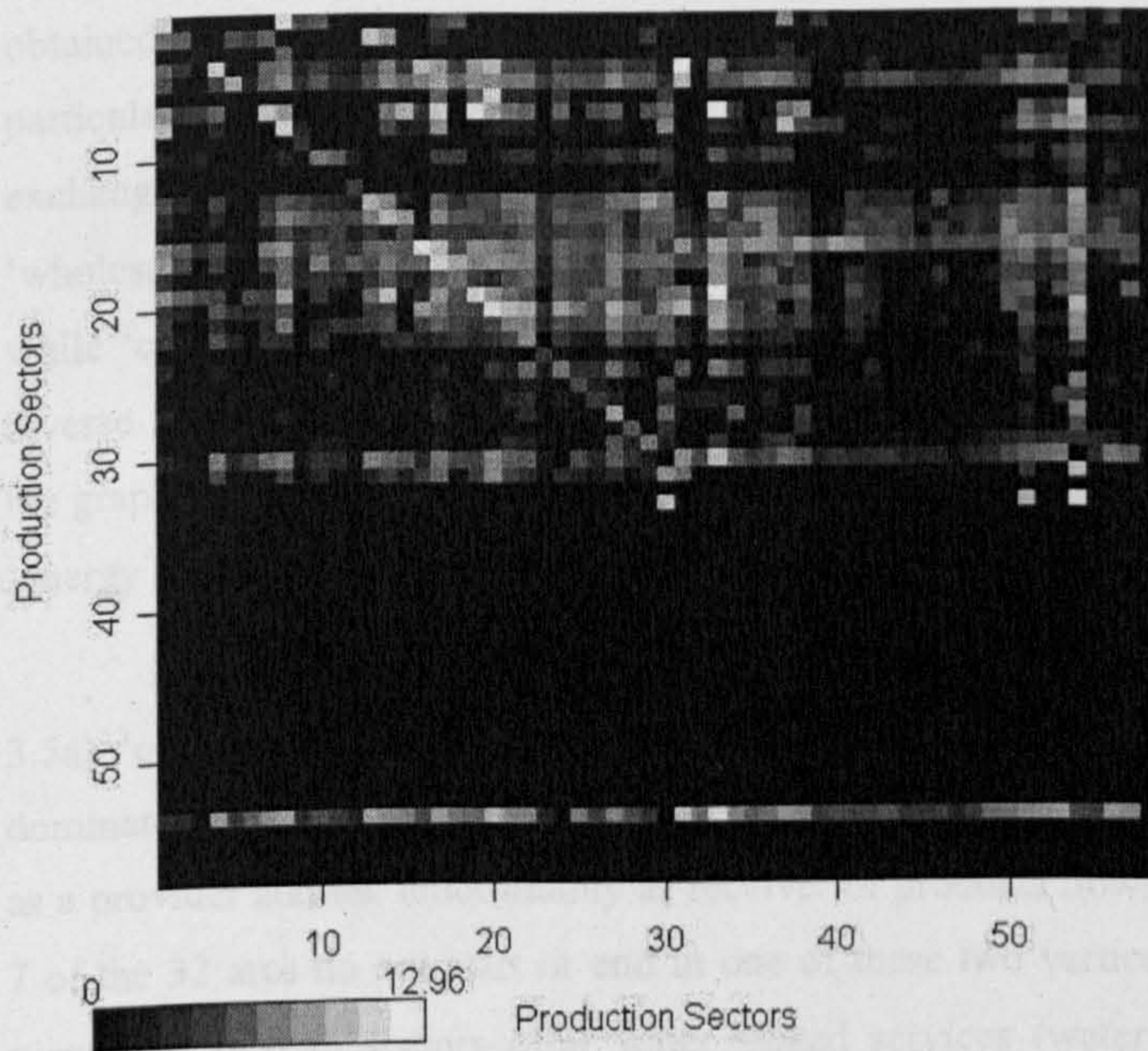


Figure 3.3 – Matrix plot (log) of intermediate flow matrix of PIOTnw

For sector names please refer to Table 3.3

These insights can be built upon using the graph-theoretical toolkit provided by qualitative input-output analysis. In Figures 3.4a-3.6a the graphs of the adjacency matrices (Equation 3.3) of the MIOT as well as the PIOTs with and without water are presented. For highlighting the differences between monetary and physical representations of the production structure, the inclusion of the same number of flows in the three different adjacency matrices seemed most appropriate. Alternatively, the number of flows required to represent the same proportion of the total intermediate flows could have been used. However, due to a very different concentration of product flows in monetary and physical tables this would have caused problems for the interpretation of the differences in the graphs of the connectedness matrix  $H$  (see Equation 3.6; Figures 3.9-3.11). Variables filter values were used in order to control for the influence of including different numbers of flows and in order to analyse the sectoral integration of the production structure in higher production layers with an increasing number of direct delivery paths. The graphs of the adjacency matrices are presented with 32 intersectoral flows.

Focussing on the graphs of the adjacency matrices first, the general impression obtained from the matrix plots is supported: Figure 3.4a highlights that – given the particular filter level – manufacturing and service sectors are at the centre of the direct exchange relationships in the monetary network graph. ‘Finance’ (sector 11) and ‘wholesale and retail trade’ (sector 10) are the main providing sectors (senders of arcs) while ‘construction’ (sector 9) and ‘machinery manufacturing’ (sector 7) have the most diverse input structure (recipients of arcs). Primary sectors only play a marginal role in the graph maintaining only a single direct exchange relationship with other sectors, while ‘energy and water’ and ‘environmental services’ are fully isolated at the given filter level.

In contrast, in the diagraph of the PIOTw with water flows included (see Figure 3.5a) ‘energy and water’ (sector 8) and ‘environmental services’ (sector 14) totally dominate the direct exchange relationships in the production network: the former mainly as a provider and the latter mainly as receiver of products flows from other sectors. Only 7 of the 32 arcs do not start or end in one of these two vertices. This dominance is not surprising as both sectors offer water-related services (water supply and waste water treatment) in a PIOTw, in which water makes approximately 83% of the total weight of all intermediate product flows. Hence, what is shown in Figure 3.5a are mainly deliveries and receipts of water flows by sectors. This already suggests that unless very specific water-related policy questions are concerned, such a production structure might therefore not be a very useful ingredient in environmental input-output modelling applications.

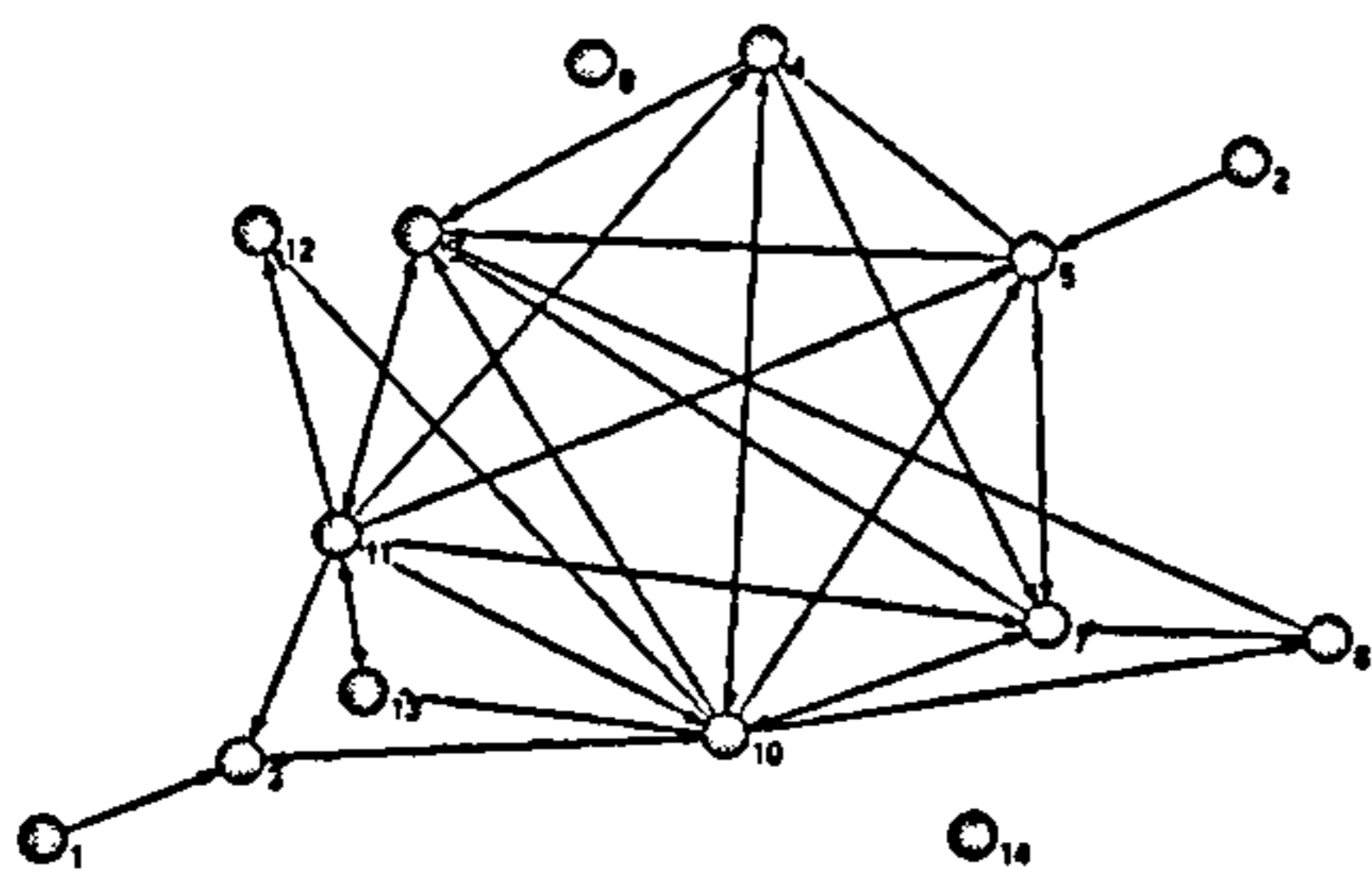


Figure 3.4a – Network representation of 32 largest intersectoral product flows in MIOT without considerations of flow size

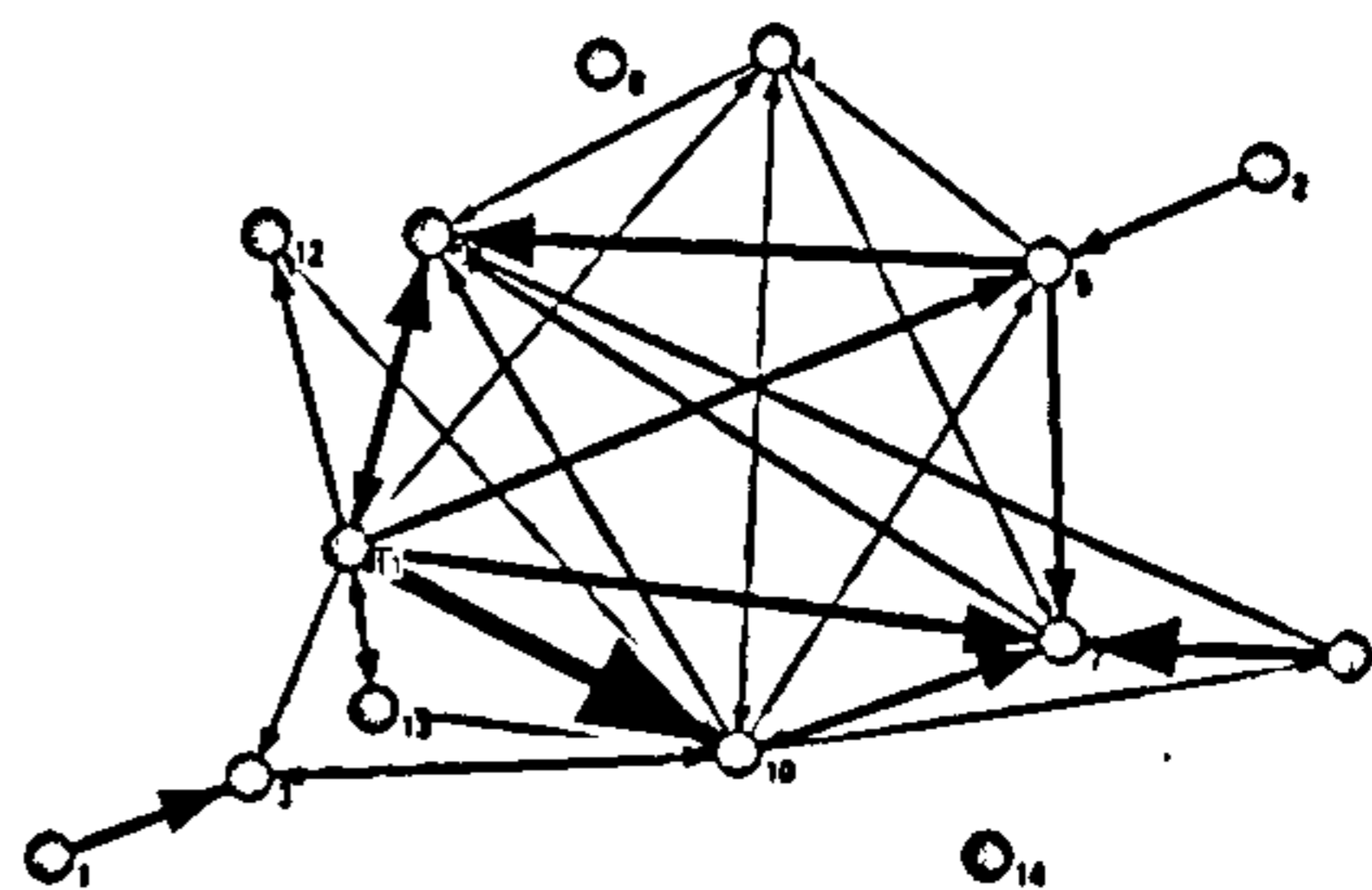


Figure 3.4b – Network representation of 32 largest intersectoral product deliveries in MIOT with flow size represented by thickness of arcs

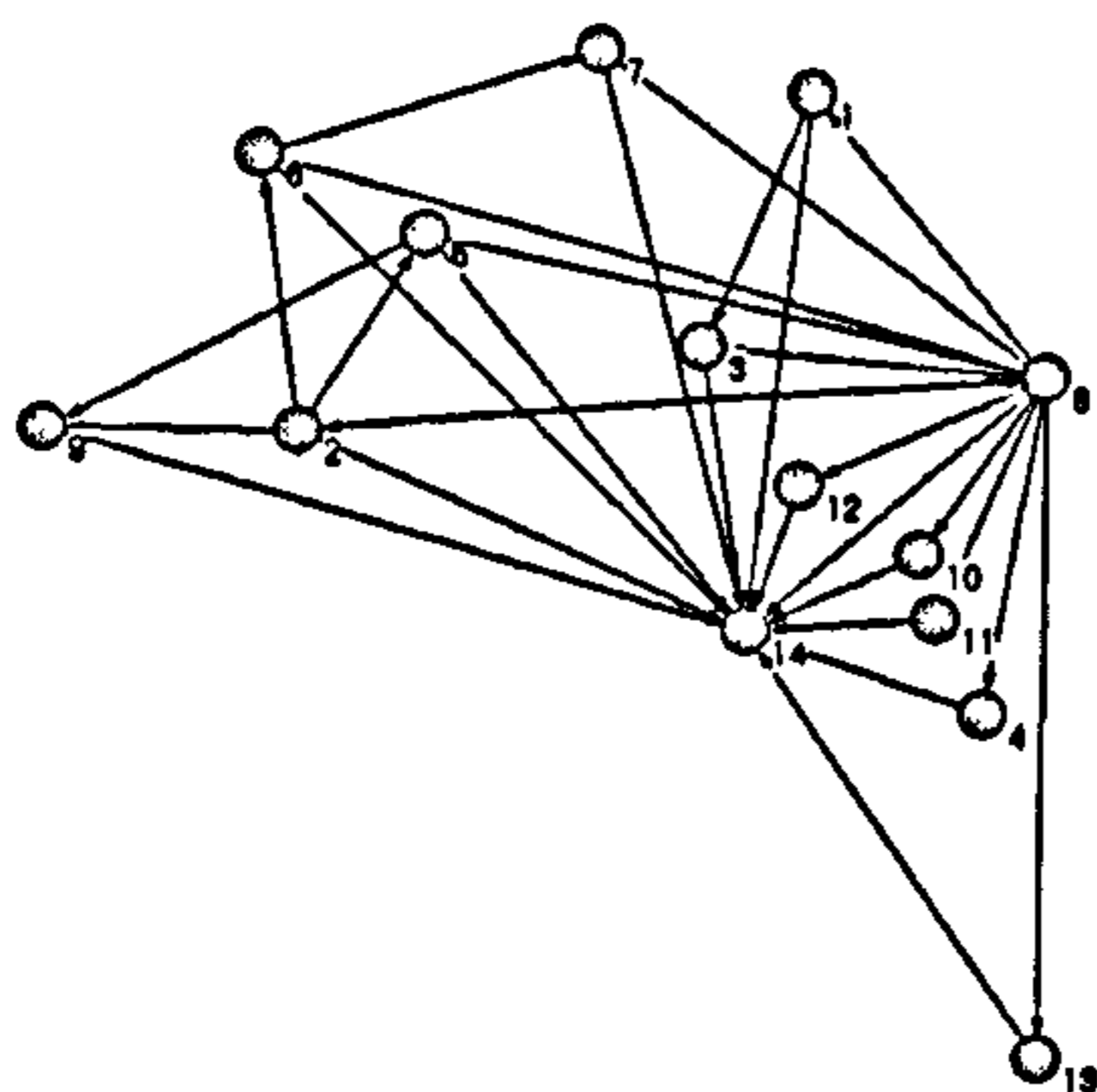


Figure 3.5a – Network representation of 32 largest intersectoral product flows in PIOTw without considerations of flow size

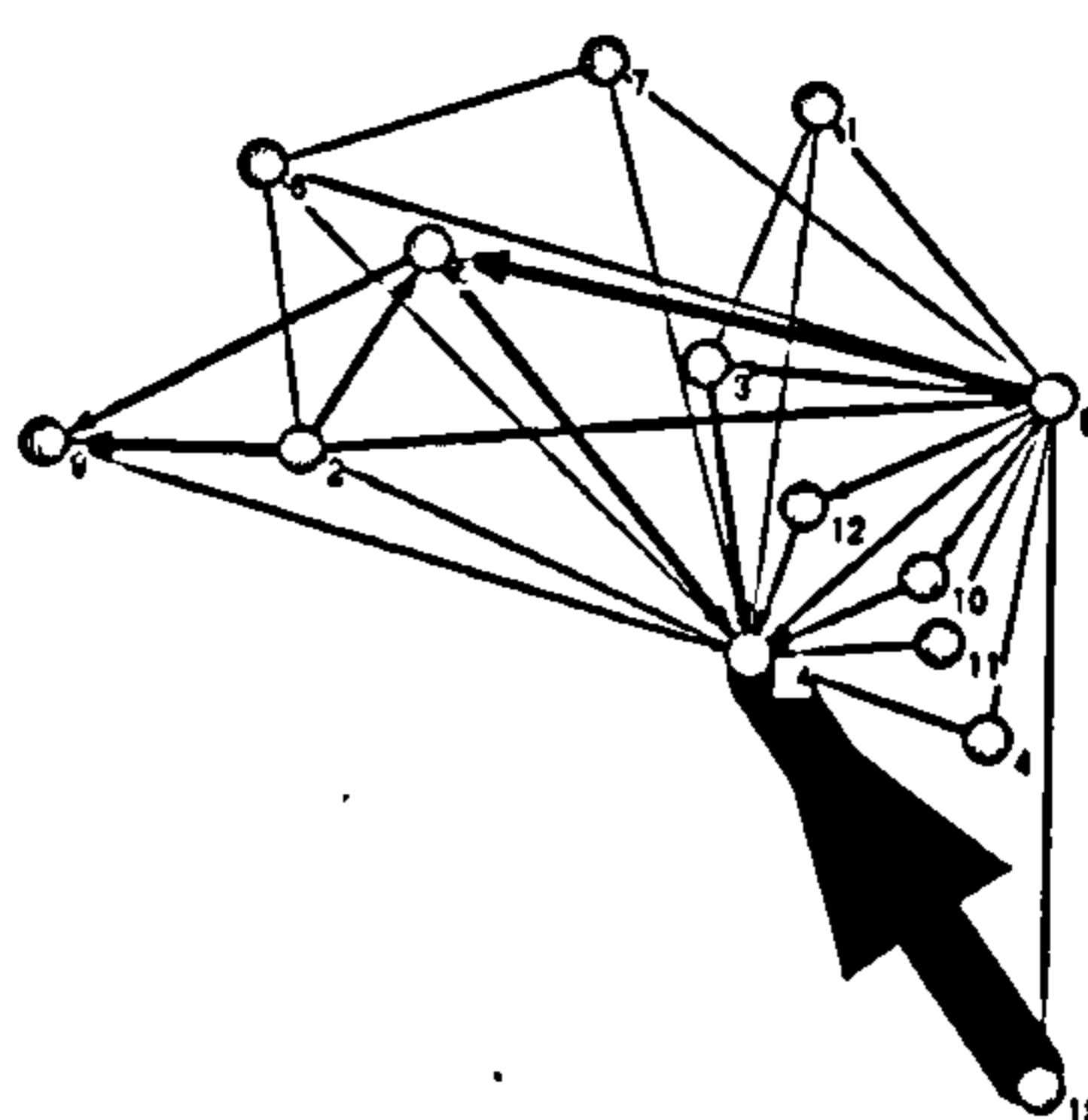


Figure 3.5b - Network representation of 32 largest intersectoral product deliveries in PIOTw with flow size represented by thickness of arcs

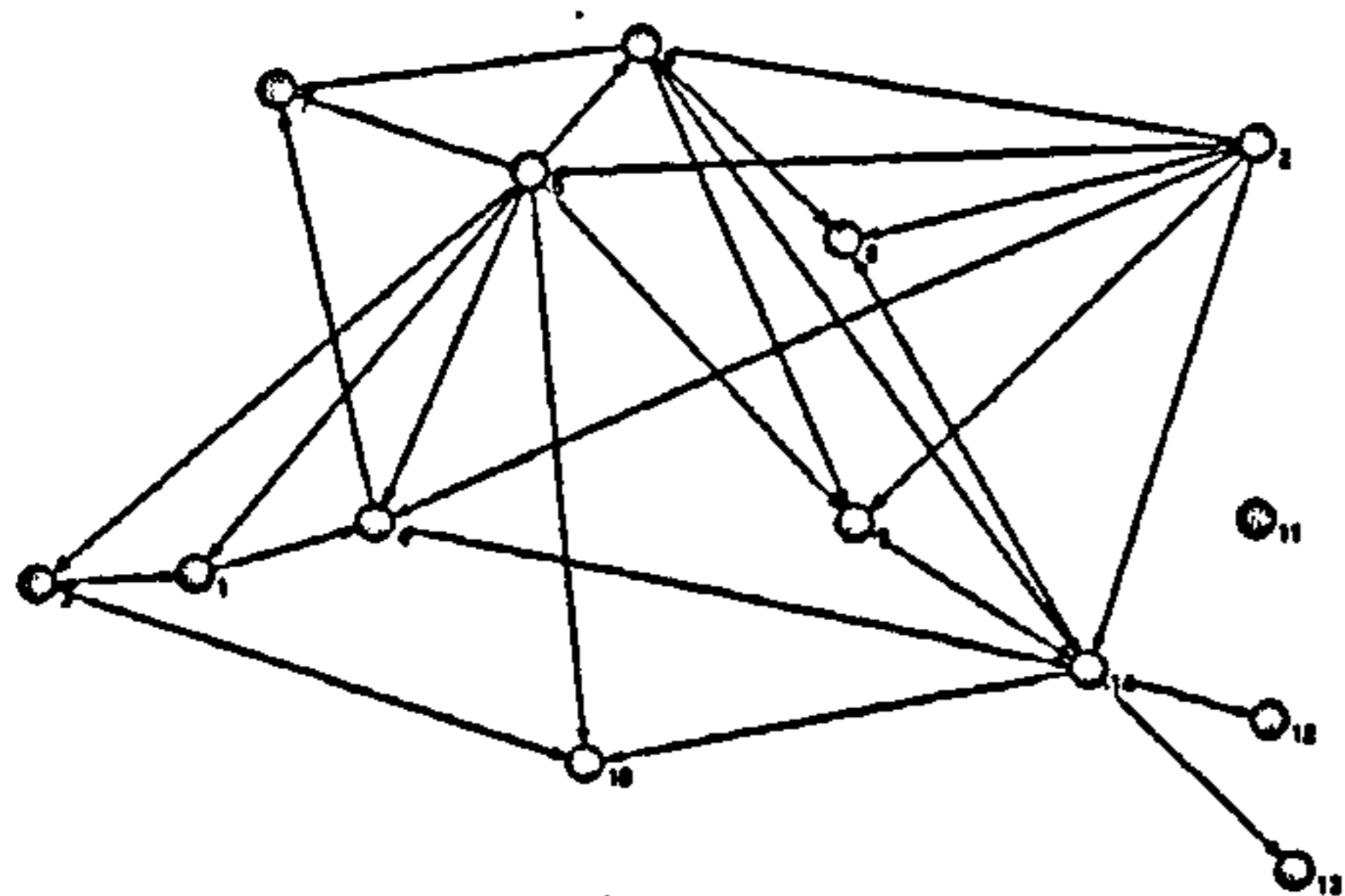


Figure 3.6a – Network representation of 32 largest intersectoral product flows in PIOTnw without considerations of flow size

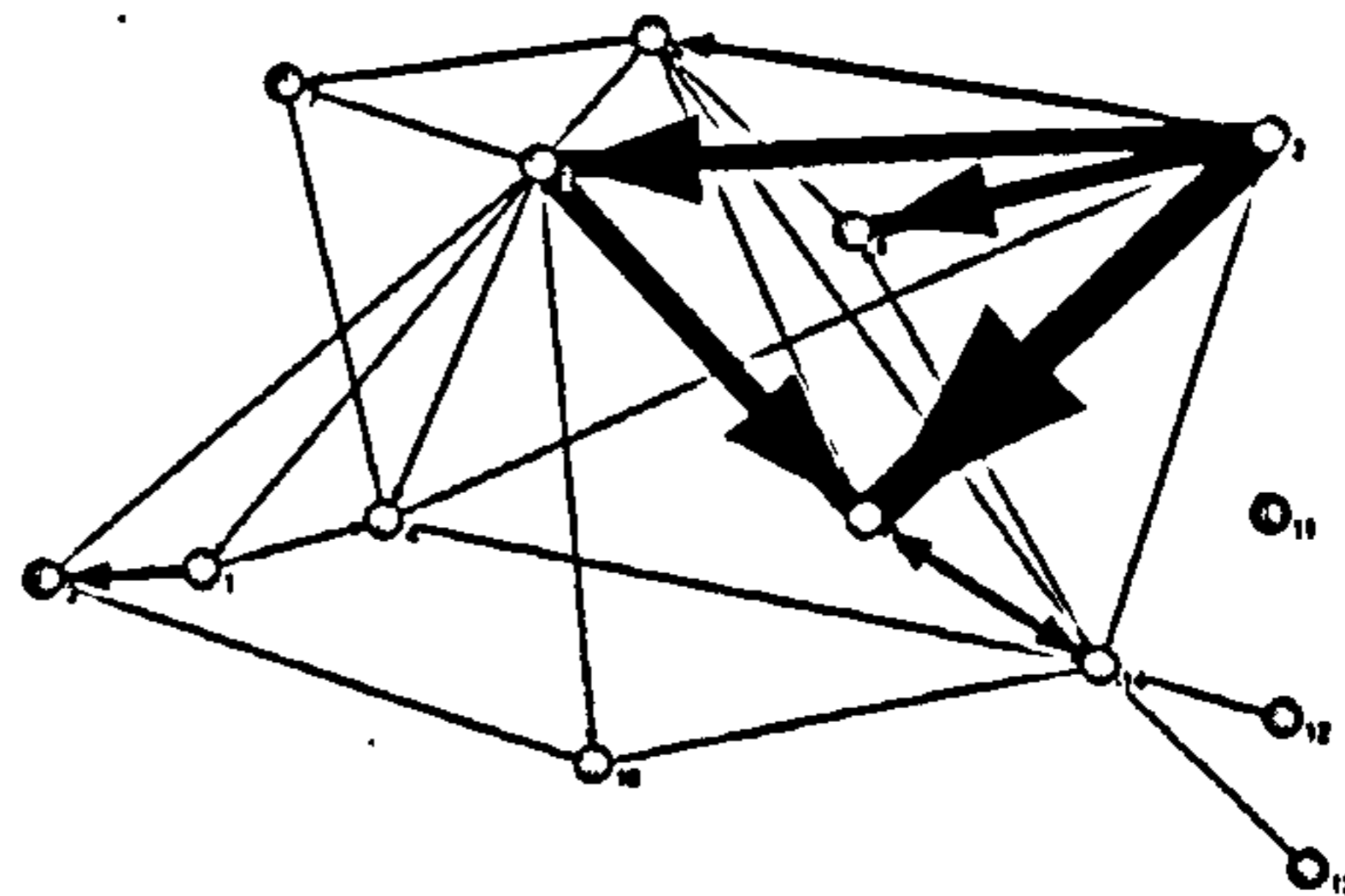


Figure 3.6b - Network representation of 32 largest intersectoral product deliveries in PIOTnw with flow size represented by thickness of arcs

(for sector names please refer to Table 3.4)

Once water flows are removed from the graph, the arcs become much more evenly connected among primary and secondary sectors, as can be seen in Figure 3.6a. ‘Mining and quarrying’ (sector 2) and ‘Refined petroleum’ (sector 5) become the main providing sectors in the network. In comparison with/in contrast to Figure 3.5a environmental services show a more diverse output than input structure. This implies that once water is removed from the table, recycling activities in the ‘environmental service’ sector gain in importance compared to waste treatment activities dominating in the “full” PIOTw.

While a topological representation of the interlinkages in the production structure as that shown in Figures 3.4a-3.6a is very clear, Mesnard (1995) rightly pointed out in his criticism of qualitative input-output analysis that important information can be gained once the size of the product deliveries is considered. The flow size between sectors is indicated by the thickness of the arrows in Figures 3.4b-3.6b.

A comparison of the graphs highlights the fact that the size of the direct (intermediate) deliveries between sectors in the production structure is much more evenly distributed in monetary than in physical representations. A striking feature of the PIOT tables is the presence of few flows with very large values and of many flows with zero entries. Flows seem to be even more unevenly distributed in the PIOTw with water than in the PIOTnw without.

This suggests the use of flow concentration as a measure of differences between tables in alternative units that takes into account both this qualitative and quantitative difference. We can measure the intermediate flow concentration using the so-called Lorenz curve, which is a graphical representation of the empirical cumulative distribution function of a probability distribution of flows. The Lorenz curve is typically employed in economics to address the issues of income inequality and market concentration. Concentration will have serious consequences on IO computations: for instance, the presence of many zero flows, increases the possibility of singularity and the stability of the numerical results (see also: Table 3.6).

Every point on the Lorenz curve represents a statement like “the bottom 20% of all flows constitute 10% of the total output”. A perfectly equal production structure would be one in which every intermediate flow has the same value. In this case, the bottom N% of intermediate flows would always amount to N% of the total output. This can be depicted by the straight line  $y = x$ ; called the line of perfect equality or the 45 line. By contrast, a perfectly unequal distribution of flows would be one in which one intermediate



flow amounts to the total output and every other flow is zero. In that case, the curve would be at  $y = 0$  for all  $x < 100%$ , and  $y = 100%$  when  $x = 100%$ . This curve could be called the line of perfect flow concentration.

Figure 3.7 shows the Lorenz intermediate flow concentration curve. As suggested in the comparison of graphs 3.4b-3.6b, flows are much more concentrated in the PIOTs than in the MIOT, as indicated by a lower position throughout Figure 3.7. In fact, in the detailed 58 sector PIOTw with a total number of 3364 inter-sectoral links in the production structure, the largest product delivery from sector  $i$  to  $j$  makes 30% of total intermediate production output in the PIOTw with water, and only 44 deliveries make more than 90%. In order to get a better impression of the scale of the difference we complement Figure 3.7 and 3.8 with Table 3.6, which chooses an alternative presentation of the results by mapping the minimum number  $n_{min}$  of product deliveries required to provide a certain proportion of total intermediate output. The only additional thing we would like to stress is the much larger number of zero flows, mainly due to the lack of coverage of immaterial service flows in PIOTs, which can easily lead to sparsity-related computational problems.

Intermediate output proportion	PIOTw		PIOTnw		MIOT	
	$n_{min}$	%	$n_{min}$	%	$n_{min}$	%
10%	1	0.03	1	0.03	4	0.12
20%	1	0.03	2	0.06	11	0.33
30%	1	0.03	3	0.09	20	0.59
40%	2	0.06	4	0.12	36	1.07
50%	2	0.06	7	0.21	59	1.75
60%	3	0.09	10	0.30	98	2.91
70%	9	0.27	14	0.42	164	4.88
80%	20	0.59	28	0.83	286	8.50
90%	44	1.31	64	1.90	523	15.55
100%	1115	33.15	1025	30.47	2435	72.38
total number of elements ( $n_{tot}$ )	3364		3364		3364	

Table 3.6 – Minimal number of intermediate output deliveries required for provision of a certain output proportion

Lorenz curves can be used to rank the IO tables. To do so we need to check whether the curves cross. Because of the changes in slope, the difference between MIOT and PIOT and, particularly, the difference between the PIOT curves with water and without water are difficult to assess visually. In general, Lorenz Curves may only give a “partial ordering,” i.e., they may fail to fully rank a set of distributions of flows if the curves cross. Logarithms can be used to simplify the comparison.

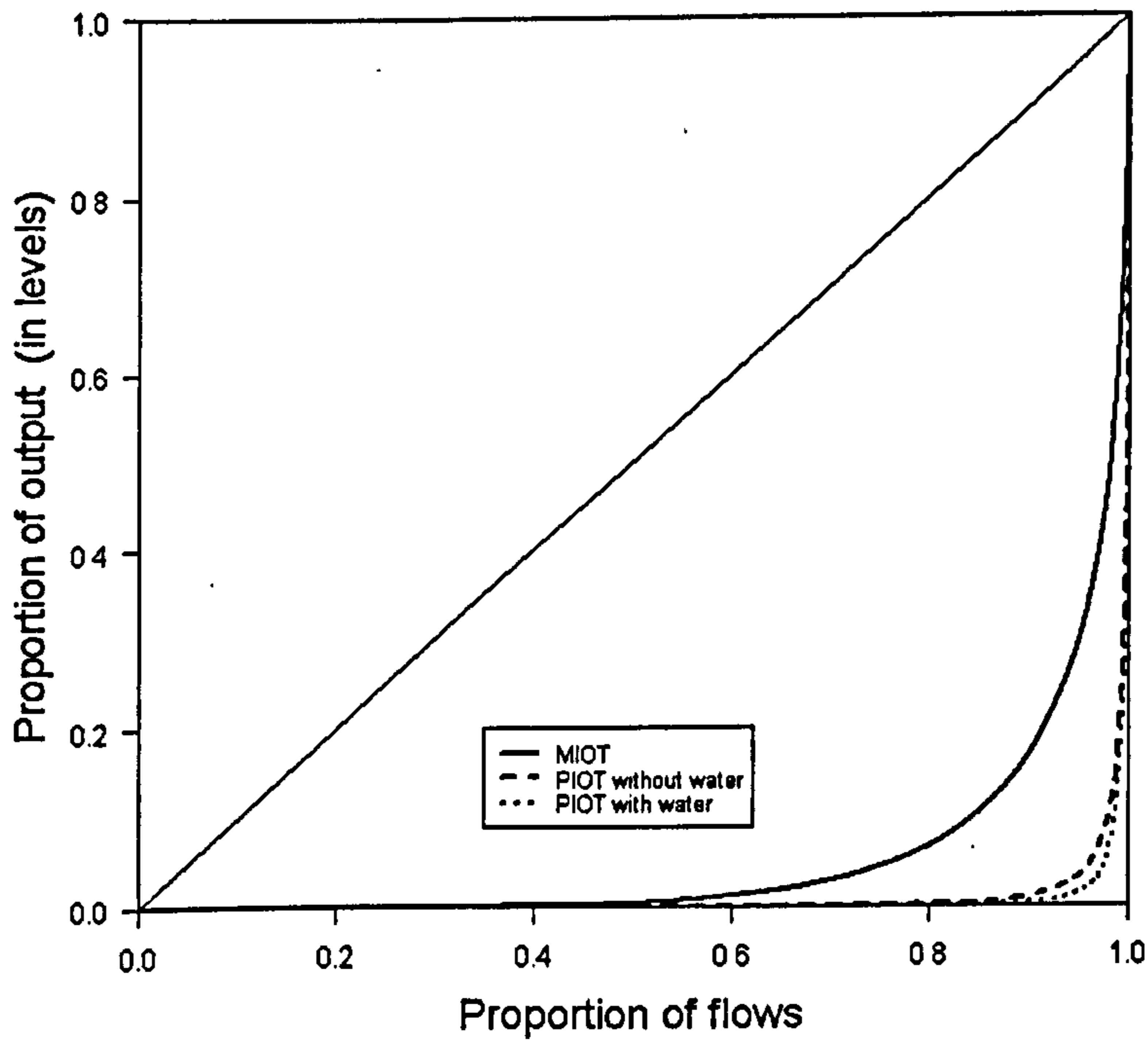


Figure 3.7 – Lorenz intermediate flow concentration curve (level)

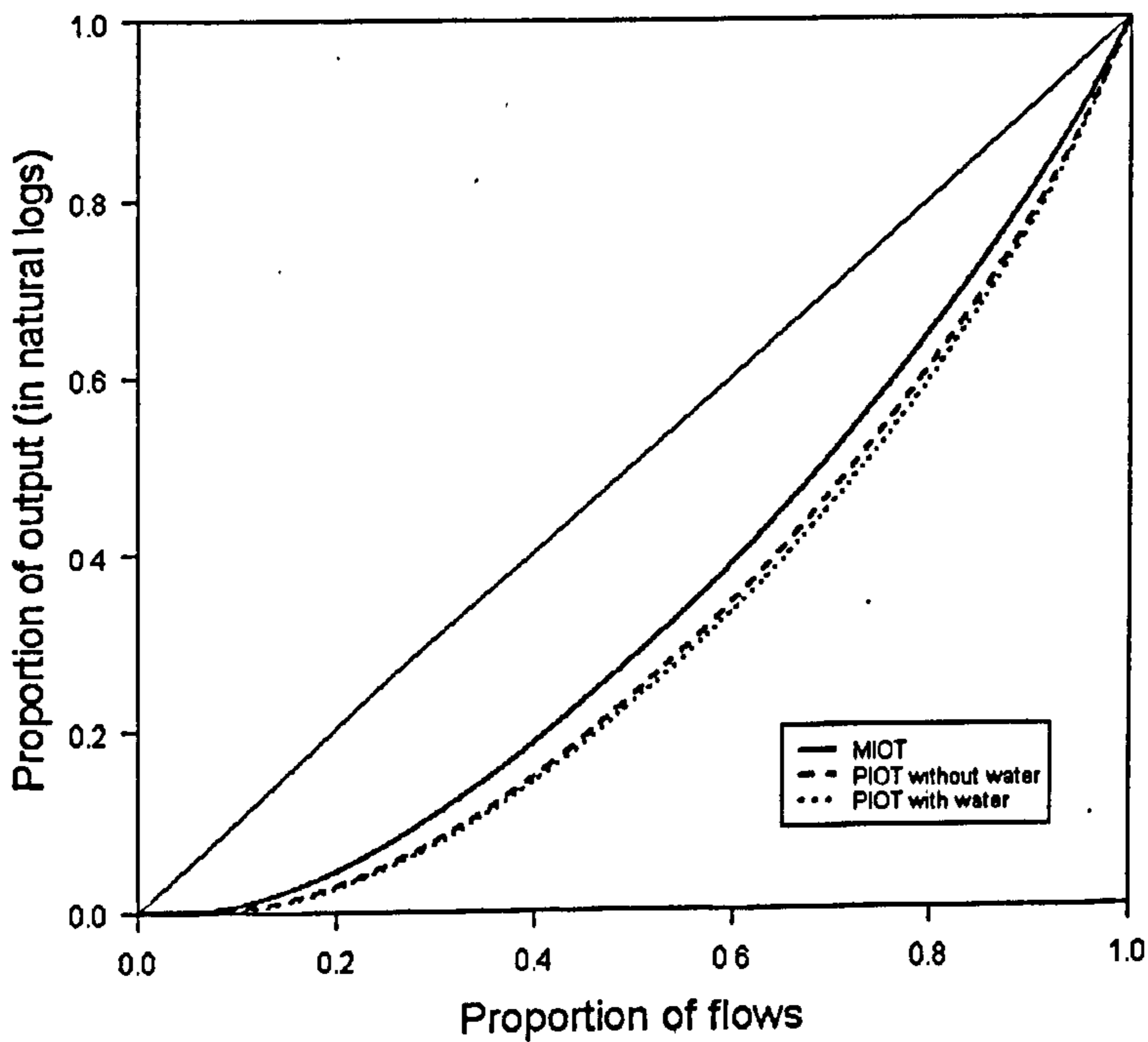


Figure 3.8 – Lorenz intermediate flow concentration curve (natural log)

Figure 3.8 shows the Lorenz intermediate flow concentration curve using flows transformed with the natural log function. The log being monotonic does not change the relative position of the curves. This graph clearly shows that the MIOT curve is always above (i.e., dominates) the PIOT curves. Also the PIOT without water is always above (i.e., dominates) the PIOT with water.

The Gini coefficient is the area between the line of perfect equality and the observed Lorenz curve, as a percentage of the area between the line of perfect intermediate flow equality and the line of perfect intermediate flow concentration. The Gini coefficient can be used as an flow concentration index. Here, 0 would correspond to perfect intermediate flow equality and 1 corresponds to perfect intermediate flow concentration. The Gini index of flow concentration for the MIOT German table is 0.893. For the PIOT tables the Gini coefficients are very close to 1, i.e., close to a perfect concentration of intermediate flows case. This is true particularly for the PIOTw with water table. The Gini coefficient for the PIOTs without and with water are 0.984 and 0.991 respectively.

Hence, it seems that there is not only a shift in emphasis in terms of general type of economic activity highlighted in the data, from primary and secondary industries in PIOTs to secondary and tertiary sectors in MIOTs, but also a big difference in the concentration of product flows in monetary and physical representations. The almost perfect concentration in the two PIOTs further reinforces a discussion of PIOTs from a computational viewpoint. This might also be relevant for their application in environmental input-output models with mixed unit production structures. However, the differences in concentration most certainly also have implications for how sectors are interlinked in higher production layers.

In Figures 3.9-3.11 all bi- and uni-lateral connections between sectors are represented at the '32 flow' filter level of the adjacency matrices. Recall that these graphs take all potential direct and indirect connections between sectors in higher production layers of the domestic supply chain into account. In the graphs thick edges identify bi-lateral and thin edges uni-lateral connections between production sectors.

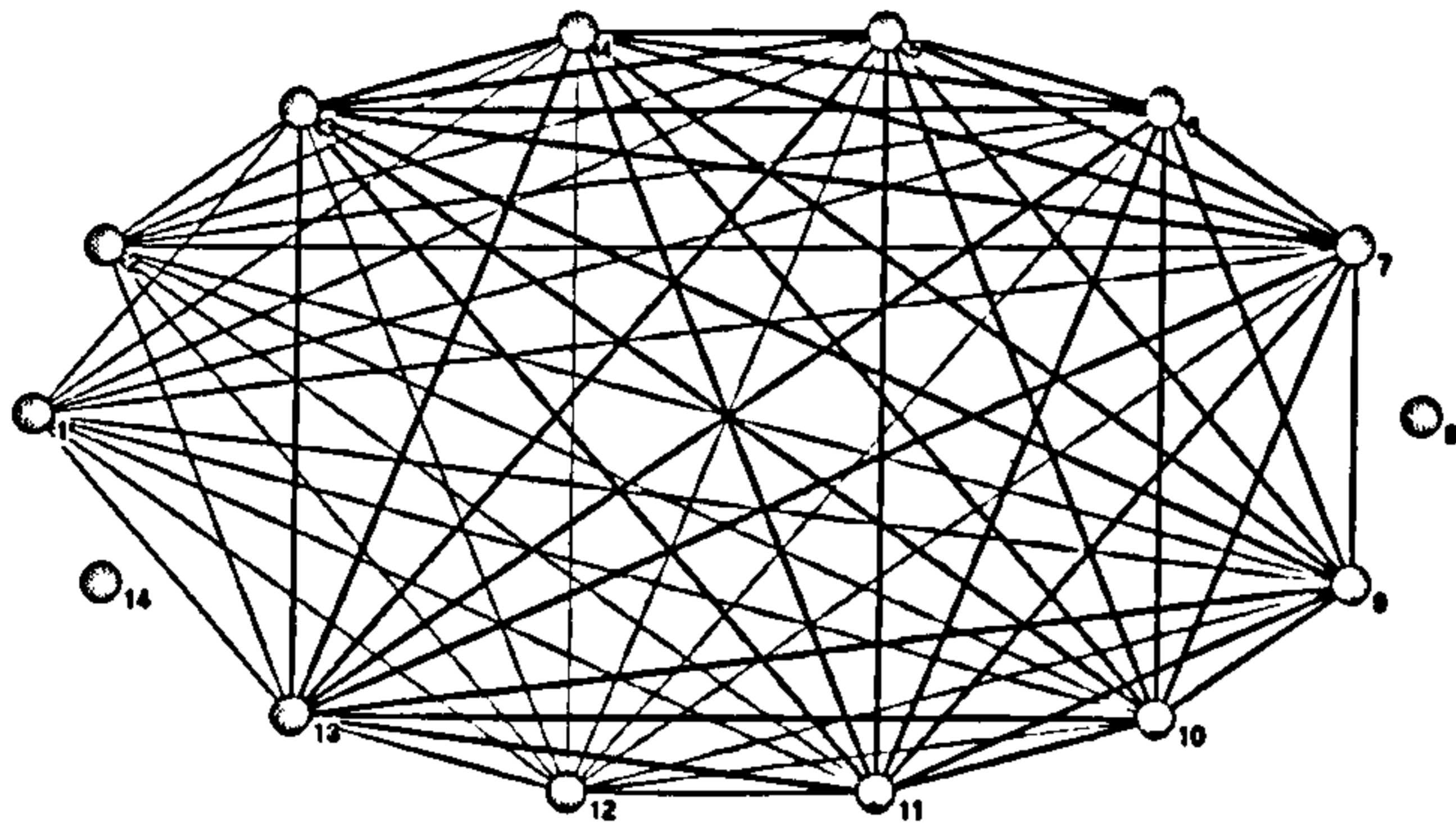


Figure 3.9 – Graph of uni- and bi-lateral connections (MIOT)

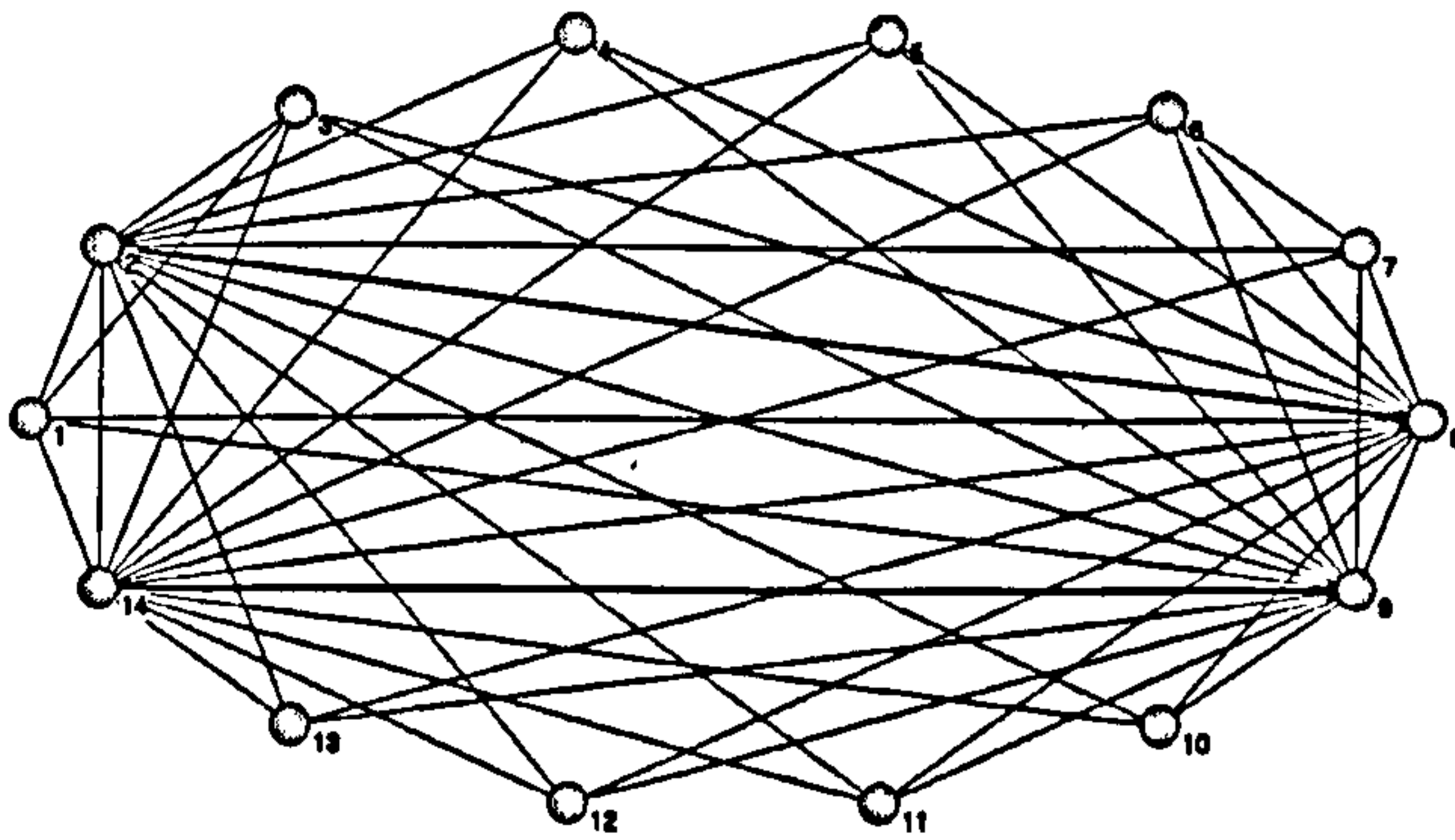


Figure 3.10 – Graph of uni- and bilateral connections (PIOTw)

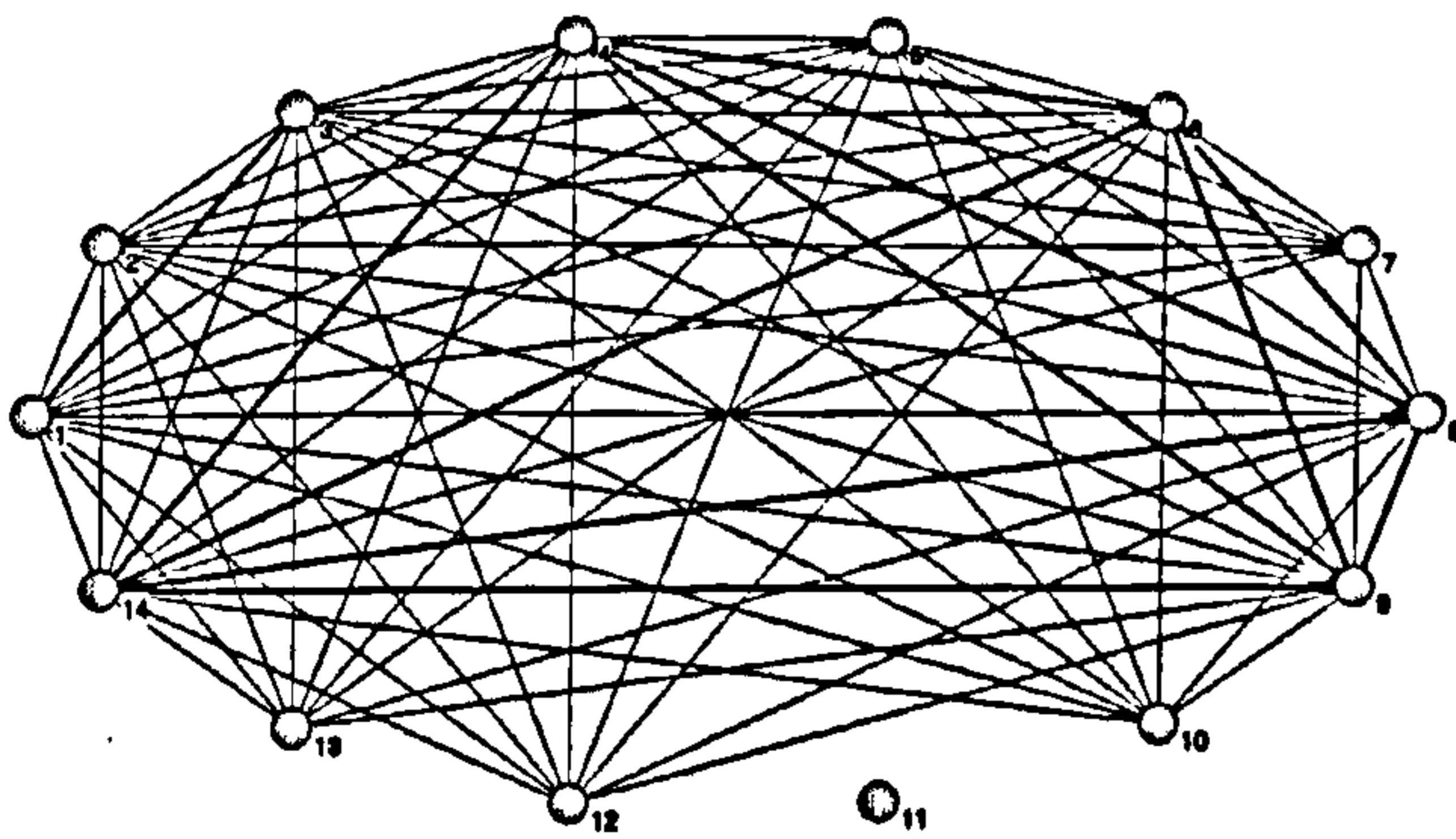


Figure 3.11 – Graph of uni- and bilateral connections (PIOTnw)  
 (For sector names please refer to Table 3.4)

A brief glance at the graphs of the connectedness matrix  $H$  is sufficient to see that the MIOT has the most bi-lateral connections even though the total number of uni- and bi-lateral connections is larger in the PIOT without water as shown in Tables 3.7-3.9. By contrast, the graph of the PIOTw with water is much sparser and therefore more weakly connected. Moreover, like in the graph of the adjacency matrix the network connections are more unevenly distributed, mainly evolving around the four vertices of the ‘mining and quarrying’ (sector 2), ‘energy and water’ (sector 8), ‘construction’ (sector 9) and ‘environmental service’ (sector 14) sectors.

Beside the arbitrariness problem, it is particularly important to study the graphs of the connectedness matrixes at variable filter values because of the large differences in intermediate flow concentrations in monetary and physical tables. A comparison of the different tables shows that the connectedness pattern of the PIOTnw without water and its evolution through the different ‘filter stages’ are certainly more similar to the MIOT than to the PIOT, although differences remain. A closer look suggests that this might be due to the lack of any physical outputs of the service sectors, as discussed in Section 2.3.1. For this very reason the graph of PIOTnw does not become fully connected at any filter rate.

By contrast, the graph of the PIOTw with water flows remains relatively weakly connected up to the connectedness graph of the adjacency matrix with 35 flows included, where 98 uni-lateral and 4 bi-lateral connections exist. However, once the next flow is included the graph immediately becomes fully connected. This might again be seen in the context of the dominance of water flows, but also in the context of the concentration issue. The higher concentration in (both!) PIOT graphs might give more weight to particular connections or pathways in the production structure. For a robust specification of environmental input-output models with production structures in hybrid units, it seems important to know where these are. This seems to highlight the importance of further quantitative investigation of the production structure: error propagation methods (e.g. Bullard and Sebald, 1988; Stäglin and Schintke, 1988.) seem appropriate, as well as quantitative graph theoretical approaches such as structural path analysis. It might turn out to be important in any specification process to routinely study the production structure with such methods.

Number of flows in adjacency matrix	Number of uni-lateral connections	Number of bi-lateral connections	Total number of connections
5	10	0	10
10	18	6	24
15	70	12	82
20	62	42	104
25	72	56	128
30	58	72	130
32	58	72	130
35	60	72	132
40	80	72	152
45	88	90	178
50	70	110	180
55	50	132	182
60	50	132	182
65	26	156	182
70	26	156	182
85	26	156	182
86	26	156	182
87-182	0	182	182

Table 3.7 - Unilateral and Bilateral Connections at variable filter levels in the MIOT

Number of flows in adjacency matrix	Number of uni-lateral connections	Number of bi-lateral connections	Total number of connections
5	12	2	14
10	24	2	26
15	36	4	40
20	50	14	64
25	60	14	74
30	112	22	144
31	122	22	144
32	122	22	144
35	72	72	144
40	72	72	144
45	72	72	144
49	60	90	150
50	80	90	170
51-182	80	90	170

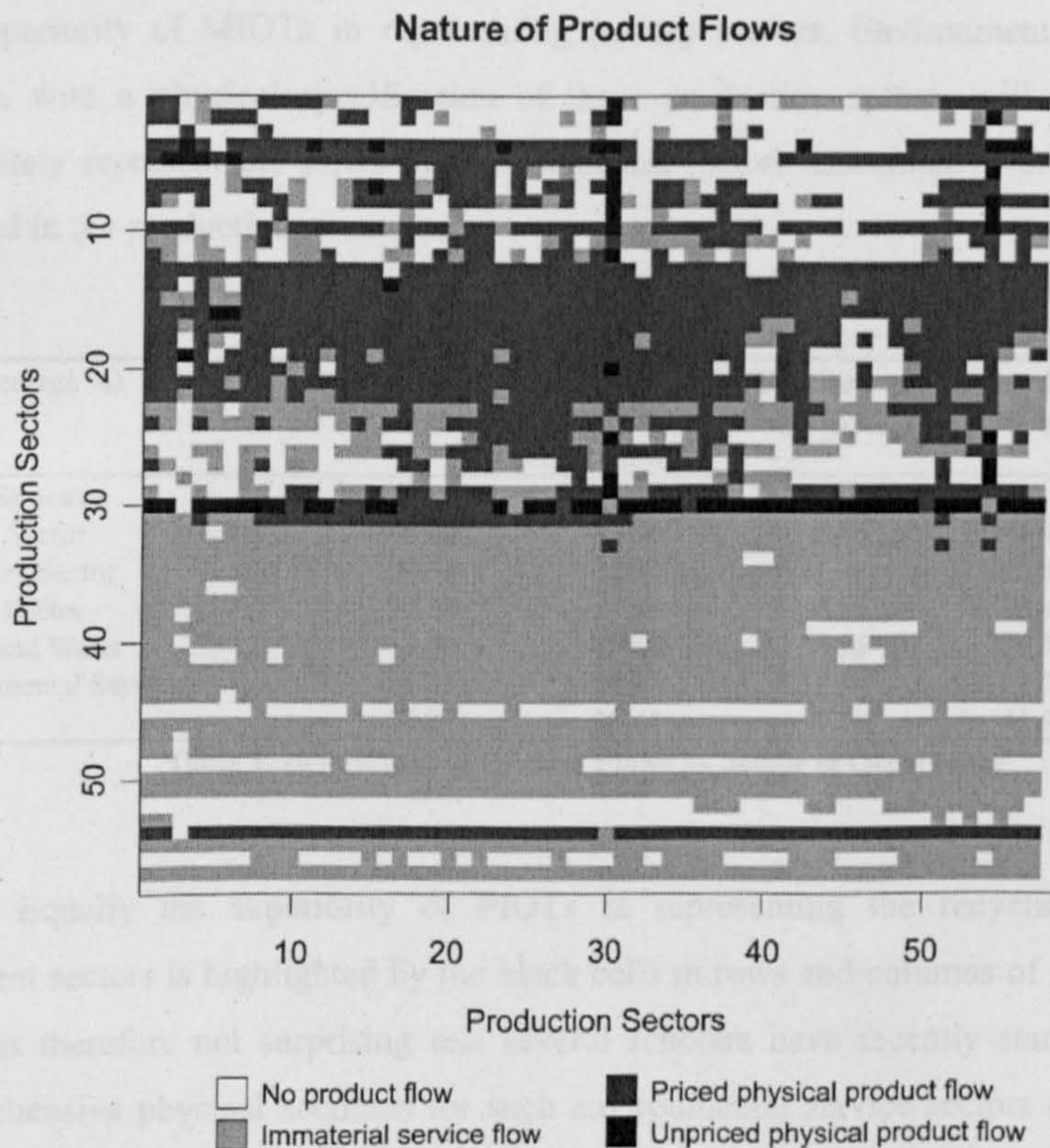
Table 3.8 - Unilateral and Bilateral Connections at variable filter levels in the PIOTnw

Number of flows in adjacency matrix	Number of uni-lateral connections	Number of bi-lateral connections	Total number of connections
5	14	0	14
10	26	0	26
15	42	0	42
20	52	2	54
25	76	4	80
30	90	4	94
31	90	4	94
32	92	4	96
33	94	4	98
34	96	4	100
35	98	4	102
36-182	0	182	182

Table 3.9 - Unilateral and Bilateral Connections at variable filter levels in the PIOT

### 3.5.2 On the nature of product flows

The matrix plot in Figure 3.12 provides a visual representation of structural concordances and differences in monetary and physical input-output tables. Each cell represents a link in the production structure between two sectors  $i$  and  $j$ . The colour of the cell further specifies the quality of this link: whether a product exchange takes place or not, and if so, what the nature of these product flow is in terms of pricing and physicality as specified above. White cells indicate the absence of a product flow, light grey cells identify immaterial service flows, dark grey cells priced physical product flows and black cells unpriced physical product flows. Hence, white and dark grey colour in Figure 3.12 represent structural concordance and light grey and black cells structural differences in the representation of production activities in MIOTs and PIOTs. Several insights can be gained from a visual analysis of Figure 3.12.



**Figure 3.12 – The Nature of Product Flows in the German Production Structure at a 58 sector aggregation level**

Structural differences in the representation of the production structure are a *defining* characteristic of the relationship between MIOTs and PIOTs. Only 55% of corresponding entries in the intermediate flow matrices are jointly zero ( $\Omega_{ij}=2$ ) or jointly non-zero ( $\Omega_{ij}=0$  cells). All other product flows have either no price (unpriced physical products) or no physical manifestation (immaterial service flows), and MIOT and PIOT paint two fundamentally different pictures. Still, both constitute two sides of the same coin, and it is important to look at both to obtain all the information required to make informed choices about an appropriate specification of environmental input-output models. In this sense, Figure 3.12 can be seen as visual reinforcement of the central claim made in this article that studying the differences between MIOTs and PIOTs is of fundamental importance in an empirical debate.

Most of the differences in the representation of the production structure in MIOTs and PIOTs are associated with the immaterial service outputs of tertiary sector as discussed earlier in Section 3.2.1 by the light grey cells between sectors 32 and 58. The ‘consistent’ occurrence of immaterial services in these sectors is a visual manifestation of the superiority of MIOTs in representing tertiary sectors. Environmental input-output models with a physical specification of these production sectors will not be able to adequately represent the flows of environmental factors associated with a certain final demand in the production structure.

(in Percentage %)	No Product Flow	Priced Physical Product Flow	Unpriced Product Flow	Immaterial Product Flow	Total
Output Structure					
Primary Sector	48.52	36.70	6.65	8.13	100
Secondary Sector	23.76	52.77	1.35	22.11	100
Tertiary Sector	22.84	1.44	0.29	75.43	100
Energy and Water	1.72	70.69	0.86	26.72	100
Environmental Services	3.45	59.48	35.34	1.72	100
Total	24.91	30.44	2.71	41.94	100

Table 3. 10 – Nature of Product Flows by Sector of Occurrence

Equally the superiority of PIOTs in representing the recycling and waste treatment sectors is highlighted by the black cells in rows and columns of sectors 30 and 54. It is therefore not surprising that several scholars have recently started compiling comprehensive physical accounts for such environmental service sectors (Takase et al., 2005; Tukker et al., 2006) and integrated these with MIOTs in environmental input-output models with mixed unit production structures.



However, black cells might also occur where they are not necessarily expected. In Figure 3.12 this is for example the case for sectors 19 ('Mineral products'), 16 ('Coke and refined petroleum') or 7 ('Other mining and quarrying'). Inquiries at the Statistical office (Stahmer, 2006) revealed that these differences are due to a more-updated physical database. In the German input-output publications also such product flows are included, which are produced in one establishment of one enterprise delivered to a different establishment within the same enterprise (see UN, 1993). These product flows do not have a market price. Their inclusion in the MIOT therefore requires monetisation of physical data. In the process of compiling the PIOTs more of these non-marketed product flows were identified. In order to ensure consistency of the MIOT with the remaining national accounts, these new flows were not included in the moneray table, whilst it was the intention to provide the PIOT using the best available information. The physical flows are not very large in size. However, this discussion still underlines the statistical value of compiling PIOTs as highlighted by Stahmer et al. (1998), as well as the usefulness of the proposed methodology to identify potential inconsistencies between monetary and physical tables.<sup>15</sup>

Figure 3.12 finally highlights that immaterial services also play a prominent role in primary and secondary sectors. This issue has been neglected by authors in the debate so far (except Chapter 2). In fact, 20% of the intermediate product flows in these sectors have a monetary, but no physical representation. This is not surprising as the German input-output tables assign all different commodities produced by an enterprise to its main activity. Aggregate product groups therefore usually contain a service component. The output definition of the agricultural sector, for example, comprises landscape gardening services, while the manufacturing of electrical equipment also includes installation services.

These patterns are often particularly relevant in sectors which produce capital goods, but have a high service component. A good example is the construction industry (sector 33), where 93% of all monetary intermediate flows are immaterial building services, because the finished buildings are recorded as part of the capital investment (and therefore final demand). Similarly 83% of the total value of intermediate flows associated with the production of wearing apparel are services, and a fifth of the intermediate flows

---

<sup>15</sup> The same argument could be made for immaterial service flows in primary and secondary sectors. However, their frequent occurrence imposes some limitations on the practicalities of checking each one individually. In the context of this research it has shown to be useful to identify the immaterial service flows of relevant size first (this would be equivalent to an extremely low filter in qualitative input-output) and inquire what these represent at the Statistical Office subsequently.

in the production of computer and office equipment (sector 23) and transport equipment (sector 28).

In this sense Figure 3.12 highlights two important issues in the context of environmental input-output modelling. *Firstly*, it stresses the importance of endogenising capital investment. While most of the environmental factors used and released by producers of capital goods are directly associated with their production, emissions are allocated to final demand in the environmental input-output model, often according to a relatively small service component, as long as capital investments remains exogenous to the model. This might seriously distort the results.

*Secondly*, and more important in the context of this article, primary and secondary sectors are the major concern when it comes to a robust hybrid specification of production structures in mixed monetary and physical units for environmental input-output modelling, because the nature of their product outputs is much less homogenous than in tertiary sectors including priced physical products, unpriced physical products and immaterial services. General recommendations are no longer possible and decisions will usually need to be made on a case-by-case basis.

In this sense, the analysis has helped to identify the problem, but cannot fully resolve it. A first step would be to use the information from Figure 3.12 in combination with further quantitative data to assess the size of the immaterial service and unpriced physical product flows. Such an analysis might still be limited as a substantial amount of immaterial services might be subsumed in a sector's priced physical product flows. Ultimately, only additional information from Statistical Offices would help to make fully informed decisions. However, even in this case the choice of measurement unit might not be obvious and will depend on various other factors, such as the type of a sector's product output, the environmental factor under consideration as well as the research question under consideration. The only way to provide further decision support in this specification process seems to rely on a good understanding of how differences in model specification transmit in the production structure of environmental input-output models. Various quantitative methods are available for studying the issue, such as structural path analysis. This is a line of research we would like to stimulate with this article.

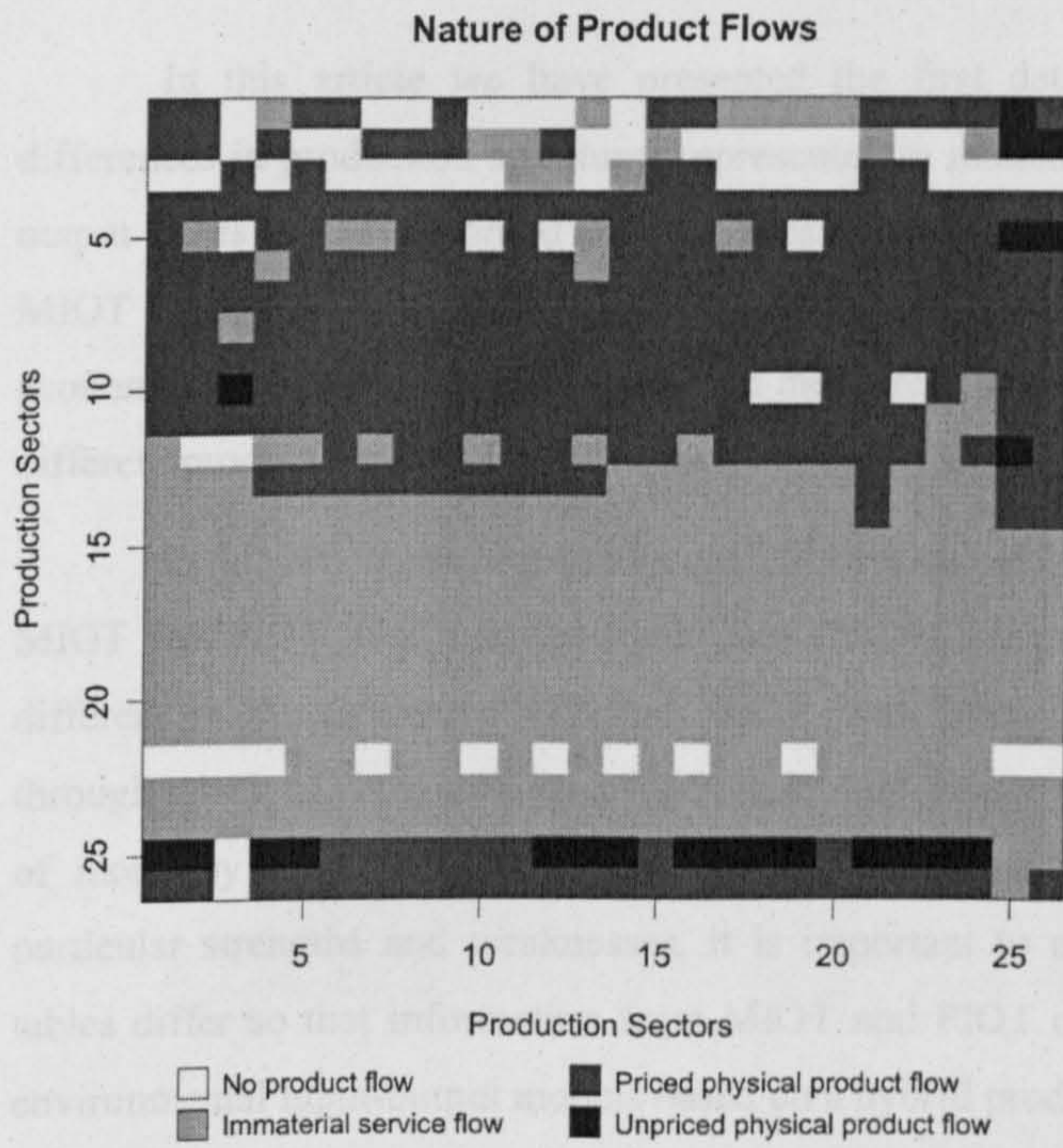
An alternative way of dealing with the issue can be identified when the nature of product flows is compared between the German and Danish PIOTs, as shown in Figures 3.13 and 3.14. Perhaps the most striking difference between the two is the absence of immaterial service in primary and secondary sectors and unpriced physical flows in the

Danish tables. While the latter is a result of an exogenous treatment of recycling and the absence of any waste treatment activities, the former is due to the industry-based compilation of the Danish input-output accounts.

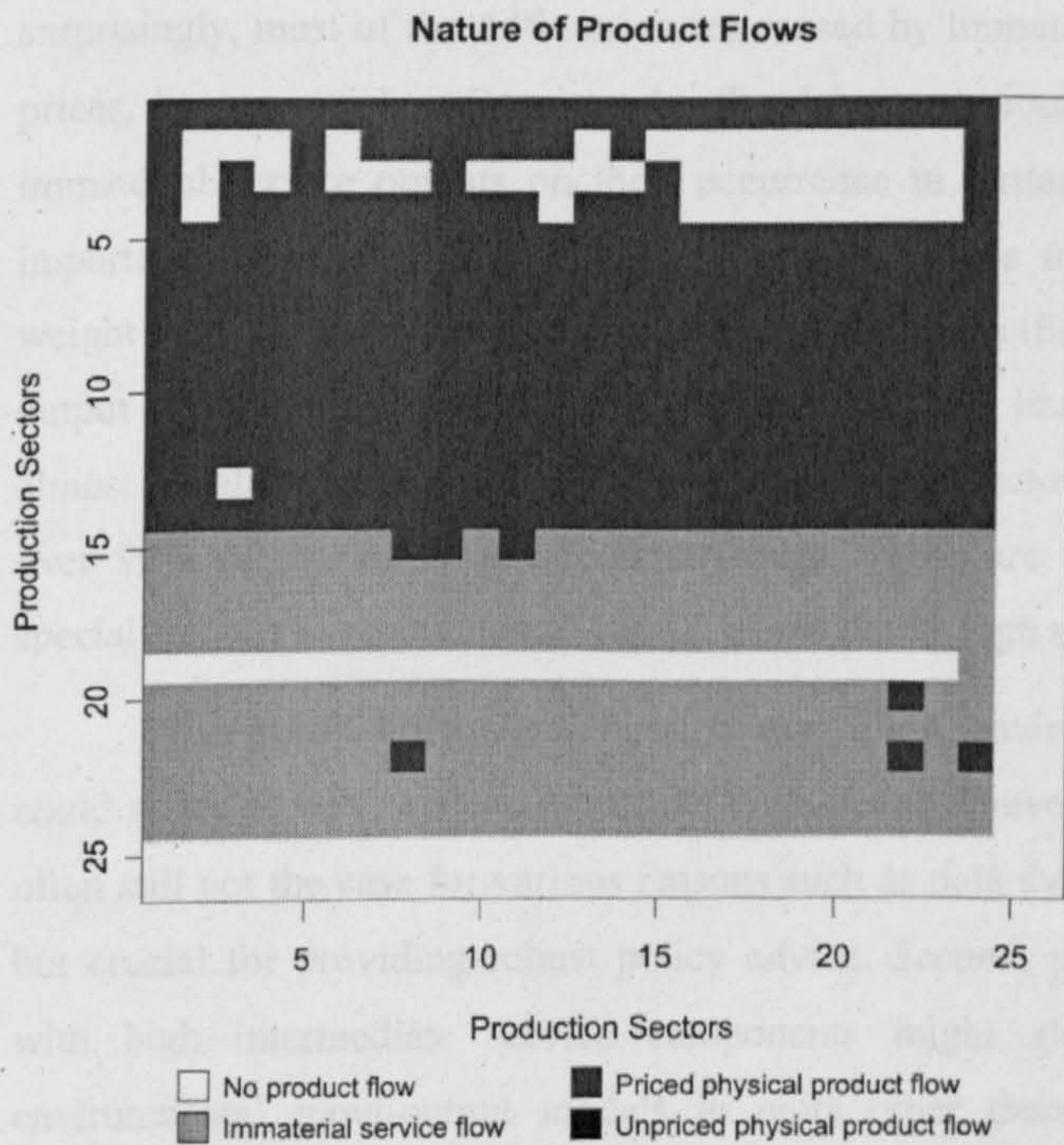
In the Danish tables all secondary outputs of an establishment are assigned to the industry, where this output is part of the main activity instead of the main activity of the establishment itself like in the German case. In the modelling debate a similar problem is discussed under the heading of taking an industry- or product-technology assumption in the context of input-output models based on supply-and-use tables (see Bacharach, 1970; Gigantes, 1974; Wiedmann et al., 2006: see Appendix A).

Hence, the way in which input-output tables are constructed provides different levels of control over differences and similarities between monetary and physical input-output analysis. This has two implications for the further debate: *First*, some of the required quantitative analysis of differences between monetary and physical input-output tables might be better carried out with the Danish input-output tables. *Second*, it highlights the potential need for a renewed discussion between the particular activity concept applied in the construction of tables and their suitability for environmental input-output analysis involving providers as well as users of the statistics.

3.8 CONCLUSION



**Figure 3.13 - The Nature of Product Flows in the German Production Structure at a 26 sector aggregation level**



**Figure 3.14 - The Nature of Product Flows in the Danish Production Structure at a 26 sector aggregation level**

### 3.6 CONCLUSION

In this article we have presented the first detailed empirical comparison of differences in production structures represented in monetary (MIOT) and physical input-output tables (PIOT) recorded solely in tons by using qualitative input-output techniques. MIOT and PIOT both try to depict production in terms of the product flows between economic sectors. Monetary and physical measurement in tons will lead to fundamentally different production structures for (environmental) input-output analysis.

In this article we proposed a qualitative method for revealing differences between MIOT and PIOT. Our analysis found that 45% of the product flows are fundamentally different in the German PIOT and MIOT from 1995. These differences do not arise through a lack of comparability of the tables, but mainly through differences in the scope of monetary and physical measurement. As both monetary and physical units have particular strengths and weaknesses, it is important to understand where and why the tables differ so that information from MIOT and PIOT can be adequately combined in environmental input-output models based on a hybrid production structure.

We found that it is informative to discuss differences between MIOT and PIOT in terms of the nature of product flows with respect to physicality and price. Not surprisingly, most of the differences are caused by immaterial service flows, which have prices, but no weights. Consistently, the debate previously focussed the discussion of immaterial service outputs on their occurrence in tertiary sectors and highlighted the importance of their representation in a more suitable measurement unit than tons of weight (e.g. monetary measurement) for a robust specification of environmental input-output models. However, our analysis revealed that immaterial service flows can be almost equally important in primary and secondary sectors, where they can make up to over 90% of the intermediate output share. These are usually manufacturing sectors specialised on the production of capital goods with a high service component.

This result highlighted three issues: *First*, environmental input-output models could arrive at very misleading results unless capital investment is endogenised. This is often still not the case for various reasons such as data availability or added complexity, but crucial for providing robust policy advice. *Second*, primary and secondary sectors with high intermediate service components might also be better represented in environmental input-output models in units other than tonnes of weight. *Third*, a comparison between German and Danish data revealed that the occurrence of immaterial

service flows in primary and secondary sectors depend on the accounting concepts applied in the construction of the tables. As soon as an industry concept rather than an establishment concept is chosen, immaterial service outputs can be consistently assigned to tertiary sectors.

Unpriced physical product flows provide the second fundamental source of differences between MIOT and PIOT. They highlight the strength of physical measurement for representing commodity flows without price tags directly attached. The analysis revealed that unpriced physical product flows make up for more than 35% of all commodity flows in the recycling and waste treatment sectors. As the vast majority of environmental flows continue to specify these environmental service sectors in monetary units, this provides additional evidence for the importance of research efforts aiming at the detailed representation of waste and recycling streams in physical units (Tukker et al., 2006b; Nakamura and Kondo, 2002).

Our analysis further highlights that one immediate consequence of choosing a physical over a monetary production structure for environmental input-output analysis is that the flow concentration in the intermediate flow matrix of PIOTs is considerably higher than in MIOTs. In fact, product flows are almost perfectly concentrated in PIOTs manifested in a Gini coefficient, which is just smaller than 1 (0.98 and 0.99 for PIOT<sub>nw</sub> and PIOT<sub>w</sub> respectively). Such high intermediate flow concentration as in PIOTs could have serious consequences for input-output computations: for instance, the presence of many zero flows may negatively affect the quality of numerical results.

Further graph-theoretical analysis showed (visually) that this high concentration caused by some very large flows occurring in very few material-intensive sectors can be the dominant factor in the evolution of the pattern of inter-sectoral connectedness. This is particularly true for the PIOT<sub>w</sub>, where the water flows associated with the water provision and waste water treatment sector make almost 80% of the total weight of the intermediate flow table. We showed that this has direct consequences for environmental input-output models, where most connections between sectors are dominated by the indirect links through the water providing and waste water treatment sectors. Due to this dominance the analysis suggested that the inclusion of water flows in environmental input-output models based on PIOTs might often not be appropriate unless very water specific policy questions are asked – a finding that has been previously suggested by Stahmer et al. (1997) and is similar to practise in the material flow accounting community (Eurostat, 2001).

A variety of strands for future research open from here. *First*, the qualitative analysis provided in this paper should be complemented by quantitative analysis. For example, due to the potentially strong influence of individual flows in highly concentrated physical production networks it is important to know where these flows are. Therefore subsequent quantitative study should aim at their identification. This might provide other important insights on how production structures in hybrid units might be most appropriately specified. Error propagation methods (e.g. Bullard and Sebald, 1988) or quantitative implementations of graph theoretical approaches such as structural path analysis (Lenzen, 2003; Heijungs and Suh, 2006) should provide the appropriate methodological toolkit.

*Second*, there are a variety of unresolved theoretical issues associated with environmental input-output analysis based on hybrid unit production structures. For example, higher concentration and increased sparsity could translate into potentially ill-conditioned IO problems. As results become more sensitive to measurement errors, further research is needed to validate results obtained by using information from PIOT tables.

*Third*, the choice of measurement units will also depend on the policy question under consideration as recently highlighted by Suh (2007). Due to the little practical experience in combining information from MIOTs and PIOTs (and environmental accounts) a comprehensive discussion of the issue with empirical examples, could provide an intuitive entry point for environmental input-output practitioners into the debate and highlight the importance of such specification questions for an adequate attribution of environmental factors to final demands.

*Finally*, a renewed discussion of input-output table construction in the light of the specification of environmental input-output models might be very valuable for improving the robustness of models in the future. This discussion should address the choice of accounting concepts as highlighted above and also widen the attention from PIOTs in single to PIOTs in multiple measurement units. The availability of such a table for China would allow this discussion to begin right now.<sup>16</sup>

---

<sup>16</sup> Thanks to Karen Polenske for pointing out the availability of this Chinese Table at the 16<sup>th</sup> International Input-Output Conference in Istanbul.

# **4. THE IMPACT OF LIFESTYLES AND SOCIO-ECONOMIC FACTORS ON GREENHOUSE GAS EMISSIONS IN POST-UNIFICATION GERMANY**

**Abstract:** The most recent climate change strategy of the German government highlights the need for policy to focus on greenhouse gas emissions from households to fulfil its Kyoto commitments. An understanding of the direct and indirect greenhouse gas emissions of households and socio-economic determinants is crucial for informed decision making, particularly with regard to the more ambitious post-Kyoto targets recently agreed on a European level.

This article identifies such socio-economic determinants behind the direct and indirect greenhouse gas emissions arising from the household consumption patterns of 41 different lifestyle groups in Germany between 1991 and 2002. Acknowledging the severe limitations of environmental input-output models to reveal social background factors, structural decomposition analysis and panel regression methods are applied. The usefulness and complementarity of both approaches for understanding greenhouse gas emission patterns and for informing climate change policies are highlighted.



## 4.1 INTRODUCTION

Climate Change has rapidly climbed the political agenda since the start of the international negotiations in Rio de Janeiro in 1992. Key to this development was the dismissal of the common practice to define global environmental problems almost solely in terms of poverty and population growth in the international policy arena. Instead it was acknowledged that “[...] the major cause of the continued deterioration of the global environment [...]” are “[...] the unsustainable patterns of consumption and production, particularly in industrialized countries [...]” (UNCED, 1992, paragraph 4.3).

The subsequent climate change negotiations saw the first attempts of industrialised countries to live-up to their responsibility of leading the way out of the environmental crisis. While further increases in the atmospheric carbon concentration are unavoidable within the next few decades, the only feasible option for a stabilisation in the long run seems to be an engagement into a global process of contraction and conversion (see Global Commons Institute, 2007).

In Kyoto, a first important, but very modest attempt was made to start such a process. For industrialised countries as listed in Annex 1 of the Kyoto Protocol, binding emission targets were negotiated. However, regardless of these on-going international negotiations, the global release of greenhouse gases (GHG) keeps rising rapidly. Some of this failure to slow the growth in emissions might be attributed to flaws in the design of the Protocol: for example, not all GHGs are accounted for in the international process. Equally, problems of carbon leakage have been widely discussed in this context (Brack et al., 1999).

However, problems associated with the *implementation* of the Kyoto Protocol seem far more substantial. Despite the increasing acknowledgement that the human induced release of GHGs is at the root of the observed increases in global temperature, mounting scientific evidence about the severe, potentially irreversible damage caused (IPCC, 2007) as well as more and more agreement among economists that strong action today will minimise the economic and social costs associated with climate change (Stern, 2006), some of the most polluting countries like the US have neither *ratified* the treaty nor taken any serious actions to combat climate change themselves uni-laterally. Moreover, there is a serious problem of *compliance*: even some Annex 1 countries, which

have ratified the Kyoto Protocol, have fallen far behind in living up to their commitments and do not seem likely to meet their targets until 2012.

This compliance problem is also widespread within the European Union (Table 4.1), which stands in sharp contrast to Europe's leadership role in the international negotiation processes (Brack et al., 1999) and comparatively high-flying greenhouse gas emission reduction targets. European leaders recently decided to cut emissions by 20-30% by 2020 and by 60-80% by 2050 (BMU, 2006). To meet both sets of targets it will be important to learn from the successes made in emissions reductions in some countries.

Germany is one of the countries in the EU-15, which is likely to fulfil its Kyoto target. So far 18.5% of the 21% reduction in greenhouse gases compared to 1990 has been achieved. A considerable part of the success is related to the country's particular history with the re-unification in 1990 and the associated contraction and re-design of the comparatively greenhouse gas intensive Eastern German economy. However, environmental policy making has also been progressive – particularly in the second half of the 1990s. Germany was not only one of the first European countries to introduce a green taxation scheme, but also an early mover in supporting renewable energies on the supply side and energy saving devices on the demand. These have contributed to some unique successes in climate change policies. As highlighted in the most recent climate change strategy, Germany is, for example, the only European country, which managed to reduce greenhouse gas emissions associated with private transport (BMU, 2006).

In order to achieve its Kyoto targets the Government has reviewed progress and outlined a detailed plan to secure the required GHG emission cuts in its climate change strategy (BMU, 2005; BMU, 2006). Reductions on the production side are sought to be delivered by the European emission trading scheme, but the initial over-allocation of permits throughout participating countries has prevented effective trading so far (WGBU, 2007; SFU, 2006). This questions the feasibility of a timely delivery of these reductions. The major challenge for government action, however, is seen in curbing household related GHG emissions. To meet the Kyoto target and the more ambitious future goals (see BMU, 2006) a sound understanding of the development in greenhouse gas emissions and the underlying driving forces is crucial.

	Reference Year*	1990	1995	2000	2002	2003	Absolute Change (2003/Reference Year)	Change (2003/Reference Year)	Kyoto Target (EU burden sharing)
in Million tons CO <sub>2</sub> Equivalents							in %		
Austria	78.5	79	80	81	86	91.6	13.1	+16.6	-13.0
Belgium	146.8	146	152	148	145	147.7	0.9	+0.6	-7.5
Denmark	69.9	69	77	68	69	74.0	4.4	+6.3	-21.0
Finland	70.4	70	71	70	77	85.5	15.1	+21.5	0.0
France	568.0	568	563	560	554	557.2	-10.8	-1.9	0.0
Germany	1248.3	1244	1103	1017	1015	1017.5	-230.8	-18.5	-21.0
Greece	111.7	109	114	132	134	137.6	25.9	+23.2	+25.0
Ireland	54.0	54	58	69	69	67.6	13.6	+25.2	+13.0
Italy	510.3	511	528	551	555	569.8	59.5	+11.6	-6.5
Luxembourg	12.7	13	10	10	11	11.3	-1.4	-11.5	-28.0
Netherlands	213.1	212	224	214	213	214.8	1.7	+0.8	-6.0
Portugal	59.4	59	70	80	86	81.2	21.8	+36.7	+27.0
Spain	286.1	284	315	380	399	402.3	116.2	+40.6	+15.0
Sweden	72.3	72	73	67	69	70.6	-1.7	-2.4	+4.0
United Kingdom	751.4	748	691	652	644	651.1	-100,3	-13.3	-13.5
EU-15	4252.5	4238	4129	4100	4126	4179.6	-72.9	-1.7	-8.0

\*Reference Year 1990 for CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O; Reference Year 1995 for HFC, PFC, SF<sub>6</sub>

Table 4.1 - Development of Greenhouse Gas Emission in the EU-15 1990-2003 (European Environment Agency, 2005)

This article sets out to provide an in-depth analysis of the German progress in reducing greenhouse gas emissions between 1991 and 2002. Consistent with the government's focus on household emissions, a unique data set combining traditional input-output data with Social Accounting Matrix or SAM-type extensions is used to compare the climate change impacts of 41 different household groups framed in a consumer lifestyle analysis (see Bin and Dowlatabadi, 2005). The underlying input-output methodology links production and consumption in a systemic approach and allows the assessment not only of the direct GHG emissions from households, but also their indirect ones arising from the production of consumer goods in the global supply chain.

However, input-output approaches fall short in providing a detailed understanding of the socio-economic determinants driving emissions. Structural decomposition analysis and a panel regression approach are used to reveal such information. The results are used to derive important policy implications for the achievement of short and long-term climate change targets of the government. Moreover, important lessons can be learned by other countries, which have been less successful in curbing greenhouse gas emissions, for designing effective climate change policies.

The next Section introduces the lifestyle concept, its particular implementation in the input-output literature and the associated shortcomings in revealing socio-economic background information highlighting the need for alternative approaches. In Section 4.3 a way is outlined to deal with the problem without leaving the general methodological framework of input-output analysis. Applying a structural decomposition approach, changes in GHG emissions between 1991 and 2002 are broken down into technological and lifestyle determinants in the spirit of the IPAT formula (e.g. Commoner, 1972; Ekins, 1993). The discussion of the results in Section 4.4 highlights the value of such an approach to gain a better understanding of these various determinants, but highlights the limitations in isolating the effects of specific socio-economic factors, whilst controlling for 'everything else'. This is the realm of regression analysis. Section 4.5, therefore, uses the results from the input-output model in combination with additional social accounting data to provide an understanding of the impact of such socio-economic factors before Section 4.6 concludes..

By doing so this article makes three unique contributiony to the literature:

- For the first time the detailed SAM-type income and expenditure data provided by the German socio-economic reporting system is used for analysing the greenhouse gas emissions of 41 different lifestyle groups for all

consecutive years between 1991 and 2002. In the wider literature not a single study could be found with a similar level of detail.

- Only such a wealth in data allows the estimation of a panel regression model. No other input-output based study could be found in the literature, which has applied a panel regression methodology in an input-output context apart from our own attempts in a cross-sectional context.
- To our knowledge this is the first detailed decomposition analysis taking socio-economic groups and the detailed demographic structure of society into account.

## **4.2 ON THE CONSUMER LIFESTYLE APPROACH FOR ANALYSING ENERGY USE AND GHG EMISSIONS**

### **4.2.1 Households and Lifestyles in the Climate Change Context**

The lifestyle concept, as commonly applied in marketing research (and the sociological literature) since the 1960s (see Todd et al., 1998), has proven useful in analysing household consumption, its energy consumption as well as climate change impacts in a wider behavioural context. Lifestyles reflect different modes of living and have usually been associated with the choices people make. These, for example, comprise decisions about an individual's work-life balance, fertility or the acquisition of consumer goods (see Duchin, 1998; Duchin and Hubacek, 2003). Many of these choices are interdependent and influenced by a variety of determinants such as an individual's positions in the life cycle, her beliefs, attitudes, motivations or the institutional setting as highlighted by Bin and Dowlatabadi (2005).

Due to their focus on choices and peoples' behaviour, lifestyles have often been juxtaposed with approaches focussing on technological aspects such as the energy and resource efficiency of production processes and supply side policies. Minimising carbon emissions in car manufacturing or designing more fuel efficient cars would be framed as an issue of technology (or production). Buying a Porsche with a fuel consumption three times higher than the average car and using it instead of a bike to go to the nearby squash court are typical lifestyle choices (or consumption). Products often act as the interface between the two, linking technological and behavioural issues systematically together.

Because lifestyles are often rooted in deep seated habits, beliefs and routines, environmental policy makers have often favoured purely technological solutions (see Jackson, 2005; Sustainable Consumption Roundtable, 2006). However, in order to make significant progress in the climate change challenge, the full inclusion of demand side issues seems unavoidable: In particular, when atomic power is not seen to play a significant part for achieving short-term, medium-term and long-term targets. There are four major arguments why the inclusion of demand side issues is crucial:

- Households are the by far the largest final demand entity and are directly or indirectly associated with the majority of the greenhouse gas emissions (Table 4.4). They are the entity where most decisions about peoples' lives are taken. However, households consume very differently and it is important to know who consumes what and why. A sound understanding of the socio-demographic driving forces behind a certain final demand pattern are therefore crucial to scope and design effective policy responses to the climate change challenge.
- The Government tries to influence peoples' choice behaviours in its policies. 1999 saw the introduction of a green tax on energy in Germany. There are also long-standing efforts to reduce the climate change impacts of consumer choice through eco-labels, such as the "Blue Angel" or the EU energy label for household appliances, as well as information campaigns of various other forms. In order to fulfil policy targets associated with the introduction of these measures, it is, for example, key to know whether or not such demand side policies actually make a difference, which household groups respond more than others and why this might be the case.
- It is widely acknowledged that social and demographic trends themselves can strongly influence energy demands and greenhouse gas emissions over time. Savings in GHGs from more energy efficient houses, for example, are partially off-set by a continuous expansion of residential living space per capita, mainly driven by a decreasing household size. Equally, the ageing German society is likely to require more energy for heating homes as older people spend more time at home and have a preference for higher average room temperatures (see Schipper, 1997, Haq et al., 2007). Another prominent example is the increase in car travel during the 1970s and 1980s driven by an increased proportion of female and young drivers. Without an analysis of lifestyles and associated socio-demographic trends, a detailed assessment of scope of the challenge Germany

faces and a design of appropriate policy responses for tackling climate change will be very difficult.

- Finally, technological improvements themselves can trigger substantial behavioural responses, changing the effectiveness of a particular policy. This has been discussed most prominently in the energy economic literature under the heading of rebound effects (see Greening et al., 2000). In the most general way, rebound effects can be defined as a “behavioural or systemic response to a measure taken to reduce environmental impacts that offsets (part or all) of the measure” (Hertwich, 2005: 86): These have been discussed on the micro and macro level as well as in the context of resource/energy efficiency (Greening et al., 2000; Binswanger, 2001) and time saving innovations (see Binswanger, 2002; Jalas, 2002; Jalas, 2005).

#### **4.2.2 Input-Output based analyses of lifestyles**

The analysis of the energy requirements from household consumption based on an input-output methodology has a longstanding history in the energy economic literature (see Miller and Blair, 1985: chapter 6). While the interest in the 1970s and 1980s was mainly sparked by the oil crisis and fears associated with the limited availability of fossil energy carriers (e.g. Bullard et al., 1977; Proops, 1977; Hannon et al., 1984; Stahmer and Beutel, 1982), the attention has shifted to energy-related greenhouse gas emissions and climate change impacts since the early 1990s (e.g. Common and Salma, 1992; Gay and Proops, 1993; Hetherington, 1996).

Because households’ choices manifest themselves in particular expenditure patterns, their final demands have often been interpreted as an economic representation of a lifestyle (e.g. Duchin, 1998; Weber and Perrels, 2000; Duchin and Hubacek, 2003; Bin and Dowlatabadi, 2005) . With final demands usually treated exogenously in the model, we often find studies comparing the energy requirements and climate change impacts of different lifestyles across time (Peet et al., 1985, Munksgaard et al., 2000; Kim, 2002), space (Proops et al., 1992; Morioka and Yoshida, 1995, Reinders et al., 2003; Lenzen et al., 2004; Moll et al., 2005; Lenzen et al., 2006) or socio-economic cohorts (Bullard and Herendeen, 1975; Herendeen and Tanaka, 1976; Herendeen, 1978, Herendeen et al., 1981; Vringer and Blok, 1995; Morioka and Yoshida, 1997; Wier et al., 2001; Pachauri

and Spreng, 2002; Cohen et al., 2004; Pachauri, 2004).<sup>1</sup> These studies usually aim to identify less carbon intensive lifestyles and driving forces in order to design effective policies for curbing energy demand and associated CO<sub>2</sub> emissions on the demand and supply side of the economy.

#### 4.2.2.1 Advantages of input-output based approaches to lifestyle analysis

The input-output approach for the assessment of energy requirements and greenhouse gas emissions associated with different lifestyles has some particular strengths in the policy context outlined above: *Firstly*, it takes the direct as well as indirect greenhouse gas emissions associated with household consumption patterns into account. Direct emissions arise when households use energy carriers themselves. People, for example, heat their homes or drive their cars. Indirect emissions arise in the supply chain from the use of energy in the production of consumer goods. The emissions from all different production stages including resource extraction, manufacturing, and distribution are said to be “embodied” in the final goods people buy (like a jar of jam, a diary or a bottle of water). Approximately, two thirds of the total emissions from household consumption occur during the production of products in the supply chain as highlighted in Table 4.4. Even though the German government has focussed in its climate change strategy only on direct household emissions, it is clear that a more comprehensive approach will be required to achieve the ambitious post-Kyoto emission targets.

*Secondly*, input-output approaches to lifestyle analysis deal with issues of technology and lifestyle within one comprehensive modelling framework.

*Thirdly*, by taking a *consumer emission approach* the full global impact of German households is taken into account regardless of where the emissions occur. This stands in sharp contrast to the emission accounts used in the Kyoto process, which include all greenhouse gases released from a country’s territory. The difference lies in the treatment of trade related emissions. The consumer emission approach includes the greenhouse gases embodied in imports, while the territorial approach factors export related emissions to a country’s national GHG emission account.<sup>2</sup> The difference between the two is represented in the physical trade balance (see Munksgaard and Pedersen,

---

<sup>1</sup> Note that some of the studies could be assigned to two categories. However, for brevity they are only listed once here in the category, which is perceived of prime interest.

<sup>2</sup> For completeness it should be mentioned that some authors have also proposed mixed or hybrid responsibility approaches (Ferng, 2003; Gallego and Lenzen, 2005, Lenzen et al., 2007).



2001). This is not only important to estimate the full global climate change impacts of consumption patterns, but also allows for the control of the problem of carbon leakage.

#### 4.2.2.2 Methodological Challenges

However, input-output based approaches to lifestyle analysis can also be criticised for at least three reasons: The *first* line of criticism is directed towards the purely expenditure based conceptualisation of a lifestyle. We will never be able to get a complete picture of people's lifestyles as long as we purely concentrate on what they spend rather than on what they do. Schipper et al. (1989) therefore emphasise the need for a re-definition of lifestyle in terms of activity patterns. On similar lines (Gershuny, 1987, p.55) argues that “[. . . ] if we are to understand the processes of structural change in ‘the economy’, we need to consider evidence about behaviour outside it: we need to know more about the everyday life.” Because monetary data is largely restricted to the market sphere and is unable to comprehensively cover non-market activities, authors have proposed to complement monetary and physical with time use data. We have provided a comprehensive outline of the value of time-use data for the inclusion of social and behavioural issues in sustainability research elsewhere (Minx and Baiocchi, 2007; see Chapter 5 of this thesis).

As a result, also in the input-output literature, people have started to introduce time-use data. Inspired by some Danish research on the relationship between time and consumption (Brodersen, 1990), J alas (2002, 2005) was the first to link expenditure and time-use data and analyse energy and resource use in an environmental input-output based lifestyle model. More recently, Kondo (2006) and Minx and Baiocchi (2007) have further added to the literature on similar lines. Stahmer (2004) and later Schaffer and Stahmer (2005) have gone one step further and developed a set of socio-economic input-output tables in monetary, physical and time units mapping not industrial sectors, but socio-economic groups against each other. Their approach, which directly feeds into the discussion of sustainable consumption and life-work balances, allows the attaining of a much more complete overview of what people do inside and outside the market, how they consume within their activity patterns and what GHG emissions are triggered.

The *second* line of criticism is directed towards the way of estimating the GHG emissions embodied in imports in consumer emission accounts. Because of limited data availability and work intensity of the task, applied input-output models usually impute

imports purely based on data for the (one) region under investigation assuming that the structure of the economy and the sectoral GHG intensities are the same ‘abroad’ and ‘at home’. A more appropriate way of dealing with the issue therefore is to base estimations on a multi-regional input-output model as done for example by Lenzen et al. (2004) or Peters and Hertwich (2006). A state-of-the-art review can be found in Wiedmann et al. (2007). The issue is dealt with comprehensively in Appendices C and D of this thesis (Munksgaard et al., 2005; Munksgaard et al., 2007).

A final line of criticism can be directed towards the lack of exploitation of the social information hidden in the input-output data. While it is interesting to see how groups with different socio-economic characteristics compare in terms of their energy use and climate change impacts, it can be argued that it is important to go one step further and develop an understanding of how individual characteristics relate to environmental impacts. Does education have a positive or a negative impact on energy use and GHG emissions? How does ‘sharing’ change people’s behaviour in the use of fossil fuels? What other characteristics have a significant influence on GHG emissions arising from household consumption directly and indirectly?

These are all questions that have been heavily discussed in various strands of the environmental literature. In the literature on green product service systems ‘sharing’, for example, is seen as a key factor for reducing resource consumption and the resulting environmental impacts (Weizsäcker et al., 1995; Hawken et al., 1999). At the same time there is an extensive discussion surrounding common property resources, where ‘sharing’ in terms of joint/communal ownership and access/use leads to a mis- or overuse of resources (Hardin, 1968). The same argument can be applied to any shared property. Even though shared goods might be better seen as ‘club goods’ for which we pay a certain (weekly, monthly, yearly, one-off) fee to get access, similar problems in their careful use occur.

Also the environmental merits of education have been discussed. The green consumerism literature often argues that a higher education level is likely to be associated with greener environmental choices due to the complexity of the issue. “If one seeks to become an effective green consumer, [...] a great amount of learning must be undertaken” (Pettit & Sheppard, 1992, p.340). However, higher education levels are also often associated with a higher income as often assumed in the economic literature. The positive environmental implications of greener choices might therefore be eaten up by the higher levels of consumption.

Some authors (e.g. Vringer and Blok; Lenzen et al., 2006) have therefore further analysed the results from environmental input-output models in regression models. However, so far no study could be found, which applies a full-fledged panel regression approach.

### 4.3 INPUT-OUTPUT METHODOLOGY AND DATA

#### 4.3.1 Estimating the energy demands and climate change impacts of lifestyle cohorts

Let  $Z_d$  denote an  $n \times n$  matrix of domestically produced intermediate deliveries of the  $i^{th}$  to  $j^{th}$  industrial sector ( $i, j = 1, 2, \dots, n$ ), and  $Y_d$  denote a  $n \times m$  matrix of domestic final deliveries of the  $i^{th}$  industrial sector to the  $k^{th}$  final demand category ( $k = 1, 2, \dots, m$ ). Total domestic output  $x_d$  of the  $i^{th}$  industrial sector can be defined as the sum of its intermediate and final deliveries, that is

$$x_d = Z_d \mathbf{1} + Y_d \mathbf{1} \quad (4.1)$$

where the  $\mathbf{1}$ 's represent unit vectors conformable for matrix multiplication. A  $n \times n$  matrix  $A_d$  of domestic technological coefficients can be estimated by post-multiplying  $Z_d$  with the inverse of the diagonalised total domestic output vector  $x_d$ .

$$A_d = Z_d \hat{x}_d^{-1} \quad (4.2)$$

where the hat symbol “ $\hat{\phantom{x}}$ ” indicates diagonalisation. Using Equation (4.2), Equation (4.1) can be re-written:

$$x_d = A_d x_d + y_d \quad (4.3)$$

where  $y_d = Y_d \mathbf{1}$  is the  $n \times 1$  total final demand vector. Solving Equation (4.3) for  $x_d$  provides the basic Leontief (quantity) model:

$$\mathbf{x}_d = (\mathbf{I} - \mathbf{A}_d)^{-1} \mathbf{y}_d \quad (4.4)$$

The standard input-output assumptions apply (see Miller and Blair, 1985). Further, consider a  $1 \times n$  vector  $w$  of total energy use in the  $i^{\text{th}}$  industrial sector (for  $i=1,2,\dots,n$ ). A  $1 \times n$  vector of energy intensities can then be estimated by post-multiplying  $w$  with the inverted diagonal of the total domestic output vector  $\mathbf{x}_d$ :

$$\mathbf{e}^{ind} = \mathbf{w} \hat{\mathbf{x}}_d^{-1} \quad (4.5)$$

Employing an  $1 \times n$  vector  $f^{ind}$  of GHG emissions coefficients released per unit of total energy use in the  $i^{\text{th}}$  industrial sector, the basic Leontief model of Equation (4.4) can be generalised (see Leontief, 1972; Miller and Blair, 1985) for the estimation of energy use and associated GHG triggered by the various final demands:

$$P^{prod} = (\mathbf{f}^{ind} \# \mathbf{e}^{ind}) (\mathbf{I} - \mathbf{A}_d)^{-1} \mathbf{y}_d + (\mathbf{f}^{hh} \# \mathbf{e}^{hh}) \mathbf{y}^{hh} \quad (4.6)$$

where  $\#$  indicates element-by-element multiplication;  $\mathbf{y}^{hh}$  is a  $n \times 1$  vector of household final demand (for  $i=1,2,\dots,n$ );  $\mathbf{e}^{hh}$  is a  $n \times 1$  vector of energy intensities per unit of final household demand in the  $i^{\text{th}}$  industrial sector (for  $i=1,2,\dots,n$ );  $f^{hh}$  is a  $n \times 1$  vector of GHG emissions per unit of direct household energy use in the  $i^{\text{th}}$  industrial sector (for  $i=1,2,\dots,n$ ). The first term on the right-hand-side of Equation (4.6) estimates the indirect  $\text{CO}_2$  emissions triggered by final demands in the course of the production of non-energy goods and services, while the second term gives the direct  $\text{CO}_2$  emissions from household purchases of energy goods and services.<sup>3</sup>

A hybrid specification of Equation (4.6) with a production structure  $(\mathbf{I} - \mathbf{A}_d)^{-1}$  in mixed monetary and energy units would have been preferable (see Bullard and Herendeen, 1974; Proops, 1977; Beutel and Stahmer, 1982), but could not be implemented due to data shortages. However, on-going talks with the Federal Statistical Office and the German Environment Agency raise hopes that results from a hybrid model can be included in the final version of this PhD thesis. However, tests with available energy data show that it would only lead to minor changes in the results.

<sup>3</sup> Note that GHG emissions from purchases of electricity are not included as they are released higher up in the supply chain. Therefore, they are part of the indirect emissions.

The GHG account estimated from Equation (4.6) follows the territorial or producer responsibility concept as applied in the Kyoto process (see Munksgaard and Pedersen, 2001; Munksgaard et al., 2007: Appendix C of this thesis). However, to estimate the full climate change impacts of lifestyles in Germany the dual consumer responsibility needs to be applied. The embodied GHG emissions are estimated from a competitive, single region model assuming that the production structure, energy efficiencies and GHG intensities are the same abroad and at home. This brave assumption is taken here to simplify the already very data intensive analysis undertaken here. The issue of trade related emissions is dealt with comprehensively in Appendices C and D of this thesis (see, Munksgaard et al., 2005; Munksgaard et al., 2007). As Lenzen et al. (2004) suggest an under-estimation of import related CO<sub>2</sub> emissions by 30% associated with the use of a single instead of a multi-regional model in their study for Denmark, the results will be interpreted as lower-bound-estimates of the climate change impacts of German lifestyles.

Let  $A = Z\hat{x}_d^{-1}$  be a  $n \times n$  direct coefficient matrix representing the use of domestic and imported intermediate products from the  $i^{th}$  in the  $j^{th}$  industry per unit of domestic output of industry  $j$ ;  $Z_{imp}$  a  $n \times n$  matrix indicating the use of intermediate imports from the  $i^{th}$  industry used in the  $j^{th}$  industry, where  $Z = Z_d + Z_{imp}$ ;  $y = y_d + y_{imp}$  a  $n \times 1$  matrix of final demand for domestically produced ( $y_d$ ) and imported ( $y_{imp}$ ) products and services. We can then establish a complementary consumer emission account by

$$\begin{aligned}
 P^{cons} &= (f^{ind} \# e^{ind})(I - A)^{-1} y^{*ex} + (f^{hh} \# e^{hh}) y_d^{*ex} = \\
 &= (f^{ind} \# e^{ind})(I - A_d)^{-1} y_d^{*ex} + (f^{ind} \# e^{ind})[(I - A)^{-1} - (I - A_d)^{-1}] y_d^{*ex} + \\
 &+ (f^{ind} \# e^{ind})(I - A)^{-1} y_{imp}^{*ex} + (f^{hh} \# e^{hh}) y_d^{*ex}
 \end{aligned} \tag{4.7}$$

where the superscript “\*ex” indicates the exclusion of exports from final demand. The difference between a consumer and producer responsibility account has been termed as the physical or GHG trade balance (see Munksgaard and Pedersen, 2001; Sanchez-Choliz and Duarte, 2004) and can be written as

$$P^{trade} = P^{cons} - P^{prod} \tag{4.8}$$

Hence, if  $P^{cond} > P^{prod}$  then the production of a country's import cause more GHG emission than the production of its exports. In such a case the global GHG emissions associated with a country's lifestyle are larger than its territorial emissions: the country is a net importer of GHG emissions.

The GHG caused directly and indirectly by the consumption activities of 45 different household groups can be estimated by modifying Equation (4.7) marginally. Let us re-write the final demand matrix  $Y$  in partitioned form  $Y=[y^{hh}|Y^{hh}]$ , where  $y^{hh}$  denotes a  $n \times 1$  vector of household consumption of imported and domestic goods and services and  $Y^{hh}$  the remaining final demand matrix of size  $(n \times (m-1))$ . Let us further expand the final household demand vector  $y^{hh}$  to a  $n \times r$  matrix  $Y^{hh, fct}$  recording the expenditure of households from the  $i^{th}$  industrial sector (for  $i=1,2,\dots,n$ ) in the  $l^{th}$  functional spending category (for  $l=1,2,\dots,r$ ). Note that  $y^{hh} = Y^{hh, fct} \mathbf{1}$  must hold. The GHG emissions directly and indirectly associated with the final consumption in the  $r$  different functional spending categories can be estimated by:

$$p^{hh, fct} = (\mathbf{f}^{ind} \# \mathbf{e}^{ind})(\mathbf{I} - \mathbf{A})^{-1} Y^{hh, fct} + (\mathbf{f}^{hh} \# \mathbf{e}^{hh}) Y^{hh, fct} \quad (4.9)$$

In a next step the emissions associated with the consumption patterns of different socio-economic groups can be calculated. Let  $\bar{Y}^{hh, fct}$  denote the proportional household spending on final goods and services of the  $i^{th}$  industrial sector in the  $l^{th}$  functional spending category per unit of total spending in that category. Defining a  $s \times r$  matrix,  $Y^{soc}$ , measuring the total spending of the  $q^{th}$  socio-economic group (for  $q=1,2,\dots,s$ ) in the  $l^{th}$  spending category, we can estimate the direct and indirect emissions triggered directly and indirectly by the different groups:

$$p^{soc} = (\mathbf{f}^{ind} \# \mathbf{e}^{ind})(\mathbf{I} - \mathbf{A})^{-1} \bar{Y}^{hh, fct} Y^{soc} + (\mathbf{f}^{hh} \# \mathbf{e}^{hh}) \bar{Y}^{hh, fct} Y^{soc} \quad (4.10)$$

Note that relationship  $\mathbf{1} Y^{hh, fct} = \mathbf{1} Y^{soc}$  must hold.

### 4.3.2 Structural Decomposition Analysis: Identifying driving forces behind changes in GHG emissions

Structural decomposition analysis aims to disentangle changes in a dependent variable into a set of independent variables. Due to this ability to separate the forces at play simultaneously in an input-output model, the technique has been very popular in the literature (for reviews see Rose and Casler, 1996; Hoekstra and Van Den Bergh, 2002). Usually changes in the dependent variable are observed over time (e.g. Chang and Lin, 1998; Llop, 2007), but they may also be derived from comparisons of economic systems across spatial entities – usually countries (e.g. Alcantara and Duarte, 2004; Nooij, M. et al., 2006).

The energy-economic literature has focussed on the decomposition of changes in energy use or a set of related air pollutants. Most studies have decomposed overall changes and only very few authors have provided a more detailed decomposition of final household demand (e.g. Munksgaard and Pedersen, 2000). Various structural decomposition models of changes in CO<sub>2</sub> emissions for Germany have recently been proposed by Seibel (2003). To our knowledge this is the first study, which identifies the driving forces behind the differences in household consumption patterns across socio-economic groups.

Methodologically, the models applied by the various authors in the literature differ in terms of the specification of the underlying input-output model, the general decomposition method applied and the number and type of determinants (independent variables) distinguished. Very recently, Dietzenbacher and Stage (2006) have shown that structural decomposition techniques fail to provide reliable results when input-output models based on production structures in mixed units are used, as frequently done in the energy-economic literature (e.g. Gowdy and Miller, 1987; Lin and Polenske, 1995; Mukhopadhyay and Forssell, 2005). Instead, inferior energy coefficient models need to be applied, as in the current paper, to avoid “mixing oil and water” (Dietzenbacher and Stage, 2006).

The decomposition technique employed here has been proposed by Betts (1989) and been applied, for example, in the energy-economic context by Munksgaard et al. (2000). It is *exact* in that it does not need to introduce a residual term, *general* in that it can be applied to any matrix product of  $n$  variables, and *non-arbitrary* in that it provides

one solution to the base year by averaging calculations with both time periods included as base year respectively.<sup>4</sup>

Formally, the decomposition problems can be described as one of decomposing changes in a matrix product of  $n$  variables. Let  $\Phi_\delta$  be a series of  $\omega$  matrices (for  $\delta=1,2,\dots,\omega$ ), which are conformable for matrix multiplication, and  $\Omega$  be a result matrix, which is related to matrices  $\Phi_\delta$  in the following way:

$$\Omega = \prod_1^\omega \Phi_\delta \quad (4.11)$$

A change in  $\Omega$  over two time indicated by superscripts 1 and 0 (with 1 being the more recent time period) can then be decomposed into the changes in the  $\omega$  variables  $\Phi_\delta$  in the following way:

$$\Delta(\Omega^1 - \Omega^0) = 0.5 \sum_{\lambda=1}^{\omega} \left[ \prod_{\kappa < \lambda} \Phi_\kappa^0 (\Phi_\lambda^1 - \Phi_\lambda^0) \prod_{\mu > \lambda} \Phi_\mu^1 \right] + 0.5 \sum_{\lambda=1}^{\omega} \left[ \prod_{\kappa < \lambda} \Phi_\kappa^1 (\Phi_\lambda^1 - \Phi_\lambda^0) \prod_{\mu > \lambda} \Phi_\mu^0 \right] \quad (4.12)$$

Equation (4.12) represents the general decomposition model applied here. We frame our decomposition of change in GHG emissions associated with household consumption patterns of socio-economic groups in the context of the IPAT relationship, as proposed by Ehrlich and Holdren (1971) and Commoner (1972), which discusses environmental impacts (I) in the light of population (P), affluence (A) and technology (T). Hertwich and Katzmayer (2004) have operationalised the relationship in an input-output context, while Guan et al. (2008) have demonstrated the value of structural decomposition analysis for quantifying the influence of these three determinants (each broken down into several components) of environmental impacts over time in an empirical application to China.

To limit the scope in the context of the current paper, we focus on the decomposition of the indirect GHG emissions of these different lifestyles across socio-

---

<sup>4</sup> This is where Betts (1989) argument has one weakness as this does not resolve the base year problem, but just provides one, arbitrary solution. In fact, we believe that the problem of the choice of the base year cannot be resolved without arbitrariness, even though more elegant solutions might be available (see Rormose and Olsen, 2005). However, using the average as proposed by Betts seems to provide the most reasonable and justifiable empirical solution to the problem.



demographic strata, which make the largest emission share and are most complex due to the involvement of the full global supply chain. For our following decomposition efforts we might, therefore, rewrite the indirect emission part of Equation (4.10) as:

$$p^{soc,ind} = (f^{ind} \# e^{ind})(I - A)^{-1} \bar{Y}^{hh, fct} \bar{Y}^{hh, soc} \hat{y}^{hh, soc, cap} y^{hh, tot, cap} \bar{d}^{soc} d^{tot} \quad (4.13)$$

where  $\bar{Y}^{hh, soc}$  is the  $s \times r$  matrix indicating the proportional spending of the  $s$  socio-economic groups in the  $r$  different functional spending categories;  $\hat{y}^{hh, soc, cap}$  is the diagonalised  $s \times s$  vector of per capita spending of the  $s$  socio-economic groups across all  $r$  functional spending categories relative to the average per capita spending of the whole population;  $y^{hh, tot, cap}$  is a scalar of the average per capita spending of the population;  $\bar{d}^{soc}$  is the  $s \times 1$  vector of population shares of the  $s$  different socio-economic groups and  $d^{tot}$  is a scalar indicating the size of the population. In the context of IPAT, the  $f, e$  and  $(I - A)^{-1}$  variables would represent the technological component  $T$ , the various final demand variables  $\bar{Y}^{hh, fct}$ ,  $\bar{Y}^{hh, soc}$ ,  $\bar{y}^{hh, soc, cap}$  and  $y^{hh, tot, cap}$  the affluence component and the demographic variables  $\bar{d}^{soc}$  and  $d^{tot}$  the population component. To our knowledge, inclusion of the demographic structure in a decomposition analysis has not been done before.

Combining Equations (4.13) and (4.12), we can decompose changes in greenhouse gas emissions over time induced by the production of non-energy goods consumed in Germany into nine components:

- $\Delta f$  is the effect of changes in the  $n$  sectoral GHG emission coefficients;
- $\Delta e$  is the effect of changes in the average energy intensity of economic activities in the  $n$  different production sectors;
- $\Delta(I - A)^{-1}$  is the effect of changes in the input structure of the  $n$  different production sectors;
- $\Delta \bar{Y}^{hh, fct}$  is the effect of changes in the composition of final demand in the  $r$  different functional (COICOP) spending categories;
- $\Delta \bar{Y}^{hh, soc}$  is the effect of changes in the composition of the consumption baskets of the  $s$  different socio-economic groups;

- $\Delta \bar{y}^{hh,soc,cap}$  is the effect of a change in per capita final demand of the  $s$  socio-economic groups relative to average per capita final household demand.
- $\Delta y^{hh,tot,cap}$  is the effect of changes in per capita final household demand;
- $\Delta \bar{d}^{soc}$  is the effect of shifts in the population structure across the  $s$  different socio-economic groups;
- $\Delta d^{tot}$  is the effect of changes in the size of the German population.

Based on Equation (4.12) we can, for example, isolate the effect of changes in the composition of the population structure:

$$\begin{aligned} \Delta \bar{p}^{soc} = & (0.5(\mathbf{f}_0 \# \mathbf{e}_0)(\mathbf{I} - \mathbf{A}_0)^{-1} \bar{\mathbf{Y}}_0^{hh, fct} \bar{\mathbf{Y}}_0^{hh, soc} \bar{\mathbf{y}}_0^{hh, soc, cap} \mathbf{y}_0^{hh, tot, cap} (\bar{\mathbf{d}}_1^{soc} - \bar{\mathbf{d}}_0^{soc}) d_1^{tot}) + \\ & + (0.5(\mathbf{f}_1 \# \mathbf{e}_1)(\mathbf{I} - \mathbf{A}_1)^{-1} \bar{\mathbf{Y}}_1^{hh, fct} \bar{\mathbf{Y}}_1^{hh, soc} \bar{\mathbf{y}}_1^{hh, soc, cap} \mathbf{y}_1^{hh, tot, cap} (\bar{\mathbf{d}}_1^{soc} - \bar{\mathbf{d}}_0^{soc}) d_0^{tot}) \end{aligned} \quad (4.14)$$

Decomposing the other eight variables in the same way, the total change in the indirect GHG emissions from household consumption can be represented as:

$$\begin{aligned} \Delta \mathbf{P}^{hh, ind} = & \Delta \mathbf{f} + \Delta \mathbf{e} + \Delta (\mathbf{I} - \mathbf{A})^{-1} + \Delta \bar{\mathbf{Y}}^{hh, fct} + \Delta \bar{\mathbf{Y}}^{hh, soc} + \Delta \bar{\mathbf{y}}^{hh, soc, cap} + \\ & + \Delta \mathbf{y}^{hh, tot, cap} + \Delta \bar{\mathbf{d}}^{soc} + \Delta \mathbf{d}^{tot} \end{aligned} \quad (4.15)$$

### 4.3.3 DATA DESCRIPTION

Estimating the energy demands and greenhouse gas impacts associated with different lifestyles in Germany between 1991 and 2002 involves a large amount of data as well as a large number of computations. Germany has a very comprehensive economic and environmental account database. Recent efforts to build-up a socio-economic reporting system (Stahmer, 2004b) have added large number of social statistics. Usually this information needs to be pulled together from a variety of different sources such as population statistics, census data or private household accounts and are usually not directly linked to the standard macro-economic aggregates. In the socio-economic reporting systems all this information is integrated consistently and they provide an ideal and unique data platform for the estimations intended in this paper.

The input-output calculations are based on the standard input-output tables published by the Federal Statistical Office of Germany. For the years 1991-2000 a consistent set of input-output tables at constant 1995 prices (Federal Statistical Office of Germany, 2002) is available. It is based on the accounting concepts and definitions applied at the Federal Statistical Office of Germany before the revision of the national accounts in 2005. For the subsequent years 2001 (Federal Statistical Office of Germany, 2006b) and 2002 (Federal Statistical Office of Germany, 2006c) only input-output tables in current prices based on the new accounting definitions after the revision are available. Based on sectoral price indices the tables were deflated and converted to constant 1995 prices (see Proops et al., 1992).

The final household demand vector of outputs of the 71 production branches was expanded to distinguish 16 functional consumption categories (see Table 4.2) as classified by COICOP using a consistent set of consumption integration tables from 1991-2002 (Federal Statistical Office, 2005a). However, these tables are recorded at purchasers prices, while the input-output data is provided at basic prices. Based on two consumption integration tables for the years 1995 and 1997 at basic prices (courteously provided by the Federal Statistical Office of Germany) and available information on the ratio between basic and purchasers prices for each year, the tables were converted into basic prices.

Information about the purchasing behaviour of different households from 1991-2002 (see Table 4.3) was obtained from a special publication on socio-economic development in Germany containing data on employment, income, education, demographics and consumption (see Federal Statistical Office of Germany, 2005b) These data were published in an effort by the Statistical Office to establish a more comprehensive socio-economic reporting system in Germany (Stahmer, 2004), and is fully consistent with the national account data. The data distinguishes 9 different household groups of which the expenditure of group 9 “unemployed households with non-public money sources” was obtained residually from the data. Each household group is further broken down according to 5 different household sizes. Ultimately, information about household consumption expenditure patterns of 45 socio-economic groups over the period 1991-2002 could be obtained.

Abbreviation	COICOP Code	Description
Food	01	Food and non-acholic drink
Alcohol	02	Alcoholic Drink
Clothing	03	Clothing and Footwear
Housing	041-044	Housing and Water Supply
Energy	045	Electricity, Gas and other Fuels
Furniture	05	Furnishings, household equipment and routine household maintenance
Health	06	Health
PrivTrans	071-072	Purchase and Operation of Personal Transport Equipment
TransServ	073	Transport Services
Communication	08	Communication
DurGoods	091-093	Major Durables and other items and equipment for recreation and culture
RecServPack	094,096	Recreational and cultural services and package holidays
Books	095	Newspapers, Books and Stationary
Education	10	Education
Restaurants	11	Restaurants and Hotels
Misc	12	Miscellaneous Goods and Services

Table 4.2 - Household Consumption Categories Distinguished In Study

Finally, emission-relevant energy data and corresponding GHG intensities were taken from the annual environmental accounts publication covering data for the whole time period (Federal Statistical Office of Germany 2006d). However, these data only contain information on total direct energy use of households. Therefore, they were split into direct energy use from transport activities and housing using special reports published by the Federal Statistical (2004b; 2006e). Direct emissions from housing and transport were further assigned to the different socio-economic household types, proportional to their spending on “electricity, gas and other fuels” and “purchase and operation of personal transport equipment”. The latter seems to be rather restrictive due to the mixing of energy (fuels) and non-energy goods (vehicles) in this category. Therefore, we heroically assume that buying a more expensive car also means that it is less fuel efficient in the absence of better data for this breakdown. As a consequence we suggest that direct GHG emissions from car travel for high income groups might be best seen as higher-bound emission estimates, while they might be under-estimated for low income groups.

No.	Household Groups	Household Sizes
1	Self-employed households	A 1 person household
2	Public Servants	B 2 person household
3	Other Employed Households	C 3 person household
4	Blue Collar Workers	D 4 person household
5	Unemployed households, who recently lost their jobs, job seekers	E 5 and more person household
6	Pensioners	
7	Retired Public Servants	
8	Households receiving (social) benefits	
9	Other unemployed households: income from non-public money sources	

Table 4.3 – Households Groups and Household Sizes Distinguished in this Study

## 4.4 RESULTS AND POLICY IMPLICATIONS

### 4.4.1 On the climate change impacts of household consumption

Table 4.4 highlights our previous assertion in Section 4.1 that households are by far the largest emitters of greenhouse gases among domestic final demand entities and have continued to increase in relative importance since 1991. In Table 4.5 the direct and indirect emissions from household consumption are further broken down according to 16 functional consumption categories. Results confirm the general finding in the literature (see Tukker et al., 2006) that Transport, Housing and Food are the three household consumption categories of major concern in the climate change context being responsible for more than 75% of all greenhouse gas emissions from household consumption.<sup>5</sup> Policy measures need to focus on these three larger areas to make progress on tackling climate change.

Between 1991 and 2002 the greenhouse gas emissions from household consumption decreased by 119 Mt from 887 Mt to 768 Mt of CO<sub>2</sub>E. These reductions were achieved throughout all 16 different consumption categories. The only exception is “communication”; the category with the second smallest climate change impacts, where emissions rose from 2.7Mt to 4.8Mt.

Most of household direct and indirect GHG emissions were associated with the use of energy. In 1991 312Mt of CO<sub>2</sub>E were associated with these energy services. This could only be reduced by 5% or 15.6 Mt until 2002 regardless of the introduction of a

<sup>5</sup> However, note that all household energy demands are lumped together into the category “Electricity, Gas and Other Fuels” instead of assigning, for example, the electricity required to fuel domestic appliances to the respective consumption purpose making a comparison of different consumption activities more complex.

green tax by the German Government in 1998. Increases in overall emissions from household consumption between 2000 and 2001 from 753Mt to 789Mt can be fully explained by increased energy use triggering an additional 47Mt GHG emissions due to a particularly severe winter. The largest reductions in GHG emissions between 1991 and 2002 could be achieved in “transport” and “food” amounting to 28Mt (17.4%) and 22Mt (14.6%) respectively.

Table 4.6 shows the development of “consumption efficiencies” over time: the GHG emissions triggered directly and indirectly per Euro spent in a particular COICOP category. As with the total amount of GHG there is a general trend towards greater efficiency in final household consumption processes throughout the various functional spending categories. “Electricity, gas and other fuels” show by far the highest GHG impacts per Euro spent, ranging between 10.99 kg/Euro and 8.33 kg/Euro. This high impact is explained by the nature of the consumption items summarised in this spending category as energy goods and services on the one hand, and the high level of homogeneity in the definition of the category, on the other hand.

	Year															Change e (%)	Change e
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002					
Household Consumption – direct	228.8	222.5	234.3	224.4	226.8	241.3	238	231.3	218.8	209.7	221.7	208.5	-20.3	-8.9			
Household Consumption – indirect	658.4	638.6	623.3	600.2	590.3	591.5	564.7	567.5	563.6	543.3	567.4	559.5	-98.9	-15			
Non-Profit Institutions Serving Households	6.9	6.7	6.6	6.5	6.8	7.2	6.8	6.7	7	6.9	6.5	6.3	-0.6	-8.7			
Government Consumption	120.2	119.9	111.8	110	108.8	113.5	100.9	92	89.6	88.3	85.7	83.9	-36.3	-30.2			
Gross Fixed Capital Formation & Other FD	203.4	184.7	171.6	179.3	182.0	168.6	167.6	168.9	159.7	174.6	139.3	117.0	-86.4	-42.5			
Exports	375.4	353.1	320.4	338.9	349	357.7	387.2	387	403.4	431.7	423.4	442.5	67.1	17.9			
Total	1593.1	1525.5	1468	1459.3	1463.6	1479.8	1465.2	1453.4	1442.1	1454.6	1444	1417.8	-175.3	-11			
of that: imports	415	397	356.8	366.8	379.3	375.6	400.2	415.4	440.3	454.7	433.8	421.1	6.1	1.5			
Producer Responsibility	1178.1	1128.5	1111.2	1092.5	1084.3	1104.2	1065	1038	1001.8	999.9	1010.2	996.7	-181.4	-15.4			
Consumer Responsibility	1217.6	1172.3	1147.6	1120.4	1114.6	1122.1	1078	1066.4	1038.7	1022.8	1020.6	975.3	-242.3	-19.9			
Trade Balance	39.5	43.9	36.4	27.9	30.3	17.9	13	28.4	36.9	22.9	10.4	-21.4	-60.9	-154.2			

Table 4.4 – Development of Greenhouse Gas Emissions 1991-2002 by Final Demand Category (in million tonnes)

COICOP Code	Group Name	Year												Change (abs)	Change (%)
		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002		
1	Food	150.3	145.2	140.8	134.3	134.5	131.3	125.7	128.6	130.6	131.1	127.9	128.4	-21.9	-14.6
2	Alcohol	15.4	14.8	14.4	13.8	14.6	14.1	13.7	13.5	14.1	14.2	13.5	13.7	-1.7	-10.7
3	Clothing	29.7	28.4	27.7	26.8	26	25.8	24.3	23.6	25.6	23.7	23.1	22	-7.7	-26
041-044	Housing	36.2	36	36.8	35.3	34.4	33.6	31.4	30.3	29.6	29.8	27.9	26.3	-9.9	-27.3
45	Energy	312	302.9	309.2	300.4	297.8	319.3	309.9	304.8	276.7	260.6	307.6	296.5	-15.6	-5
5	Furniture	36.7	35.2	33.9	32.5	31.3	30.4	28.7	28	28.7	28.9	27.4	26.5	-10.2	-27.8
6	Health	13.6	13.8	14.3	14.4	14.5	14.7	12.4	9.8	9.6	9.6	13.4	13.6	0	0
071-072	PrivTrans	159.1	153.3	153	144.4	145.3	146.4	146.3	151	154.2	140.1	135.8	131.4	-27.7	-17.4
73	TransServ	17	18	17.4	17.8	17.7	17.5	15.8	15	15.8	15.6	13.4	13.5	-3.6	-20.9
8	Communication	2.7	2.7	2.8	2.8	2.9	2.8	2.7	2.9	3.5	4.2	5	4.8	2.1	76.5
091-093	DurGoods	28.2	26.5	25.4	24.5	24.7	24	23.5	23.2	23.6	24	24.9	25.1	-3.1	-11.1
94,096	RecServPack	11.7	11.8	11.3	11.3	11	11.2	10.3	10.7	11.7	11.6	11.5	11.4	-0.3	-3
95	Books	7.3	6.8	6.5	6.2	6	6	5.8	5.8	6.1	6.1	5.7	5.7	-1.6	-21.8
10	Education	1.9	1.9	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.5	1.5	-0.4	-23.3
11	Restaurants	34.6	34.6	34.3	31.5	28.9	28.1	26	25.5	25.6	25.4	24.5	22.7	-11.9	-34.4
12	Misc	30.5	29.2	28.1	27	26	25.9	24.7	24.6	25.5	26.6	26	25	-5.5	-18.1
	Total	887.2	861.1	857.6	824.6	817.1	832.8	802.7	798.8	782.5	753.1	789.1	768	-119.1	-13.4

Table 4.5 – Development of Greenhouse Gas Emissions by Functional Final Consumption Category (in million tonnes)



COICOP Code	Group Name	Year												Change (abs)
		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	
1	Food	1.34	1.28	1.23	1.19	1.17	1.14	1.09	1.10	1.09	1.07	0.99	0.99	-25.96
2	Alcohol	0.77	0.72	0.71	0.69	0.71	0.69	0.67	0.66	0.65	0.65	0.60	0.59	-22.97
3	Clothing	0.50	0.47	0.45	0.45	0.43	0.44	0.41	0.40	0.42	0.38	0.37	0.36	-27.77
041-044	Housing	0.22	0.21	0.21	0.20	0.18	0.18	0.16	0.15	0.14	0.14	0.13	0.12	-44.98
45	Energy	10.99	10.45	10.28	10.09	9.61	9.34	9.07	8.68	8.33	8.57	9.09	8.86	-19.38
5	Furniture	0.57	0.53	0.52	0.50	0.48	0.47	0.45	0.43	0.43	0.42	0.38	0.37	-35.07
6	Health	0.47	0.45	0.43	0.42	0.39	0.40	0.34	0.28	0.26	0.25	0.26	0.25	-46.85
071-072	PrivTrans	1.64	1.58	1.78	1.68	1.65	1.63	1.59	1.55	1.54	1.49	1.39	1.34	-17.87
73	TransServ	0.81	0.82	0.83	0.81	0.77	0.76	0.72	0.70	0.70	0.68	0.71	0.70	-13.74
8	Communication	0.17	0.16	0.15	0.15	0.15	0.14	0.13	0.13	0.13	0.14	0.14	0.13	-25.53
091-093	DurGoods	0.89	0.82	0.79	0.78	0.78	0.75	0.73	0.70	0.69	0.68	0.63	0.65	-26.11
94,096	RecServPack	0.38	0.37	0.35	0.35	0.34	0.34	0.32	0.32	0.32	0.31	0.29	0.29	-24.81
95	Books	0.40	0.36	0.34	0.34	0.32	0.32	0.30	0.30	0.31	0.30	0.29	0.29	-27.68
10	Education	0.28	0.25	0.25	0.23	0.23	0.23	0.21	0.21	0.21	0.21	0.20	0.19	-32.15
11	Restaurants	0.70	0.69	0.71	0.65	0.60	0.61	0.56	0.56	0.55	0.55	0.44	0.41	-40.64
12	Misc	0.39	0.37	0.35	0.33	0.32	0.32	0.30	0.29	0.29	0.29	0.21	0.20	-49.80
	<b>Total</b>	<b>1.07</b>	<b>1.01</b>	<b>1.01</b>	<b>0.97</b>	<b>0.94</b>	<b>0.95</b>	<b>0.91</b>	<b>0.89</b>	<b>0.85</b>	<b>0.80</b>	<b>0.77</b>	<b>0.74</b>	<b>-30.64</b>

Table 4.6 - Development of Greenhouse Gas Emissions per € spent on Final Consumption by Functional Category (in kg/€)

This homogeneity, for example, is not safeguarded for “purchase and operation of personal transport equipment”, where energy goods and services are mixed together with the purchase of high-expenditure non-energy goods such as cars, motorbikes or camping trailers. Therefore, it is not surprising that its impact ranges only between 1 kg CO<sub>2</sub>E/Euro and 2 kg CO<sub>2</sub>E/Euro, being only slightly less efficient in terms of the release of GHGs than the purchase of one unit of food. In fact, detailed results distinguishing between 41 and 106 COICOP categories show that once the purchase and operation of vehicles are separated, the impacts per Euro spent on the operation of transport equipment rises to between 4 and 5 kg/Euro. While the large amount of GHG emissions triggered by household demand for “travel” and “housing” are mainly caused by a small expenditure share on energy goods, GHG emissions from food are also driven by the high expenditure levels in this category. This corresponds with findings of previous studies obtained from UK data (see Minx, 2002; Baiocchi et al., 2006; Barrett et al., 2008).

However, not all members of society consume in the same way. They have different wants, desires and aspirations, have different monetary (income) and non-monetary (skills, time) resources at their disposal and are interested in engaging in different activities in their leisure time. All these factors contribute to their distinct lifestyles and manifest in very different demands for the various groups of consumption items shown in Tables 4.5 and 4.6. Table 4.7 shows the climate change impacts of the (average) consumption baskets of households grouped into 9 socio-economic cohorts. In later analysis these are further distinguished according to five household sizes.

The climate change impacts triggered by the consumption patterns of all socio-economic groups decreased between 1991 and 2002. In absolute terms most GHG emissions were related to the direct and indirect energy use of group 3 “other employed households” (225Mt CO<sub>2</sub>E), followed by household group 6 “pensioners” (203.1 Mt CO<sub>2</sub>E) and group 4 “blue collar workers” (201.1 Mt CO<sub>2</sub>E) in 1991.

However, this picture had changed considerably by 2002. While the greenhouse gas emissions from “blue collar households” (group 4) reduced by 74.1 Mt CO<sub>2</sub>E, reductions of only 16.3 Mt CO<sub>2</sub>E were achieved by other employed households (group 3). At the same time, emissions from pensioners (group 6) almost stayed the same with a slight decrease of 5.8 Mt CO<sub>2</sub>E. However, relatively to the other household groups their emission share increased most from 22.9% to 25.7% of all emissions from household consumption. Only “blue collar workers” (group 4), “other employed households” (group 3) and “other unemployed household” (group 9) decreased their emission shares.

Looking at the per household and per capita figures highlights that the increasing emission share of “pensioner” households (group 6) is driven by the ageing demographic structure of the German population with an increasing number of “retired households”. In per capita terms, their emission reductions in GHGs are higher than the average in Germany: the 12.5 t CO<sub>2</sub>E/cap in 1991 were reduced by 21.5% to 9.8t CO<sub>2</sub>E/cap in 2002. Only “households receiving social benefits” (group 8) reduced their per capita emissions slightly more with 22.5% of their 1991 levels. In per capita and per household terms, “self-employed households” (group 1) emit by far the most greenhouse gases of the nine groups under consideration. This is not surprising as they are the wealthiest group with the highest disposable income and highest consumption expenditure levels. In 1991 their lifestyle was associated with direct and indirect emissions of 19.9t CO<sub>2</sub>E, which reduced by 15% to 16.9t in 2002. This is still 3 times more than the average receiver of public benefits emits.

However, such a descriptive analysis of the results from the input-output model as provided in this Section is very limited due to the complex interrelationships between production and consumption, the number of variables involved, as well as the large amount of information generated by the model. Therefore, without further processing the results it will be very difficult to confidently identify any social and economic driving forces behind the GHG emission patterns of these socio-economic groups confidently. The next Sections will therefore present two complementary ways of how this can be achieved by using structural decomposition and panel regression analysis.

Group Year	Household Group									
	1	2	3	4	5	6	7	8	9	Tot
<b>1991</b>										
tot	129.4	54	224.9	201.1	17.6	203.1	26.8	7.4	22.7	887.2
per hh	57.93	32.61	26.34	24.77	18.41	19.92	26.63	13.29	13.83	25.41
per cap	19.92	11.85	10.8	8.9	7.79	12.51	16.98	7.01	6.53	11.22
<b>1992</b>										
tot	120.3	52.7	217.5	189.6	21.2	201.8	25.7	8.5	23.9	861.1
per hh	52.72	31.48	25.76	24.17	18.48	19.37	25.32	13.38	12.54	24.35
per cap	18.35	11.46	10.62	8.65	7.81	12.14	16.09	7.06	5.95	10.8
<b>1993</b>										
tot	118.5	52.1	215.5	183	26.8	202.7	25.6	9.4	24	857.6
per hh	50.54	30.83	25.71	23.96	18.42	19.11	24.76	13.38	11.86	23.90
per cap	17.75	11.4	10.7	8.59	7.86	11.97	15.75	6.85	5.55	10.67
<b>1994</b>										
tot	118	49	206	168	28	201	25	9	22	825
per hh	48.59	29.24	24.28	22.48	17.06	18.36	23.64	12.98	11.37	22.74
per cap	17.3	10.9	10.17	8.11	7.39	11.48	15.08	6.39	5.36	10.23
<b>1995</b>										
tot	120	48	202	164	28	202	25	9	20	817
per hh	48.73	28.81	23.66	21.95	16.62	18.04	23.16	12.87	11.33	22.37
per cap	17.59	10.77	9.96	7.97	7.3	11.2	14.73	6.23	5.31	10.11
<b>1996</b>										
tot	123	48	203	163	32	209	26	10	19	833
per hh	49.45	29.14	23.81	22.15	17.07	18.51	23.88	12.86	10.96	22.66
per cap	18.05	10.98	10.06	8.08	7.54	11.47	15.15	6.2	5.01	10.27
<b>1997</b>										
tot	126	45	194	149	34	202	25	10	18	803
per hh	49.45	27.85	22.52	21.01	15.66	17.62	22.94	12.05	11.31	21.69
per cap	18.17	10.57	9.58	7.7	6.89	10.88	14.45	5.8	5.11	9.88
<b>1998</b>										
tot	127	43	195	145	33	201	25	10	19	799
per hh	49.52	27.46	22.38	20.84	15.29	17.22	22.33	11.82	12.73	21.51
per cap	18.24	10.55	9.55	7.65	6.74	10.61	14	5.72	5.69	9.83
<b>1999</b>										
tot	126	41	195	142	31	196	25	10	18	783
per hh	49.16	26.85	21.83	20.31	14.82	16.43	21.70	11.28	12.92	20.93
per cap	18.17	10.37	9.35	7.48	6.62	10.12	13.56	5.54	5.8	9.62
<b>2000</b>										
tot	118	38	190	138	28	192	24	9	16	753
per hh	45.46	25.82	20.99	19.65	14.18	15.74	21.14	10.44	11.38	19.98
per cap	16.89	10.02	9.06	7.25	6.38	9.71	13.15	5.21	5.14	9.24
<b>2001</b>										
tot	125	39	207	135	30	203	26	9	15	789
per hh	47.84	27.13	21.78	20.20	14.65	16.48	22.61	10.90	10.67	20.77
per cap	17.81	10.53	9.42	7.5	6.66	10.17	14.03	5.51	4.9	9.66
<b>2002</b>										
tot	118	38	203	127	33	197	26	9	17	768
per hh	45.47	26.49	21.18	19.73	14.10	15.92	22.12	10.68	11.96	20.11
per cap	16.92	10.35	9.18	7.35	6.39	9.82	13.74	5.43	5.51	9.38

Table 4.7 – Greenhouse Gas Emissions by Household Group (in Mt)

#### 4.4.2 Driving Forces Behind Structural Changes in GHG Emissions from household consumption between 1991 and 2002

In Table 4.8 some detailed results from the decomposition analysis are presented, highlighting the interplay between production, consumption and demography in determining the development of greenhouse gas emissions in the spirit of the IPAT formula. Overall, the indirect greenhouse gas emissions in Germany decreased between 1991 and 2002 by roughly 99Mt. Looking only at the net effects, technological factors reduced GHG emissions by 200Mt. This was partially off-set by increases in emissions from consumption/affluence (64 Mt) and changes in the demography/population (37Mt). Even though changes in consumption patterns (composition and size) remain the largest “counterforce” of technologically induced emission reductions, population drivers are also very sizable reinforcing the need to consider the development of GHG emissions in a larger socio-demographic context as highlighted by Schipper et al. (1989) and Schipper (1997) amongst others.

In the context of the population argument (e.g. Ehrlich, 1968) the results seem to send out two messages when discussed in the context of a matured economy such as Germany: *firstly*, due to the ageing demographic structure of Germany, the population question does not seem to be of the highest priority. With low fertility rates it is mainly the influx of immigrants increasing population size and therefore GHG emissions. The *second* implication is that it is too important to be neglected. In agreement with Schipper (1997), the evidence seems to support earlier claims that the consideration of demographic trends is important for a successful design of climate change policies. Therefore, they need to be integrated into quantitative models providing the evidence to support policy processes: in particular forecasting and scenario models dealing with longer time spans.

However, a closer look at the (nine) individual determinants shows that the issue is a little bit more complex. Only the two population variables are jointly positive: changes in the demographic structure (15.8Mt) and the total population size (21.2Mt) contributed almost equally to increases in GHG emissions between 1991 and 2002. Both, for technological (production) and affluence (consumption) variables the picture is more mixed. Among the technological variables, all reductions were brought about by improvements in the energy efficiency of production sectors. Changes in the fuel mix and the production structure had some minor off-setting effects. In particular, the latter result is surprising as it has been commonly suggested that in the early 90s GHG emissions were reduced through the contraction of the Eastern economy. In fact, this was one of the

reasons why more ambitious reduction targets were chosen for Germany (see Table 4.1). The data here suggest that, if the German re-union played an important role in the reductions of GHG emissions, it was mainly through easy-to-achieve energy efficiency improvements, which could be realised.

Among the 4 consumption/affluence variables the only factor driving-up GHG emissions was the increase in per capita spending between 1991 and 2002 (117Mt). However, changes in the other three variables did partially offset this considerable increase in GHG emissions. While changes in the composition of the functional household consumption categories did not have any major effect (-0.7Mt), the composition of the various consumption baskets of the socio-economic groups, as well as relative changes in their total final spending on household consumption, reduced GHG emissions by 34Mt and 18 Mt of GHG emissions respectively. Hence, household choices have become greener, but “not green enough” to compensate for the increases in per capita spending.

Reading across the columns of Table 4.8, the various factors contributing to changes in the indirect GHG emission of the different household types are revealed. The 7.7 Mt of GHG emitted more in 2002 compared with 1991 by “2 person pensioner households” (Type 6B) were mainly caused by increases from per capita spending (15 Mt) and shifts in the demographic structure towards this group (23Mt) off-setting the 27Mt reductions from energy efficiency improvements made in the production of the goods and services consumed by this household type. Similarly, the 12Mt reductions in indirect GHG emissions associated with the consumption patterns of “3 person blue collar worker households” (Type 4C) were achieved through demographic shifts away from this household type (12Mt) and improvements in the production of the goods consumed, which could not be fully eaten-up by the additional 6Mt of GHG emissions triggered through additional consumption of the group.

HH-type	ΔCO <sub>2</sub> Intensities	ΔEnergy Intensities	ΔProduction structure	ΔComposition functional spending categories	ΔComposition consumption baskets groups	Δrelative spending groups	Δtotal per capita spending	Δpopulation structure	Δpopulation level	Total
1A	-0.1	-3.5	0	0	-0.8	-0.6	2.1	4.2	0.4	1.6
2A	-0.1	-1.3	0	0	-0.2	0	0.7	0.3	0.1	-0.4
3A	0	-8.8	0	-0.1	-1.5	-1.9	5.2	6.5	0.9	0.2
4A	0.2	-4.2	0.1	0	-0.6	-1.4	2.4	-0.7	0.4	-3.9
5A	0	-1.3	0.1	0	-0.4	-0.3	0.8	3.5	0.1	2.5
6A	0.1	-17.2	0.9	0.2	-5.2	-1.5	9.7	3.2	1.7	-8
7A	-0.3	-2.4	0.1	0	-0.7	0.3	1.4	0	0.2	-1.3
8A	0	-0.7	0.1	0	-0.1	-0.2	0.4	0.5	0.1	0.1
9A	0	-1.2	0	0	-0.3	0.3	0.7	-0.4	0.1	-0.8
1B	0	-8.8	0.1	-0.1	-1.4	-0.7	5	5.6	0.9	0.7
2B	0	-3.1	0	0	-0.2	0.2	1.7	-1	0.3	-2.2
3B	0.5	-16.3	0.1	-0.3	-1.7	-1	9	4.5	1.6	-3.5
4B	0.8	-10.3	0.3	-0.1	-1.5	-2.2	5.4	-8.7	1	-15.3
5B	0.1	-2.2	0.1	0	-0.4	-0.4	1.3	5.2	0.2	3.9
6B	0.7	-27.1	1.2	0.1	-4.5	-3.6	15.3	23.1	2.6	7.7
7B	-0.3	-3.8	0	0.1	-0.9	0.5	2.1	3	0.4	1.2
8B	0	-0.7	0	0	-0.1	-0.2	0.4	1.1	0.1	0.6
9B	0.1	-1.3	0	0	0	0.6	0.7	-1.9	0.1	-1.6
1C	0.3	-7	0.1	-0.1	-1.1	0	3.8	-1.1	0.7	-4.4
2C	0.1	-2.8	0	0	-0.2	0.2	1.5	-3.1	0.3	-4.1
3C	0.8	-13.5	0.2	-0.1	-1.2	-0.3	7.2	-3	1.3	-8.6
4C	1	-11.4	0.4	-0.1	-1.7	-0.6	5.8	-11.8	1.1	-17.2
5C	0.1	-1.6	0.1	0	-0.2	-0.1	0.9	3.3	0.2	2.6
6C	0.3	-5.7	0.2	0	-0.8	-1.2	3.1	0.6	0.6	-2.9
7C	0	-0.7	0	0	-0.1	-0.1	0.4	-0.2	0.1	-0.6
8C	0	-0.6	0	0	0	-0.2	0.3	0.8	0.1	0.4
9C	0	-0.7	0	0	-0.2	-0.1	0.4	-0.4	0.1	-0.9
1D	0.4	-7.9	0.1	0	-1.4	-0.4	4.3	0.1	0.8	-4.1
2D	0.1	-3.3	0.1	0	-0.4	0.2	1.7	-2.9	0.3	-4.2
3D	0.8	-12.7	0.2	-0.1	-1.6	0.5	6.7	-1.9	1.2	-6.8
4D	1.1	-11.1	0.4	-0.1	-2	0.1	5.7	-9.4	1.1	-14.2
5D	0.1	-1.1	0	0	-0.4	-0.2	0.7	2	0.1	1.1
6D	0.1	-1.9	0.1	0	-0.3	-0.7	1	-0.6	0.2	-2.1
7D	0	0	0	0	0	0	0	0	0	0
8D	0	-0.4	0	0	-0.1	-0.1	0.2	0.4	0	0.1
9D	0	-0.6	0	0	0	-0.1	0.3	0	0.1	-0.3
1E	0.2	-4.3	0.1	0	-0.6	-0.1	2.3	-1.3	0.4	-3.3
2E	0	-1.2	0	0	-0.2	0	0.6	-1.1	0.1	-1.7
3E	0.3	-4	0.1	0	-0.4	-0.5	2.1	0.5	0.4	-1.6
4E	0.5	-5.1	0.2	0	-0.5	-0.9	2.6	-4.3	0.5	-6.9
5E	0	-0.7	0	0	0	-0.3	0.4	1.2	0.1	0.8
6E	0	0	0	0	0	0	0	0	0	0
7E	0	0	0	0	0	0	0	0	0	0
8E	0	0	0	0	0	0	0	0	0	0
9E	0.1	-1.2	0.1	0	-0.1	-0.9	0.7	-0.1	0.1	-1.3
tot	8.1	-213.6	5.6	-0.7	-34.3	-17.9	117	15.8	21.2	-98.8

Table 4.8 – Results Structural Decomposition Analysis – Indirect GHG emissions from household consumption (in Mt)

## 4.5 PANEL REGRESSION APPROACH

The decomposition analysis allows us to dis-entangle the complex interaction between various technological and lifestyle factors in the model. However, we can only control for variables as long as they can be directly linked into the multiplicative structure of the generalised input-output model. This cannot be done for many socio-demographic variables, even though they still might be important underlying determinants of changes in GHG emissions. In order to isolate the impact of individual socio-economic determinants a regression approach is required. In the next Section the construction of the regression variables is described before the model is outlined in Section 4.5.2. In Section 4.5.3 the results are briefly discussed.

### 4.5.1 Data Preparation

Table 4.9 summarises the different variables included in the panel regression analysis. GHG emission estimates derived from the input-output calculations as outlined in Section 4.3.1 are included as dependent variables of the regression.

Variables	Name	Description
dependent	GHG	Total (direct and indirect) greenhouse gas emissions by household types
	DGHGT	Direct greenhouse gas emissions from transport by household types
	DGHGH	Direct greenhouse gas emissions from housing by household types
Independent	INC	Average income of by household types
	INCSQ	Average income square by household type
	SAV	Average saving by household types
	DEBT	Household types with negative savings in reporting period (dummy)
	EXP	Average final consumption expenditure by household types
	HOU	Total number of household by household types
	POP	Breakdown of German population by household types
	POPM	Breakdown of male German population by household types
	POPF	Breakdown of female German population by household types
	GENDER	Proportion of female population by household types
	AGE	Average age of population by household types
	AGEF	Average age of female population by household types
	AGEM	Average age of male population by household types
	HSIZE	Number of people living in a household by household types
	SINGLE	Household types with only a household member (dummy)
	EDU	Average educational achievements by household types
	EDUM	Average educational achievements of male population by household types
EDUF	Average educational achievements of female population by household types	

Table 4.9 – Variable included in the regression model



All independent variables are derived from the data provided by the publication on socio-economic development in Germany (Federal Statistical Office of Germany, 2005b). Some variables such as income, savings, household consumption expenditure, population or household size could be used directly. Only estimates for household group 9 “Other unemployed households with income from non-public money sources” were derived residually as outlined previously. The gender variable was calculated by dividing the number of female members of each household type by the total number of individuals. The household size variable was estimated by dividing the total number of individuals by the total number of households for each household type.

The data provides a detailed age profile of each household group and type by mapping the number of individuals into 17 five-year age bands. In the absence of information about the average age of the individuals, this was calculated by assuming a normal distribution of individuals in each age band with a mean at 2.5. This procedure was also applied for the “residual age band” of individuals aged 80 and older.

Finally, the average education level of the different household types was estimated. Information on the education level of the population broken down by the 17 age bands is provided in three discrete categories - low, middle, high – derived from the International Standard Classification of Education (ISCED). A fourth category “unclassified” indicates individuals for which no information is available. These individuals were assigned across the three education levels proportionally to the rest of the age band assuming that they are “average” members of that age group. Assigning the discrete values of 1,2 and 3 for individuals with low, middle and high education levels, the average education level of the 17 different age bands could be determined as a natural number in the closed interval between 1 and 3. These were linked with information on the detailed age structure of each household type to estimate its average education level.

In the course of these calculations only adult household members aged 20 and older were included, because they often have not finished their basic education when they turn 16.<sup>6</sup> Therefore, households with children would always show a lower average education level as their children are still enrolled in basic education. This would not provide a good measure of the average education level of the different household types.

---

<sup>6</sup> With basic education we refer to finishing compulsory education plus an apprenticeship or the A-level equivalent school degree.

The final sample size consisted of 492 observations for the years 1991-2002 on each of the 41 household types: 2 of the 9 household groups did only exist in 3 of the 5 household sizes. The descriptive statistics are listed in Table 4.10.

Variable	Mean	Std.Dev	Minimum	Maximum	Cases
GROUP	21.20	12.12	1	41	492
INC	4.17	1.31	0.82	6.73	492
YEAR	1996.50	3.46	1991	2002	492
GHCPHH	10.38	12.73	6.84	72.75	492
GHCPC	10.38	5.41	3.44	36.56	492
INCPC	129.65	152.07	2.26	839.17	492
EDU	1.60	0.33	0.96	2.08	492
NOIND	1972.90	2133.59	213	11339	492
MAGE	37.42	13.64	20.41	75.17	492
FAGE	36.53	13.14	17.63	71.64	492
AGE	36.98	13.45	19.55	74.30	492
FSHARE	0.50	0.10	0.21	0.87	492
HHSIZE	2.89	1.46	1.00	5.66	492
INCPHH	129.65	152.07	2.26	839.17	492
FEDU	1.52	0.29	0.99	2.00	492
HEDU	1.68	0.39	0.83	2.18	492

Table 4.10 – Descriptive Statistics

### 4.5.2 Model outline

Using panel data methods we can control for the household groups and estimate the impact of various socio-economic variables on GHG emissions. Based on the variables described in Section 4.4.1, the model can be written as

$$LGHGHH_{i,t} = \alpha + \beta_1 LINC_{it} + \beta_2 LINC_{it}^2 + \beta \text{ other variables} + u_i + \lambda_t \quad (4.16)$$

where  $u_i$  and  $\lambda_t$  are type and time specific effects respectively, with  $i = 1, \dots, N$  and  $t = 1, \dots, T$  representing groups and types respectively.

The main concern in estimating this model is that income and the other variables included are correlated with the group effects. If so, a pooled OLS approach provides a biased estimator of the impact coefficients. Since outcomes within a group are likely to be correlated, allowing for an unobserved group effect is important. In the next section we present the results of estimating our model with standard OLS and Panel fixed and random effects.

### 4.5.3 Specification Testing

*Firstly*, we test for unobserved heterogeneity. The Breusch and Pagan LM-test is used to test the hypothesis that individual effects are significant. If this test did not provide any evidence for individual effects, then the model could simply be estimated by ordinary least squares (OLS). A large value of the LM statistic argues in favour of using the panel data model. The LM statistic was extremely large (1986.28) and assessed against the  $\chi^2$  distribution with 2 degrees of freedom is significant at any conventional level.

*Secondly*, we decided between a random or a fixed effects model using the Hausmann test. The Hausman test is used to decide whether the regressors are correlated with the individual effect. A small Hausman statistic argues in favour of the random effect model, a large in favour of a fixed effects one. The Hausman statistic was 199.02, which assessed against the  $\chi^2$  distribution with 8 degrees of freedom was significant at any conventional level. The fixed effect model is the preferred model.

Finally, we tested for the joint effects of the household type and periodic effects respectively. The Wald F statistic for the joint significance of the 41 household type effects was 1666.503 which, assessed against the F distribution with 40 numerator and 443 denominator degrees of freedom, is significant at any conventional level.

The Wald F statistic for the joint significance of the 12 period effects was 72.208 which, assessed against the F distribution with 11 numerator and 442 denominator degrees of freedom, is significant at any conventional level. The Wald F statistic for the joint significance of the 41 household types and 12 period effects was 1688.386 which, assessed against the F distribution with 52 numerator and 432 denominator degrees of freedom, is significant at any conventional level.

### 4.5.4 Regression results

Before we interpret the coefficient estimates, let us turn towards the periodic and household type specific effects first, as controlling for these is the major advantage of panel regression methods. Figure 4.1 shows the period effects for the post-unification years in Germany. Two standard error confidence bands are also presented to visually assess significance. Note that virtually all effects are statistically significant, with the exception of a few values close to zero, because of the small size of the effect.

Three clear trends can be derived from Figure 4.1. *Firstly*, the figure clearly represents a downward sloping trend. This is consistent with all other results presented in this article and highlights Germany's successful efforts to reduce greenhouse gas emissions from consumption. *Secondly*, the period-effects in the graph are expressed in levels to better appreciate the change in slope from the period 1990–1996 and 1996–2002. Greenhouse gas emissions fall by 15 per cent in the first period and by about 10 per cent in the second. This is consistent with other reports about the particular effects of the re-union on the development in GHG emissions (Bundesregierung, 2005) associated with the contraction of the Eastern economy and easy-to-achieve energy efficiency improvements in the existing industry infrastructure. *Thirdly*, there are two periods, 1995–1996 and 2000–2001, in which the emission increases sharply, before they return to the falling trend. In both cases this is associated with particularly cold winters. In fact, 1996 was one of the coldest years in recent decades. This result is confirmed by going back to Table 4.5. While the GHG emissions associated with all other consumption categories keep falling, there is a substantial increase in GHG emissions associated with consumption of energy services.

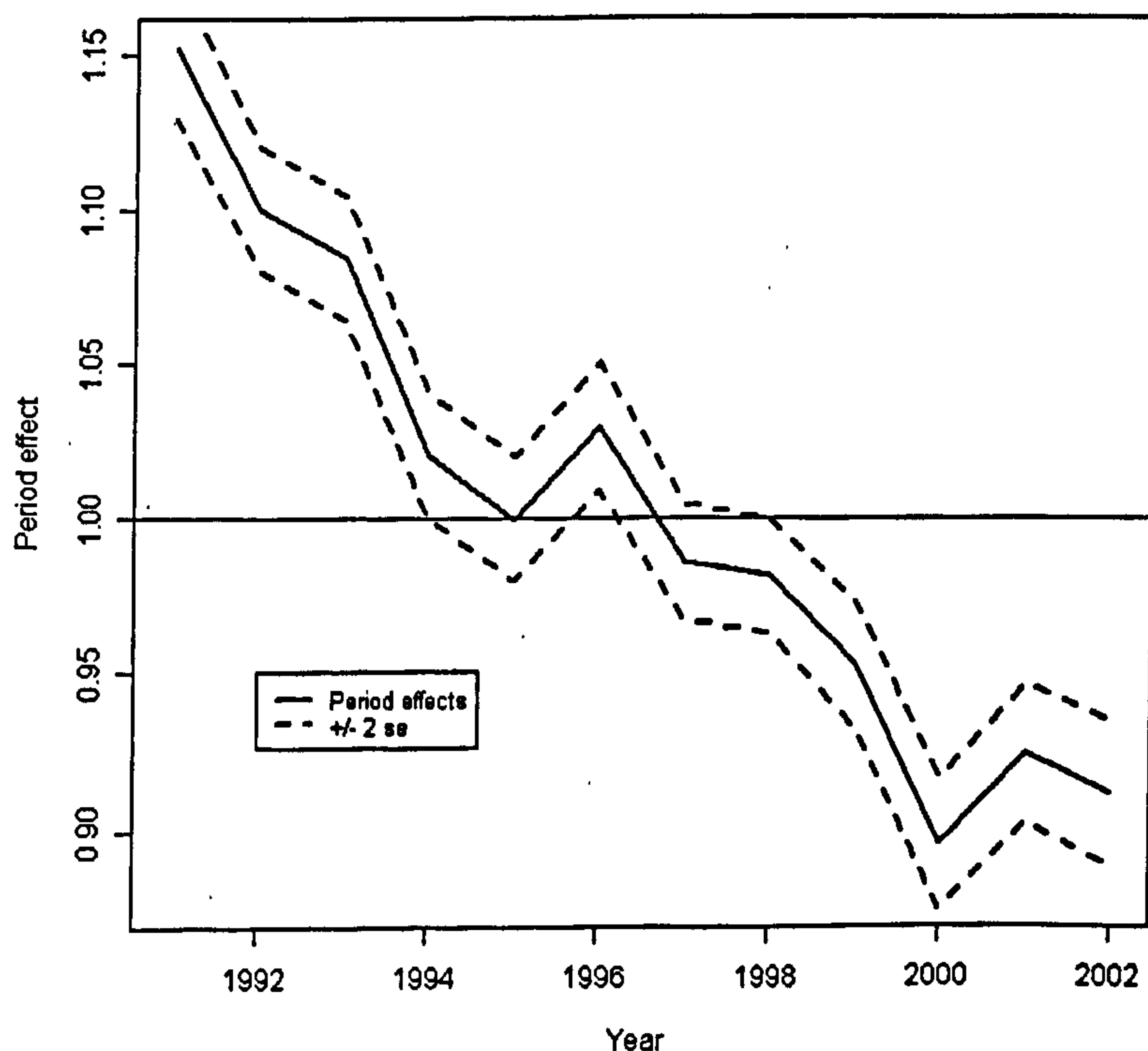


Figure 4.1 – Periodic Effects

Next, we turn our attention towards the household type specific effects. Figure 4.2 graphs the household type effect versus the household type. The labels in the Figure show the household group (1–9) and the household size (A–E).

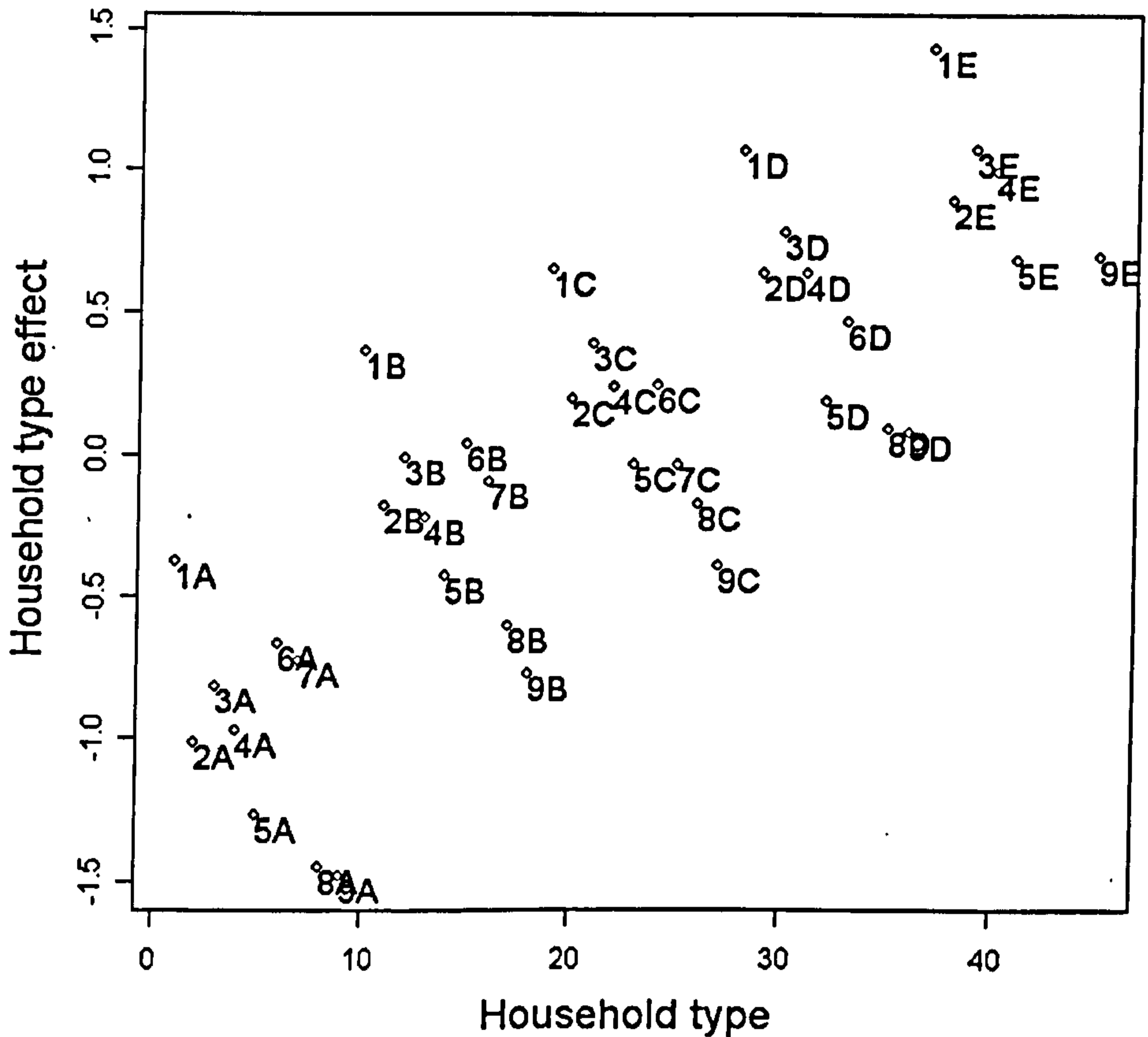


Figure 4.2 – Household type specific effects

The graph clearly shows that increasing the household size increases greenhouse gas emissions across groups, keeping everything else constant. “Self-employed” (group 1) are consistently by far the worst emitters followed at a distant by “other employed households”. This is consistent with findings in other studies in the literature (e.g. Schipper et al., 1998; Lenzen et al., 2006). “Other unemployed households” (group 9) are the lowest emitters of greenhouse gases followed by “households receiving social benefits” (group 8) and “short term unemployed” (group 5). “Public servants” (group 2) and “Blue Collars” (group 4) are consistently average emitters. Pensioners are among the worst emitter for small household sizes, but fall relative to the others as the household

size increases. In fact, they are the second worst emitter for single and 2 person households, third and fifth, for 3 and 4 persons household, respectively.

The regression results from the different models are listed in Table 4.11. As commonly found in the literature, income has a significant, positive impact on greenhouse gas emissions. Because of the quadratic term, the impact of income on greenhouse gas emissions is a function of the level of income. Also, since the variables have been transformed using the natural log function, coefficients can be interpreted as elasticities of emissions. The elasticity of greenhouse gas emissions per capita (E) with respect to income (I) is given by:

$$\varepsilon_{E,I} = 0.05749 + 0.010693 \cdot I \quad (4.17)$$

In fact, at the average level of income (4.17), a doubling of income per household determines on average a 10.21 per cent rise in emissions per household, *ceteris paribus*. At the highest level of income per household in the sample (6.73), a doubling of income determines a 12.95 per cent increase in average emissions per household, 6.62 per cent at the lowest (.81). We would like to note that controlling for lifestyles emissions are an increasing function of income.

Model	OLS		Random Effects		Fixed Effects	
	Coefficient	P[ T >t]	Coefficient	P[ T >t]	Coefficient	P[ T >t]
CONSTANT	1.2575	0.0000	2.5340	0.0000	3.3590	0.0000
LINC	0.1615	0.0042	-0.0049	0.9047	0.0575	0.1740
LINCSQ	-0.0023	0.7436	0.0150	0.0010	0.0107	0.0236
LFSHARE	0.1017	0.1861	0.2723	0.0003	0.1031	0.2040
FAGE	0.0434	0.0000	-0.0232	0.0000	-0.0091	0.0106
MAGE	-0.0313	0.0000	0.0148	0.0000	0.0081	0.0050
LFEDU	0.9190	0.0061	-0.4226	0.0010	0.1071	0.4375
LMEDU	-0.1571	0.5395	1.0397	0.0000	0.3489	0.0051
HHSIZE	0.2344	0.0000	0.1753	0.0000	-0.2635	0.1196
DEBT	-0.2604	0.0000	-0.0539	0.0000	-0.0386	0.0000

Table 4.11 – Regression results from different models

The influence of other variables vary. Female share increases greenhouse gas emissions, keeping everything else constant.<sup>7</sup> Household size has a negative impact on

<sup>7</sup> The fixed effect results show the high importance of cold winters in determining emissions. Heating seems to be an important factor. Women usually have a lower blood pressure than men. This translates into less force driving the blood round the body. As a consequence of that, women are often prone to cold hands and feet as there is not enough blood reaching the extremities and are in general more sensitive to temperature (both cold and hot).

emissions. This is mainly related to the usually fewer square metre of living space available per household member. Education increases greenhouse gas emissions. Female education is however not statistically significant. Male education has the highest quantitative impact on greenhouse gas emissions among all determinants, more than 3 times the impact of female education. This might be due to the fact that still in most households' in Germany the man is the bread-earner – particularly in high-income households.

Having debt is associated with lower emissions. This result is consistent with a liquidity constraint explanation: consumption is impeded by the lack of financial resources. This interpretation is corroborated by the positive impact of income especially for high income households, where we would expect liquidity constraints to be less binding. Some results are more difficult to interpret. Age variables are both statistically significant, but have opposite signs. Female age seems to negatively affect emissions, while an opposite sign is found for men.

## 4.6 CONCLUSION

In this article we have linked SAM-type income and expenditure accounts with environmental input-output models to estimate the greenhouse gas impacts of 41 different lifestyle groups in Germany. The basic results highlight the paramount importance of 'food', 'housing' and 'private' transport in the average consumption basket of households as drivers of GHG emissions confirming results from several other studies (see Tukker et al., 2006). However, particularly the small contribution of 'housing' to the overall reduction of 120Mt of GHG emissions from household consumption between 1991 and 2002 stresses the failure of policy to utilise the available technology to significantly reduce GHG emissions in this area. At the same time it highlights the key role for a clear re-trofitting plan of the existing housing stock, building all new houses to low carbon standard and looking at greening the supply chain in the energy sector.

Across lifestyle groups, very large differences in GHG emissions exist. Moreover, the development of GHG over time varies. Determinants of the difference in GHG emissions between 1991 and 2002 for the different groups can be studied for each group individually by applying structural decomposition analysis. Overall, the results present a typical picture: substantial energy efficiency improvement in production are partially eaten-up by increases in consumption levels. However, the increases in population as well as the changes in the demographic structure are also found to be important emission drivers. It seems that the ageing population in Germany is associated with increases in emissions. Policy responses to climate change need to take such demographic pressures into account in order to be successful. If old people, for example, need more energy at home, because of their higher demand for warmth and the longer hours they spend at home everyday as we have shown elsewhere (see Haq et al., 2007), it might be very effective to prioritise retro-fitting of houses older people live-in.

However, specific information on the influence of individual socio-economic factors can only be obtained, if we further analyse the results from our environmental input-output model in a regression analysis. The applied panel method allowed us to control for time periodic as well as household type specific effects. The time-specific effects capture the slowing progress in GHG emission reductions after the re-unification in Germany. Group-specific effects highlight the dominance of household size and social group membership for differences in GHG emissions from consumption patterns of different lifestyle groups.



Individual effects, for example, showed education levels increase GHG emissions. Equally, income increases emission and debt reduces emissions. It should be the ultimate aim of any government to lift more people out of poverty. However, ideally this should be done in a 'carbon-neutral' way. However, the income-consumption relationship implies that emissions will increase. If Germany, for example, solves its current problems in the labour market, additional GHG emissions cannot only be expected from production, but also from consumption. This calls for innovative socio-environmental policy solutions. In the UK, tradable emission permit systems for households are currently discussed (Roberts and Thumin, 2006) as one way of dealing with re-distributional and environmental issues at the same time.

While the results can demonstrate the general usefulness of such a regression approach, it seemed to suffer in terms of its policy relevance from two data related limitations: *Firstly*, particularly in the case of the household types as an interpretation of lifestyles seems far-fetched: many just differ in terms of the household size. *Secondly*, only a very limited number of independent variables could be extracted from the SAM-type income and expenditure data. Additional lifestyle related variables would seem very likely to increase the value of the data considerably: not only for environmental, but also social analysis. Additional variables such as the amount of living space, number of cars owned, occupational structure of the group and be extracted from the German Mikrozensus, which is carried out on a yearly basis. The compilation of such a 'lifestyle' module is recommended.

Also, the top-down classification of lifestyles as commonly applied in national accounting based on only a few socio-demographic descriptors such as income, occupancy and household size is seen to further limit the analysis. Of at least equal importance with people's socio-demographic characteristics are the local conditions within which they are acting: general neighbourhood characteristics (poor/rich, rural/urban etc.), the accessibility of private and public services and building properties (size, type, age, insulation etc.) and other infrastructural circumstances. They also need to be reflected in an adequate lifestyle classification.

Duchin (1998) therefore argues that the lifestyle databases usually compiled by marketing data providers are much more suitable as they are developed from spatial and rich socio-economic profiles. Indeed, elsewhere (see Appendix B) we have used such data in a similar panel regression approach applied to cross-sectional data and obtain

much richer results.<sup>8</sup> However, this analysis certainly only provides an extremely limited insight into what is possible with such data: most importantly, the generation of spatially-specific rather than “one size fits all” policy recommendations and the identification of local drivers and barriers to lifestyle change. We believe that these databases provide the most promising way of getting a better grip on the analysis of environmental impacts from lifestyles and recommend an intensification of research in this area.

---

<sup>8</sup> However, also more variables are available.

## 5 Time and Sustainability: An Input-Output Approach in Mixed Units<sup>1</sup>

**Abstract:** In this Chapter it is argued that time use data can help to improve quantitative sustainability research. It stresses the unique properties of time use data, which allow for a more comprehensive modelling of social and behavioural issues. Data frameworks in monetary, physical and time units are proposed as an ideal starting point for sustainability studies. The richness of the approach is demonstrated in an analysis of household activities based on a unique set of input-output tables in monetary, physical and time units.

---

<sup>1</sup> Minx, J.C. and Baiocchi, G., 2007, Time Use and Sustainability, in: Suh, S., *Handbook of Input-Output Methods for Industrial Ecology*, Springer, Dordrecht, forthcoming.

## 5.1 INTRODUCTION

Industrial Ecology as coined by Frosch and Galloupolos (1989) has been proposed as one operational and holistic concept for implementing more sustainable policies. However, like many other concepts that have become popular in the post-Brundtland era during the late 1980s and early 1990s, such as Cleaner Production (Baas et al., 1990), Ecological Modernisation (Jähncke, 1988) and Industrial Metabolism (Ayres, 1989), it has been open to criticism, due to the failure of environmental policies to achieve many of their ambitious goals set out during the Rio process. The shared pathology has usually been the technocratic approach and supply-side bias, as most clearly laid out in the *sustainable consumption* debate (UNEP, 2002; Princen et al., 2002).<sup>2</sup>

Researchers have responded to this criticism by adjusting their policy approaches. Much more emphasis has recently been given to the study of household behaviour and demand side issues (e.g. Gatersleben, 2000; Jackson, 2004); socio-institutional and demographic concerns have been integrated with environmental-economic ones (e.g. Cogoy, 1995; Madlener and Stagl, 2001); and more and more effort has been devoted to understanding and disclosing the complex relationship between consumption activities and well-being (Hofstetter and Madjar, 2003; Jackson et al., 2004).

However, quantitative approaches often still lack a systematic and comprehensive treatment of social and behavioural aspects. In this chapter we argue that the integration of time use data into quantitative frameworks opens a whole new array of possibilities for the representation of these aspects in sustainability research. This has been proposed in the international policy arena, for example in Agenda 21 (see programme area D of Chapter 8) and the System of Integrated Environmental and Economic Accounting (United Nations, 1993b), in the (National) Accounting (e.g. Hawrylyshyn, 1977; Pyatt, 1990; ) as well as the Household Production Literature (e.g. Juster and Stafford, 1991; Klevermarken, 1999) and in different social science disciplines (e.g. Barth, 1967; Gross, 1984).

Section 2 gives an introduction to time use data and outlines four unique properties that allow social and behavioural aspects to be better represented in

---

<sup>2</sup> For an overview of very recent research efforts in Sustainable Consumption Research, see the 2005 Special Issue of the Journal of Industrial Ecology 9(1-2).

quantitative frameworks. Section 3 proposes to integrate data in monetary, physical and time units in one comprehensive framework before Section 4 applies the time argument to the consumer-lifestyle debate within an input-output context. The value of the approach is demonstrated in an empirical assessment of household activities based on a unique set of input-output tables in monetary, physical and time units throughout Sections 5 to 8. Section 9 concludes.

## 5.2 TIME-USE DATA FOR SUSTAINABILITY RESEARCH

Time use (or time allocation) data has been collected systematically in time budget surveys since the 1960s. The subject of measurement might be best defined as the *use of human (or economic) time*; that is, “the hours of time that human beings have at their disposal and that must be allocated between alternative activities” (Sharp, 1981, p.2). Essentially, these surveys provide information about what activities a sample of a given population engages in during a representative day (or a set of representative days) within a defined reporting period. These can be used to estimate the time-allocation of the population in this particular reporting period.

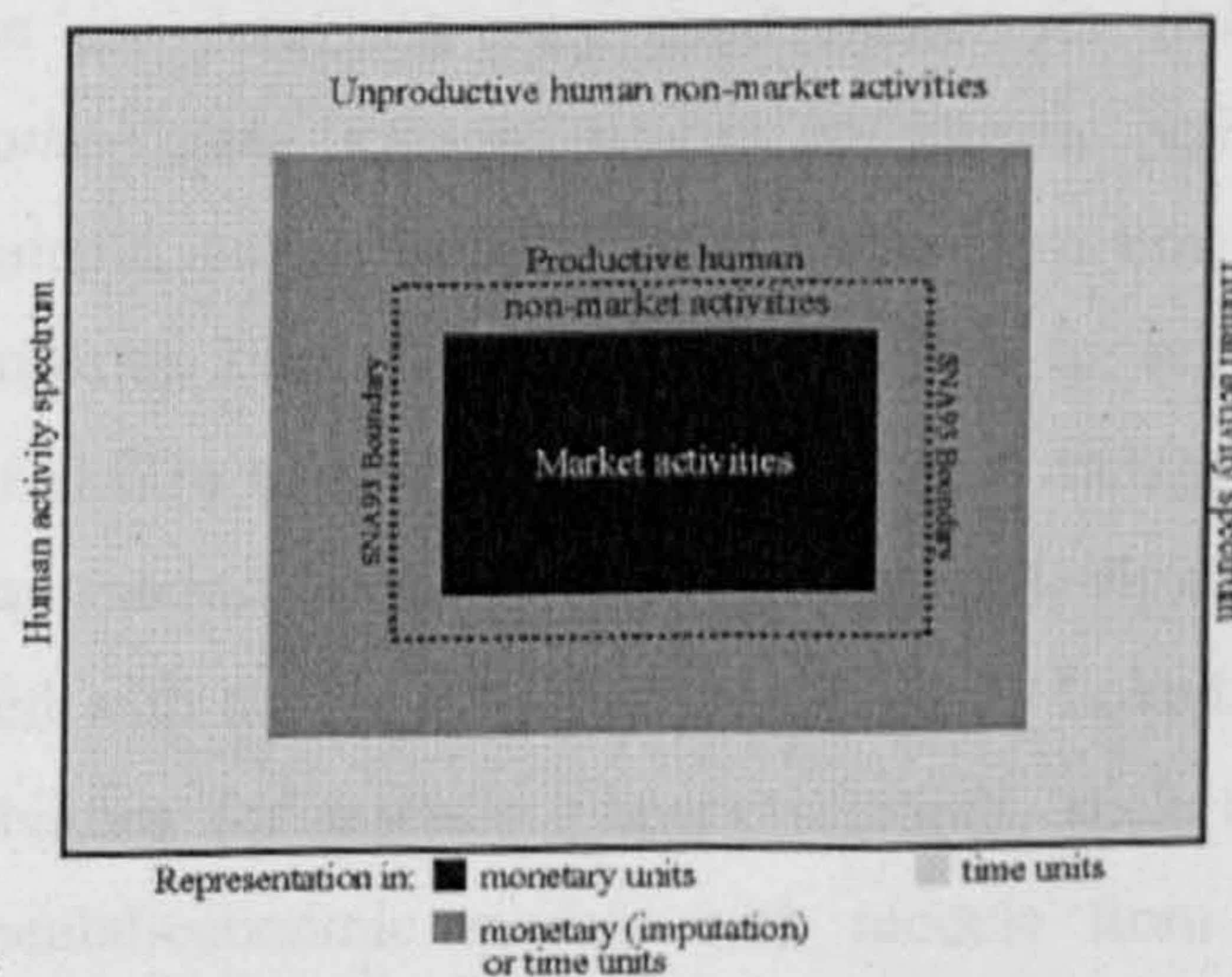
The information content of the raw data is depicted in Table 5.1 (see United Nations, 1975). Data is usually collected through the diary method (usually for two representative days (weekday, weekend)) and often augmented by information from questionnaires or interviews. Detailed information about the design of time budget surveys and methodological procedures can be found in Szalai (1972) and Juster and Stafford (1991).

Time use data has some unique properties, which make it attractive for quantitative sustainability research: *First*, there is the issue of coverage. It is highly intuitive that monetary data can only provide a limited picture of the human activity spectrum, as it is bound to the market institution and its associated exchange processes. However, researchers who have subscribed to the sustainability concept are usually interested in society as a whole, rather than its economic subsystem. Because all activities take time and all members of society must allocate the same amount of time among them during a given reporting period (i.e. time cannot be hoarded - this is the 24 hour add-up property), time use data has the unique capability to capture all human activities under equal coverage of the whole population.

Cross-sectional Data	<p>The following information can be analysed when referring to a single reporting period:</p> <ol style="list-style-type: none"> <li>1. the activities realised in the course of a representative day for different purposes,</li> <li>2. the duration of these activities,</li> <li>3. the allocation or distribution of these activities during the day,</li> <li>4. differences in activity patterns between social strata.</li> </ol>
Longitudinal Data	<p>As soon as at least two comparable time budget surveys are available, the analysis can be extended to address:</p> <ol style="list-style-type: none"> <li>5. shifts in time use patterns regarding the information pieces 1 to 4, e.g. activities with absolute time gains or losses, shifts in the allocation or distribution of activities during the day or shifts in differences among social strata.</li> </ol>

**Table 5.1 – Basic Information Content of Time-Use Data**

To extend the scope of quantitative models, time use data can be applied not only as a stand alone, but also as a basic data input for imputing the value of non-market activities in monetary terms. However, there seems to be an agreement in the National Accounting Literature that limits of monetisation need to be acknowledged, and imputation efforts should be restricted to productive non-market activities (Hawrylyshyn, 1977; Stahmer et al., 2003a). Productive non-market activities are all those non-market activities with market potential, in that they can be carried out for someone by another third person. This is the so-called third person criterion, which can be used for their identification (see Reid, 1934; Hill, 1979). All activities which do not correspond to the third person criterion are “personal” in nature and not open for valuation. Hence, the entire spectrum of human activities can only be represented adequately by means of time use data, while all productive activities – independent of whether they occur inside or outside the market - can also be depicted in money terms, as shown in Figure 5.1.



**Figure 5.1 - Relationship between monetary and time use data for the representation of human activities**

*Second*, time use data can help us to understand and model economic decisions (or economic behaviour) in a wider social context. The above definition of human time implies that it is a *scarce resource*, which *must* be allocated among alternative activities. Therefore, human time is at the heart of human decision making. Even in a utopian world without any material scarcity individuals are still left with the problem of how to allocate their time during a day, week, or year among alternative activities to maximise their life enjoyment. This is a standard economic problem of choice. Because the relationship between time and economic goods cannot be affected by their status as free goods, it must follow that the availability of time is also a crucial - even though often neglected - decision variable in today's world (Rosenstein-Rodan, 1934).

The *third* point is closely related to the previous two. Time use data captures many interesting patterns of social life related to the temporal distribution of human activities. This is not only limited to the duration of activities, but also their timing, frequency and sequential order (Szalai, 1972). Hence, beside its larger scope, time use data carries *unique information (content)* mainly associated with the *social side* of sustainability:

“T(ime)A(llocation) measures the behavioural “output” of decisions, preferences and attitudes. It provides a measure of role performance. It measures the rates at which goods are produced. TA provides primary data on many kinds of social interaction and provides the basis for defining social groups by behaviour. TA can provide important data in studies of attitudes, values, cultural style, and emotions. Any kind of behavior with an environmental effect can be observed using TA techniques, including speaking, working, repose, leisure etc.” (Gross, 1984: 519).

*Finally*, time use data is a very good *anchor for linking other models or information from other data sources* related to human activities to quantitative frameworks. For example, supplementary information from time surveys, often called *context variables* (Eurostat, 2000; UNEP, 2004), do allow for ordering human activities not only in time, but also in space (location and mode of transport) and provide scarce information on human interaction (for whom/ with whom). However, all sorts of other information associated with human activities can be easily linked. This creates a whole array of new possibilities for interdisciplinary research, such as, the integration of traditional environmental-economic models with models from other social science disciplines, which are much more focussed on the study of human activities and behaviour from a societal angle.

### 5.3 Towards a Basic Data Framework for Comprehensive Sustainability Research

For sustainability as a holistic scientific concept which is concerned with society and its natural surroundings, it is therefore crucial to integrate time use data into quantitative models for a better representation of human activities. This need has not only been stressed by researchers (e.g. Stahmer, 1995; Cogoy, 1995), but also in documents on the policy level such as Agenda 21 (see programme area D of chapter 8) or in part V of the System for Integrated Environmental and Economic Accounting (United Nations, 1993b).

Most importantly, combining data in monetary, physical and time units in a single integrative data framework allows for a complete coverage of the economic, social and environmental spheres.<sup>3</sup> Thereby, it is crucial to understand that the usefulness of the different measurement units for sustainability research is rooted in their interplay and not associated with any of them. It is a particular strength of such a data framework that monetary and non-monetary phenomena are conceptually and numerically interlinked “without relying on theoretically faulty imputation of money values to non-monetary phenomena” (Keuning, 1994, p.41). Everything is represented in a suitable measurement unit. Such a data framework, therefore, appears as a basic platform from which sustainability studies should start, *whilst other information can and should be added depending on the research purpose.*

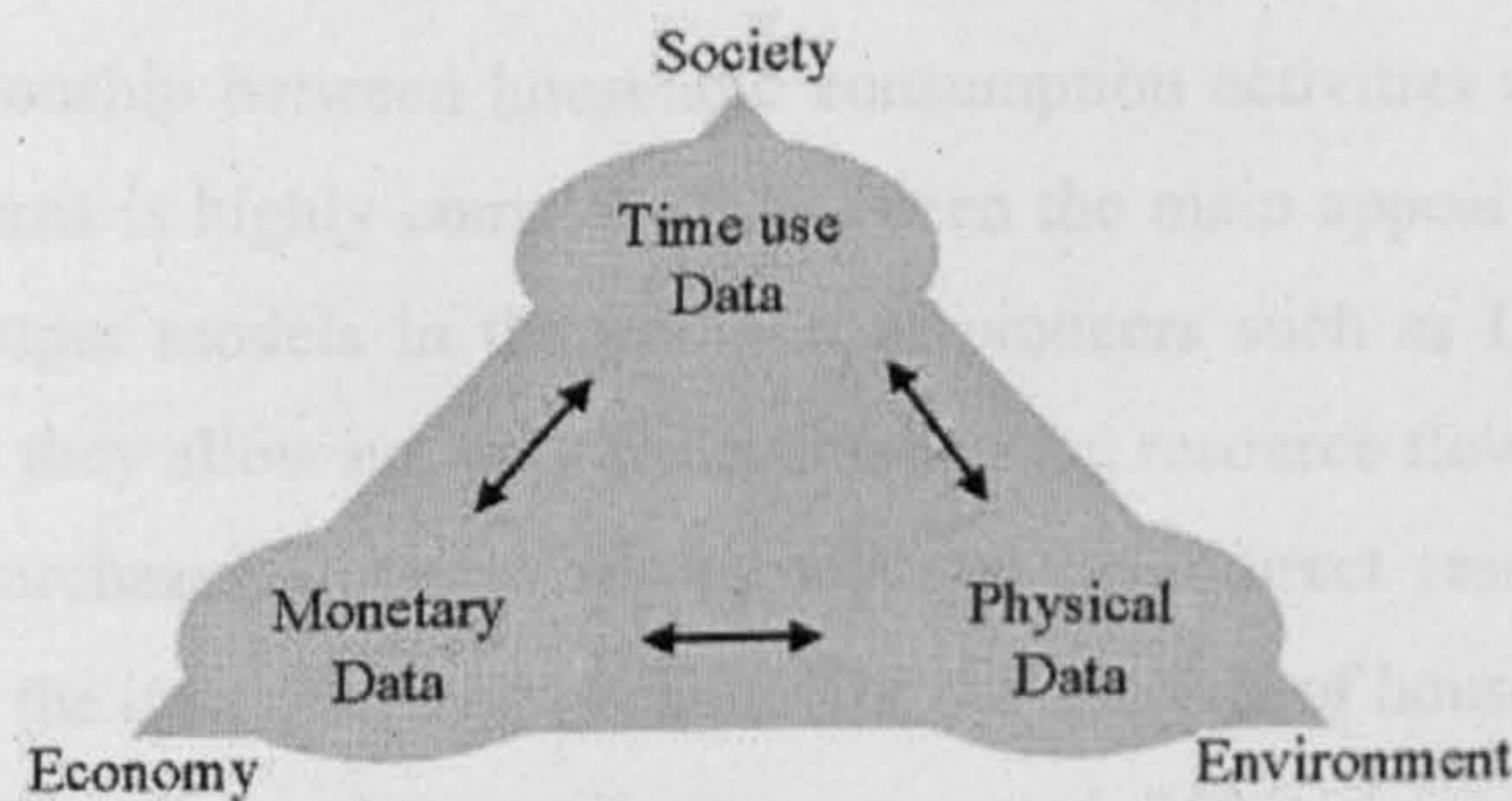


Figure 5.2 – A Magic Triangle for Quantitative Sustainability Research

<sup>3</sup>That is, all human activities, physical flows and economic transactions are covered by such a data framework.



Unfortunately, sustainability studies have only very rarely applied data in all three different units (e.g. Schipper et al., 1989; Jalas, 2002a; Stäglin and Schintke, 2002; Stahmer et al., 2003c; Stahmer et al. 2004). Even less work has been done by statistical offices to prepare data sets which bring together information in all three measurement units. To our knowledge, Carsten Stahmer’s “Magic Triangle of Input-Output” (see Stahmer, 2000; Stahmer et al., 2003a) and “Socio-Demographic Input-Output Accounting” (see Stahmer et al., 2004), as well as Keuning’s System of Economic and Social Accounting Matrices and Extensions (SESAME) (see Keuning, 1994; Kazemier et al., 1999; Keuning, 2000), published by the Statistical Offices of Germany and the Netherlands respectively, are notable and visionary exceptions.

#### **5.4 *Integrating Time-Use Data into the Analysis of Household Activities***

Having developed the “time use argument” in the previous two Sections and established the need to integrate monetary, physical and time use data in one framework, we will try to demonstrate the power of the argument in the remaining Sections by applying it to the consumer-lifestyle debate in an input-output context. In particular, in this Section we outline why time use data might help us to improve the analysis of household consumption activities, and in subsequent Sections we will turn to an empirical application.

The relationship between household consumption activities and their associated resource use patterns is highly complex. It has been the main appeal of environmentally extended input-output models in the tradition of pioneers such as Leontief (1970) and Victor (1972) that they allow not only for estimating the resource flows triggered directly by households’ purchases, but also for associating the indirect resource flows, which occur upstream in the industrial supply chain. For the analysis of household consumption, studies have usually compared the total resource use of different products or commodity groups (e.g. Kim, 2002; Suh et al., 2002), functional household consumption categories (e.g. Wiedman et al. 2005; Vringer and Blok, 1995), or consumption baskets of different socio-economic groups (e.g. Wier et al., 2001; Cohen et al., 2005). The underlying household expenditure cluster - of a region or a nation as a whole, on average or across specific socio-economic groups - has often been interpreted as the manifestation of a

particular lifestyle, and the approach is therefore often referred to as the “consumer-lifestyle approach” (see Weber and Perrels, 2000).

However, conventional environmentally extended input-output models give an overriding importance to monetary transactions in the analysis of household consumption. Such a perception might be seen in analogy to the standard model of consumer demand, which views the choice of households as constrained solely by their money income. The final goods bought in the market are assumed to be ends in themselves. They are the sole providers of utility or happiness and determine the outcome of the choices based on the individual’s set of preferences. This is shown on the left-hand side of Figure 5.3.

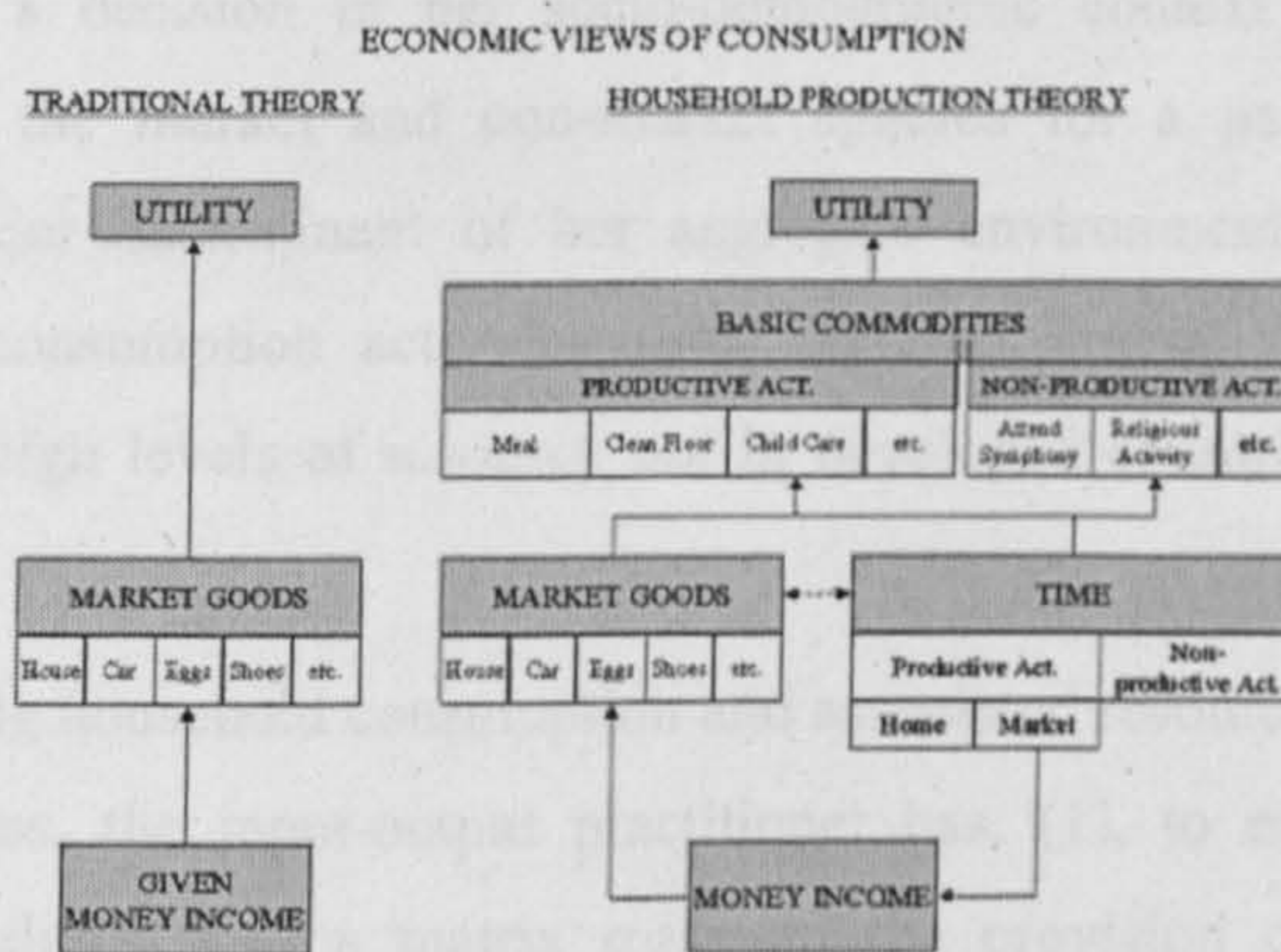


Figure 5.3 – Two Distinct Views of Household Consumption

However, goods are usually best perceived not as ends in themselves,<sup>4</sup> but as *instrumental* to the performance of an activity. In fact, it is difficult to think of a flow of goods being produced or used independently of involvement in an activity (Juster et al., 1981). Time is certainly another indispensable input for any human activity, as already argued in Section 5.2. Therefore, household consumption activities might be better viewed as processes in which households, like little factories, combine market goods and time to produce “more basic commodities” (activity outputs), as proposed in the household production literature (see Cairncross, 1958; Becker, 1965; DeSerpa, 1971; Pollak and Wachter, 1975). These basic commodities (Becker’s “Z-goods”) produced in

<sup>4</sup> Socially scarce positional goods (see Hirsch, 1977), such as paintings of one of the great masters, or a status symbol, like a Lamborghini, might be seen as ends in themselves. However, they remain exceptions.

households such as having a warm meal, seeing a play or caring for children, are the final consumption or enjoyment targets and ultimate providers of utility. This new, “productive” perception of household consumption is juxtaposed with the traditional one on the right-hand side of Figure 5.3.

Because households can substitute between time and market goods,<sup>5</sup> there are many different ways in which households can achieve a given consumption target. To have a hot meal, for example, people can cook for themselves, order take-away, or go to a restaurant. All these different “consumption technologies” for achieving a particular consumption target have very different economic and environmental implications and continuously re-define the borderline between the market and non-market spheres in consumption processes. For this reason, Cogoy (1995, 1999, 2000) convincingly argues that the consumer’s decision in her socio-demographic context where to draw the boundary between the market and non-market spheres for a particular consumption activity is one major determinant of her aggregate environmental impact. A sound understanding of consumption activities then becomes crucial for learning how to effectively reduce high levels of resource use in developed countries from the demand side.

For depicting household consumption and associated resource patterns embedded in the social process, the input-output practitioner has, (1), to expand the vector of consumption expenditure into a matrix mapping the provision of final goods from industrial sectors to a complete set of human non-market activities, and, (2), to integrate a vector of (direct) time inputs by activity into the input-output framework. There are many other options for further customising the standard input-output framework for the analysis of household consumption activities, for example, by means of table design, the extension of the production boundary in monetary tables or a more far-reaching activity representation in time units. These options cannot all be discussed in detail, but the following Sections try to illustrate the relevance of some with a simple example. The interested reader is encouraged to consult the latest series of work by Stahmer and his colleagues (Stahmer et al. 2003a; Stahmer et al., 2004) for further inspiration.

It should be clear that input-output models lack a behavioural component and cannot model the underlying problem of choice. However, they can be used to analyse the

---

<sup>5</sup>In fact, it is also possible to think of direct substitution between time and resource use. For example, in order to save energy a person might engage in ‘do-it-yourself’ (DIY) activities and improve the insulation of the house. However, as there are always some market goods and services involved, this is also covered by the substitution relationship of money and time.

outcome of choice processes. For the analysis of household consumption, we can map money, time and resource-use into an activity space in our extended framework. This enables us, for example, to observe the different consumption technologies for different activities, to identify the borderline between the market and the non-market spheres for a particular choice and to compare them through time and across socio-economic groups.

By doing so the consumer-lifestyle approach appears in a very different light. Schipper et al. (1989) have already made clear that a lifestyle is much better defined as an *activity* than as an expenditure *pattern*, which groups people according to what they *do* rather than on what they *spend*. Only such a definition takes all activities equally into account, can depict a lifestyle in its integrity and social embeddedness, and bridge the gap between the purposive ends of household consumption and associated resource use

“Once a time dimension is introduced, the field expands considerably: commodities might be consumed on at a time, or concurrently, or pure time might be consumed independently of consumer goods” (DeSerpa, 1971, p.828).

It is easy to conceive of human non-market activities which only use very little or no market goods at all, such as sunbathing, a daily walk through the village, or a housewife’s afternoon nap. These activities do not contribute any less to a person’s lifestyle, and the extent to which a person engages in these activities over her lifecycle should be adequately reflected in analysis. In fact, those activities might be of particular interest in a sustainability context and it should, for example, be worthwhile finding out what drives activity participation.

Cross-sectional and longitudinal analysis then opens a whole new array of research options that might allow for tackling problems, which have for a long time been at the heart of both the sustainability debate in general and the consumer-lifestyle debate in particular. For example, by observing consumption technologies across lifestyle groups, we can compare different ways of achieving a consumption target and identify key drivers behind these differences (Jalas, 2002b). This facilitates interesting comparisons between home-produced and market-produced services, for example, between having a dinner at home and having it in a restaurant (Jalas, 2002a). The availability of time use data also allows resource use to be expressed not only per unit of money spent, but also per hour of activity engagement (Van der Werf, 2002; Jalas, 2002a). This provides an alternative view on resource use to policy makers and brings it much closer to the use-phase of products. Furthermore, the extensively discussed relationship between technology, time use/time saving and resource use in household

production processes moves into the scope of input-output models, as analysed theoretically on the micro-level by Binswanger (2001, 2002).

Many more things can be investigated within such an extended input-output framework. Extending the SNA93 production boundary, for example, by applying time use data in imputation models allows many more household (productive) non-market activities in monetary tables to be represented. There does not seem to be any reason why the childcare, laundry, cooking and cleaning services of a housewife should be any less important for the input-output practitioner interested in sustainability than similar services provided by the market. Moreover, with an extended concept of production also comes an extended concept of income. They together allow topics such as the material well-being, poverty or income inequality of different lifestyle groups and their relationship to resource use to be expressed much more appropriately than in traditional models.

It remains doubtful, for example, whether traditional input-output frameworks with superimposed inequality measures can reflect the distributional realities adequately, as the proportion of income to non-market output is usually “larger among the poor, and among the women, the aged, and those on farms and in rural areas” (Eisner, 1988, p.1613). In a similar line of reasoning, it remains doubtful what growth of household consumption observed in a series of traditional input-output tables really depicts. Is it growth or is it just a shift of a non-market activity into the market? Both have very different implications for human welfare and environmental considerations. Once extended monetary tables are used for analysis, this relationship between growth, well-being and resource use, which has been at the heart of the sustainability debate since its beginning (e.g. Schumacher, 1974; Beckerman, 1995), can be much more adequately addressed.

With the presence of time use data any other (human) activity-specific data source like subjective enjoyment ratings, health data<sup>6</sup> can easily be integrated into an input-output context. Their contribution to lifestyle analysis should be clear. Moreover, institutional aspects, such as time regimes and time institutions, could be modelled (Ehling, 1999). Because activities are not only rooted in time, but also in space, as explained above, time use data in input-output frameworks might also facilitate a more comprehensive introduction of the space dimension into input-output modelling. Inspiration might be taken from scholars in geography, who have been using time use and

---

<sup>6</sup>This occurred to me during a presentation by Paul Stonebrook of the Department of Health as part of the National Statistics “Time Use Seminar” (CASS Business School, London, 22 June 2004).

spatial data in combination for quite a while (see Carlstein et al., 1978a, 1978b, 1978c). A first attempt has already been undertaken by Schaffer (2004).

All these applications give rise to a much richer analysis of household activities and lifestyles within an input-output framework. Not only much broader analytical options, but also much more insightful links to debates in other disciplines can be established by the introduction of time use data. For the future it is our sincere hope that more use of this potential will be made and that quantitative sustainability models can help to push sustainability research another step forward towards an integrative, multi-disciplinary science and policy approach. The last Sections are devoted to a simple empirical application.

### **5.5 The data set – a “Magic Triangle of Input-Output Tables”**

The data applied in this study is derived from a set of monetary, physical and time input-output tables for West Germany covering the reporting period 1990. It was compiled in a visionary effort by a group of statisticians lead by Prof. Carsten Stahmer and has become known under the heading of “Magic Triangle of Input-Output”. For a detailed description of the data set, see Stahmer (2000) and Stahmer et al. (2003).

The data set comes with two distinct monetary input-output tables: a traditional MIOT and an extended MIOT including a detailed breakdown of household activities, an explicit treatment of environmental services and a valuation of productive non-market activities. For our purpose we constructed a new table using information from both the traditional and extended MIOT.

The resulting table is at a 61 sector aggregation level. In addition to the 58 sectors of the traditional German input-output publications, there are two environmental sectors and one sector for education. We aggregated both time (ZIOT) and physical (PIOT) input-output tables into the same format, and treated the ten household activities, which coincide with the ten headline activity fields of the German Time Budget Survey (see, Ehling, 1999), exogenously as final demand like in the traditional MIOT.<sup>7</sup> They are listed in Table 5.2.

---

<sup>7</sup> In contrast, the extended MIOT records all goods and services used by households as intermediate inputs in the spirit of the household production literature.

Abbreviation	Activity Field
HPROD	Household Production Activities/ Household Work
DIY	Do-It-Yourself
COM	Paid Job/ Job Seeking (mainly commuting times to work)
VW	Voluntary and Community Work
EDU	Qualification/ Education
PR	Personal Sphere, Physiological Regeneration
SOC	Contacts/ Conversations/ Social Life
LEIS	Use of Media/ Leisure Time Activities
CARE	Taking Care of and Attending People
RES	Non-Allocatable Times

Table 5.2 – Household activities distinguished in the study

In some cases it appeared useful to further aggregate the ten household activity fields of the present study into four basic categories of time use, as frequently done by scholars in sociology. This allows for studying major structural shifts in time-allocation and facilitates an analysis of the social process in its role distinctions (e.g. worker, spouse, parent). The basic underlying differentiation is between productive and other activities, as discussed above. Productive activities are subdivided into “contracted time” and “committed time”, which are the productive market and non-market activities. The remaining (unproductive) non-market activities can be distinguished as “personal time” and “free time”. Travel is a “floating” fifth category connecting the four different time uses (Robinson and Godbey, 1997). This is shown in Figure 5.4.

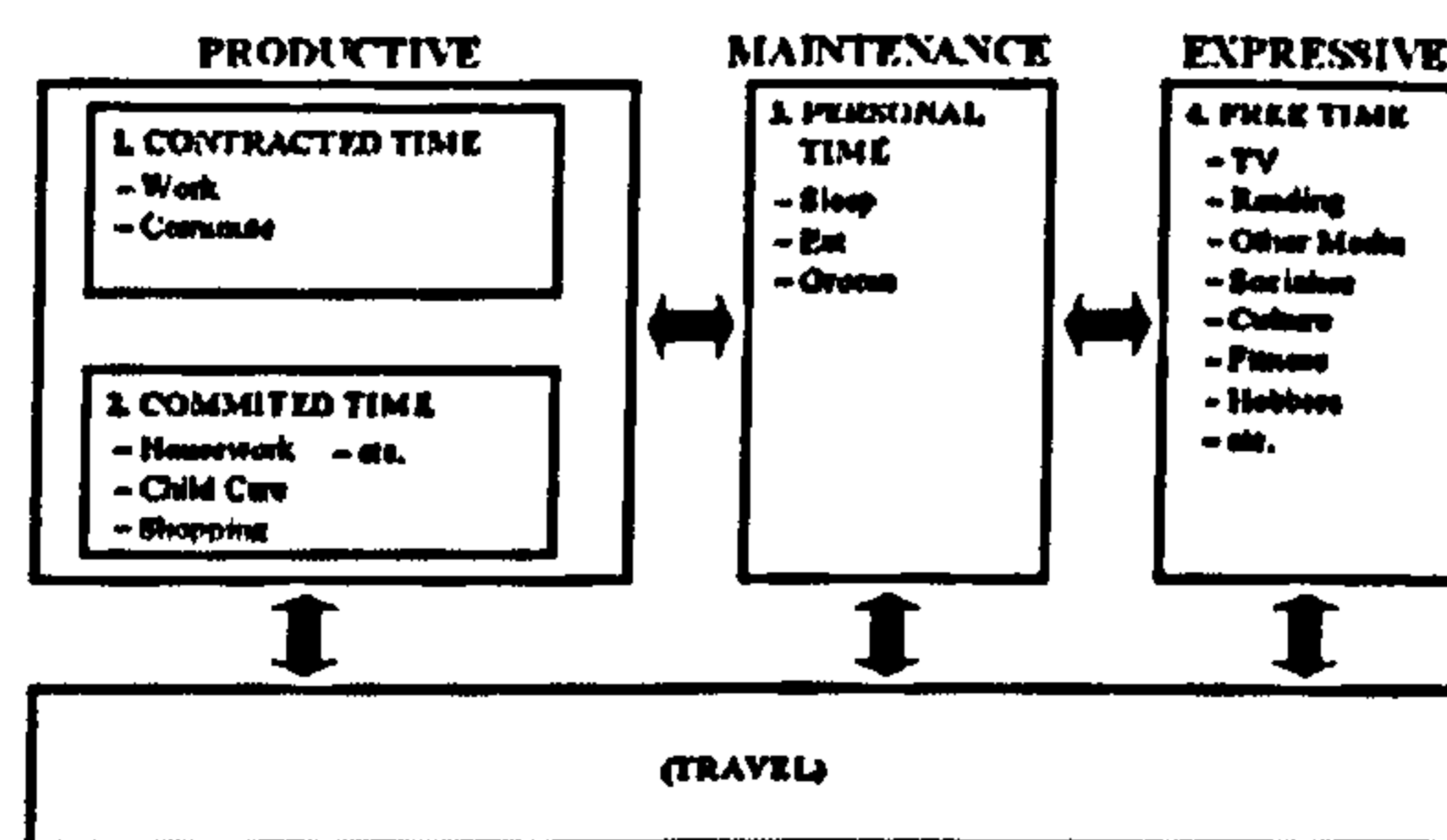


Figure 5.4 – Interrelationships across four categories of time (adapted from Robinson and Godbey, 1997)

Durable consumer goods are generally separated out from households' final demand activities and recorded as investment goods, which are part of fixed capital formation. Education and household services related to study activities are treated as changes in the educational or human capital stock. Therefore, the final household activity matrix contains only zero entries in the row associated with “education services” (see

Table 5.6). In order to bring all household activities into the scope of quantitative models, a hybrid concept is used for valuing the different market and non-market activities.<sup>8</sup> Industrial activities are estimated according to the “domestic concept” (Inlandskonzept), while household activities are recorded according to the “citizen concept” (Inländerkonzept).

From PIOT we extracted the total material flow vector of all 61 industrial sectors. Exogenizing the 61×10 sized household activity matrix, which records the tonnage of product used by households, required further transformations as resource inputs of four sectors (amounting to less than 1% of total sectoral resource flows) could not be unambiguously allocated to a particular entry in the matrix. In these cases we spread the (resource) flows across sectors proportionally to their size. In addition, we allocated primary inputs across the final household activity matrix proportionally to the flows of goods delivered. The resulting matrix maps the *direct material flows* from “delivering” industrial sectors to household activities.

From the time input-output table (ZIOT) we extracted the direct time input vectors to industrial sectors sized 61×1 and to households sized 10×1. The latter fully captures the spectrum of human non-market (household) activities. Moreover, we separated out a 10×11 matrix mapping the time use of different socio-economic groups by activities from the data set. The socio-economic groups distinguished in this study are listed in Table 5.3.

Abbreviation	Description
av	Average population
<12	Children aged younger than 12
12-65, nw, std	Students between 12 and 65 not enrolled in the labour market
12-65, nw	Citizens between 12 and 65 not enrolled in the labour market
12-65,w,std	Students between 12 and 65 enrolled in the labour market
12-65,w,ls	Employed citizens between 12 and 65 with low skill level
12-65,w,ms	Employed citizens between 12 and 65 with medium skill level
12-65,w,hs	Employed citizens between 12 and 65 with high skill level
12-65,w,av	Employed citizens between 12 and 65, average category
>65	Citizens aged older than 65

Table 5.3 – Socio-demographic groups distinguished in this study

<sup>8</sup> Stahmer (2003a) points out that such a hybrid valuation causes problems when the number of citizens working abroad is not approximately equal to the number of foreigners working in the domestic economy. However, the accounting balance for cross-border commuters is pretty much balanced so that no such problems are expected here.



## **5.6 Some descriptive statistics – an input-output based indicator framework**

Having described the construction of the data set and its main features, we now provide some basic indicators reflecting the general economic, social, and environmental conditions surrounding the average lifestyle in West Germany during 1990 (see Table 5.4). These indicators can be readily obtained from the different input-output tables.

For instance, in 1990, approximately 63 million residents lived in West German households. The total time they could allocate among different market and non-market activities amounted to roughly 554 billion hours. Of these, only 46 billion were spent in the market, 82 billion on productive non-market activities, and 421 billion hours were allocated towards unproductive non-market activities (including sleep). Productive market activities for the provision of goods and services, as measured in the Gross National Product, amounted to 2,245 billion DM. Once productive non-market activities are included this measure rises by 40%. This points towards the importance of households in the provision of the material foundations of a society's welfare and the necessity to include them in any sort of welfare assessment. Thus, as indicated in Section 5.4, using input-output tables with an extended production boundary can considerably alter our view in many areas of interest for sustainability analysis, like international wealth comparisons or various intra-societal welfare assessments, such as poverty or income analysis (and their relationship to resource flows). However, note that the whole bulk of unproductive household activities still remains unaccounted for.

The total material inputs required to provide for the West-German lifestyle summed up to 62.95 billion tons. Of these total material flows only 14.72% were converted into goods – a basic measure of the material efficiency of the societal metabolism. While West Germany showed a positive trade balance in monetary terms, this balance was negative when measured in physical units. This is due to the fact that imports comprise mostly material-intensive goods such as raw materials and intermediate goods, while exports consists mainly of manufactured, high tech, and low-material intensity goods. Many more indicators of this type could be derived to characterise, for example, the different types of capital stocks (man-made, human, natural), or the use of knowledge in the various activities (and its relation to resource use), or for a more adequate (not purely monetary) description of human well-being. We hope that this provides sufficient indication of the richness of the data set and its potentials.

Indicator	Unit	Estimate
Population	10 <sup>6</sup> persons	63.25
Total Time Budget	10 <sup>9</sup> hours	554.10
Productive market activities	10 <sup>9</sup> hours	46.27
Productive non-market activities	10 <sup>9</sup> hours	82.31
Unproductive non-market activities	10 <sup>9</sup> hours	421.36
Residual	10 <sup>9</sup> hours	4.16
GNP	10 <sup>9</sup> DM	2245
GNPextended	10 <sup>9</sup> DM	3230
Total Material Inputs (TMI)	10 <sup>9</sup> tons	62.95
Monetary Trade Balance	10 <sup>9</sup> DM	118
Physical Trade Balance	10 <sup>9</sup> tons	-0.185
Employment	10 <sup>6</sup> persons	28.49
Material Efficiency	%	14.72

Table 5.4 – Socio-economic and environmental key indicators

We have argued earlier that lifestyle analysis is rooted in the basic question of what people actually *do* during the day. Table 5.5 provides a *complete* picture of human activities of different socio-economic groups in West-Germany during 1990. Society's time patterns are largely dominated by "Physiological Regeneration" (PR) – due to the inclusion of sleep in this category – followed by fields such as leisure activities (LEIS), household production (HPROD) and market work (MW). The latter accounts for less than 9% of the total time use of the population. A quick glance at Table 5.5 immediately reveals that activity patterns widely vary with socio-demographic characteristics. The distribution of time allocated to market work, for example, supports the claim that more highly skilled people tend to spend more time on their job. Children spend a considerable amount of time on leisure and regeneration activities as well as education, and therefore require significant amounts of resources from society. Employed citizens, who spend fewer hours at work, tend to spend more time on household production activities. This seems to hint that those groups make-up for their lower market income through the generation of higher non-market incomes.<sup>9</sup> Intuitively, we expect all these different activity patterns to involve very different sets of consumption goods and to trigger very different resource flows.

However, how much time people spend on different activities does not in itself constitute a lifestyle. It is also crucial to know "how" people perform an activity. This information can be gained from expenditure data. Table 5.6 shows how people spend their money on final products provided by the different industrial sectors, and in what activities they use them. In technical terms, this is the matrix expansion of the final household demand vector, briefly discussed in Section 5.3. Ideally, this matrix should be

---

<sup>9</sup>This again seems to support the claim that traditional monetary input-output tables cannot appropriately reflect the distributional realities as outlined in Section 4.4.

further disaggregated by activities and stratified according to socio-demographic characteristics. This would facilitate an in-depth cross-sectional comparison of lifestyles and their associated resource flows rooted in the different uses of time and money in the various household production processes.

Household consumption expenditure was clearly dominated by the demand for market services, which accounted for a remarkable share of 62.54% of the total budget, while 26% were directed towards manufactured goods. Hence, the demand for services from the tertiary sectors was more than double the demand for products from secondary sectors. It would be interesting to assess the actual contribution of services to societies' resource flows in absolute and relative terms, as various authors have stressed their importance in dematerialisation efforts. Unfortunately, this is outside the scope of this Chapter. Only small shares of the household budget were allocated directly to final products from agriculture and energy.

To further deepen our insights into household consumption activities, we need to leave the purely descriptive level of analysis and develop a model that facilitates the integration of data sources in different units. More specifically, we would like to attribute money, time and resource use in society to household consumption activities and other final demand entities, and analyse the mutual relationship between expenditure, material and time flows. This will be attempted in the next Section.

	MW	HPROD	DIY	COM	VW	EDU	PR	SOC	LEIS	CARE	RES
Total	46.27	64.23	6.15	12.25	3.12	15.43	265.58	33.55	94.54	8.81	4.16
	10 <sup>5</sup> hours										
	8.35	11.59	1.11	2.21	0.56	2.78	47.93	6.06	17.06	1.59	0.75
<12	0.00	0.95	0.00	0.00	0.00	7.67	60.71	3.24	26.77	0.00	0.66
12-65, nw, std	0.00	5.25	0.93	0.00	0.27	17.9	46.99	6.85	19.38	0.65	1.70
12-65, nw	0.00	21.12	1.13	0.00	0.85	0.48	47.74	6.92	16.52	3.90	1.34
12-65, w, std	16.78	4.66	1.39	5.65	0.77	4.56	43.05	8.89	13.45	0.41	0.40
12-65, w, ls	16.31	11.92	1.46	4.52	0.14	0.37	44.49	5.79	13.37	1.30	0.33
12-65, w, ms	18.85	9.40	1.65	4.82	0.56	0.39	42.90	6.07	13.43	1.55	0.39
12-65, w, hs	20.50	8.07	1.47	5.26	0.98	0.54	42.45	5.85	12.57	1.82	0.49
12-65, w, av	18.54	9.23	1.56	4.91	0.58	0.74	43.11	6.20	13.26	1.47	0.40
65<	0.00	17.86	0.73	0.00	0.73	0.23	52.67	6.35	20.06	0.75	0.63

Table 5.5 - What do people do? Activity patterns across socio-economic groups

Sector	HPROD	DIY	COM	VW	EDU	PR	SOC	LEIS	CARE	RES	Sum	Perc
Agr	5,899	58	78	10	31	2,144	143	665	59	285	9,371	1.04%
En, Wa	14,070	740	410	80	235	9,662	1,011	6,522	488	1,199	34,416	3.83%
Man	94,799	11,603	7,557	535	1,483	83,687	6,530	16,761	2,134	9,123	234,213	26.09%
Const	862	65	69	13	0	1,260	170	817	83	183	3,522	0.39%
Serv	103,915	13,625	20,073	1,950	10,085	223,672	31,324	123,155	8,439	25,290	561,527	62.54%
Env	2,050	198	231	41	123	3,798	529	2,485	252	429	10,137	1.13%
Edu	0	0	0	0	0	0	0	0	0	0	0	0.00%
N-serv	2,619	74	313	20	2,245	12211	204	6,951	62	19,981	44,679	4.98%
Sum	224,214	26,363	28,730	2,649	14,203	336,433	39,911	157,356	11,517	56,490	897,865	100%

Table 5.6 - Household consumption by sector and activity

## 5.7 Model

In this Section we extend the consumer-lifestyle approach by entering time use data into a conventional environmentally extended input-output model. We use an augmented Leontief model combining monetary, physical and time allocation data to analyse household consumption activities. Production functions relate the amount of inputs used by a sector to the maximum amount of output that could be produced by these sectors with these inputs (Miller and Blair, 1985). In the spirit of the household production literature we assume that for producing the total output  $x$  all human activities require the use of time, goods and materials, that is

$$\begin{aligned}
 x_j &= F(z_{1j}, z_{2j}, \dots, z_{nj}, t_j, r_j) \\
 &\text{where} \\
 z_{ij} &= \text{intermediate inputs from } i \text{ used in production of } j \quad (5.1) \\
 t_j &= \text{time input to production in } j \\
 r_j &= \text{material inputs to production in } j
 \end{aligned}$$

We further assume that  $F(\cdot)$  is of Leontief type. This means that the inputs are perfect complements and only used in fixed proportions. The production function exhibits constant returns to scale. We specify our general model by

$$\begin{aligned}
 x_j &= \min \left( \frac{z_{1j}}{a_{1j}}, \frac{z_{2j}}{a_{2j}}, \dots, \frac{z_{nj}}{a_{nj}}, \frac{t_j}{\tau_j}, \frac{r_j}{\varepsilon_j} \right) \\
 &\text{with} \quad (5.2) \\
 a_{ij} &= \frac{z_{ij}}{x_j}; \quad \tau_j = \frac{t_j}{x_j}; \quad \varepsilon_j = \frac{r_j}{x_j}
 \end{aligned}$$

For estimation we therefore augment the intermediate flow matrix  $Z$  and the partitioned final demand matrix  $Y=(Y^{hh}|Y^{\neq hh})$ , where  $Y^{hh}$  is a matrix of household expenditure classified by household activities and  $Y^{\neq hh}$  is a matrix comprising the remaining final demand categories, with vectors  $(0)$  and scalars  $(0)$  of zeros, vectors of

time inputs  $t^{\text{prod}}$  and  $t^{\text{con}}$ , as well as material input vectors  $r^{\text{prod}}$  and  $r^{\text{con}}$ . The superscripts “prod” and “con” distinguish inputs to market and non-market activities of households. Hence,

$$\mathbf{Z}^{\text{aug}} = \left( \begin{array}{c|c|c} \mathbf{Z} & \mathbf{0} & \mathbf{0} \\ \hline t^{\text{prod}} & \mathbf{0} & \mathbf{0} \\ \hline r^{\text{prod}} & \mathbf{0} & \mathbf{0} \end{array} \right) \quad \text{and} \quad \mathbf{Y}^{\text{aug}} = \left( \begin{array}{c|c} \mathbf{Y}^{hh} & \mathbf{Y}^{*hh} \\ \hline t^{\text{con}} & \mathbf{0} \\ \hline r^{\text{con}} & \mathbf{0} \end{array} \right) \quad (5.3)$$

As indicated in Equation (5.2) we calculate an augmented direct coefficient matrix  $\mathbf{A}^{\text{aug}}$  by

$$\mathbf{A}^{\text{aug}} = [a_{ij}] = \frac{z_{ij}^{\text{aug}}}{x_j} \quad (5.4)$$

Defining an identity matrix  $\mathbf{I}$  of size  $\mathbf{A}^{\text{aug}}$ , we can establish the augmented, demand side Leontief model, that is

$$\mathbf{X}_{\text{act}}^{\text{aug}} = \begin{bmatrix} \mathbf{X}_{\text{act}}^{\text{tot}} \\ \mathbf{r}_{\text{act}}^{\text{tot}} \\ \mathbf{t}_{\text{act}}^{\text{tot}} \end{bmatrix} = (\mathbf{I} - \mathbf{A}^{\text{aug}})^{-1} \mathbf{Y}^{\text{aug}} = \mathbf{L}^{\text{aug}} \mathbf{Y}^{\text{aug}} \quad (5.5)$$

where  $\mathbf{X}_{\text{act}}^{\text{aug}}$  is the augmented total output matrix consisting of the total economic output vector  $i\mathbf{X}_{\text{act}}^{\text{tot}} = \mathbf{x}_{\text{act}}^{\text{tot}}$  with  $i$  being a vector of ones,  $\mathbf{r}_{\text{act}}^{\text{tot}}$  is the total material flow vector and  $\mathbf{t}_{\text{act}}^{\text{tot}}$  the total time flow vector with each element representing one of the  $k$  household non-market activities. From this model we can extract direct as well as direct and indirect requirement coefficients in various units. By extracting a sectoral total direct and indirect material intensity  $\boldsymbol{\varepsilon}^{\text{tot}}$ , we can calculate households' activity-specific material intensities in monetary and time units respectively by

$$\boldsymbol{\varepsilon}_s^{\text{act}} = (\boldsymbol{\varepsilon}^{\text{tot}})' \mathbf{Y}^{hh} (\hat{\mathbf{y}}_{\text{act}}^{hh})^{-1} \quad (5.6)$$

where  $y_{act}^{hh} = \mathbf{i}Y^{hh}$  is total household consumption expenditure by activity, the hat symbol  $\hat{\phantom{x}}$  indicates diagonalisation of a vector, and,

$$\epsilon_{time}^{act} = (\epsilon^{tot})' Y^{hh} (\hat{t}^{con})^{-1} \quad (5.7)$$

## 5.8 Results

In this Section we present some results that can be obtained from this type of model. In the first part the model estimations will be discussed. We try to demonstrate how our approach in multiple units facilitates a more far-reaching lifestyle analysis. In the second part further extensions will be discussed, based on some preliminary estimations with U.S.-data. In relation to Section 2, the first part provides an example of how analysis can benefit from an extended scope (argument 1), and of the unique information content of time use data (argument 3). The second part stresses the “anchor” function (argument 4) of time use data and its potential to understand economic choice in a wider social context (argument 2).

### 5.8.1 Model Estimations

As argued in Section 4, it is of particular interest for the sustainability practitioner to observe the shifting borderline between the market and the non-market spheres, in order to understand the resource flows triggered by different activities (Cogoy, 1995). To do so, we can either follow particular household activities through time, or compare them across socio-demographic groups or different activities. Because of the limitations in our data we are restricted to shifts of this boundary across activities, i.e. we can only study how the average household combines its time and money resources in different activities and what material (strictly speaking also time and money) flows are triggered by a particular choice of market and non-market inputs. This is shown in Table 5.7. Generally, expenditure ( $y_{act}^{hh}$ ) and resource flows ( $r_{act}^{hh}$ ), as well as embodied production time ( $t_{ind}^{hh}$ ), show very similar distribution patterns across activities, while non-market time

( $f^{on}$ ) seems to be allocated quite differently. Moreover, for some activities, such as household production and leisure, the direct ( $r^{con}$ ) and total ( $r_{act}^{hh}$ ) resource use patterns differ significantly.

These features become clearer when we further aggregate activities into the four major time use categories (plus travel) introduced in Section 5.5. Figure 5.5 presents a bar chart with activity fields on the horizontal axis and the percentage share of total expenditure, time, and resource flows on the vertical axis. It should be noted that “travel” only comprises commuting to work. The other travel activities could not be separated out easily and are left as part of the committed, personal and free times.

Several informal conclusions can be drawn from Figure 5.5. First, resource flows seem to follow monetary household consumption expenditures more closely than they do time expenditures. Second, there seems to be greater variation in time allocation than in the allocation of money and triggered resource flows across activity fields. Third, the relationship between direct and total resource use seems to differ depending on the activity field. Fourth, only for “committed time” the share of total expenditure is smaller than the percentage share of total resource flows triggered. Fifth, activity fields with relatively small time inputs seem to show relatively higher levels of resource use. This is suggestive of the frequent claim that the substitution of capital for time leads to an increased resource intensity of an activity, although we do not have sufficient data to assess this claim fully here.

Overall, we might safely conclude that the boundary between the market and non-market spheres moves across activity fields, resulting in different patterns of resource use. Therefore, this approach seems to facilitate very well a detailed and insightful analysis of household consumption activities. Of course, our results are not more than a little appetiser for more detailed analysis, and it is not difficult to envision how much further analysis with some additional cross-sectional or time series data could go.

So far, the analysis has remained on a “gross”-level. However, it is often much more interesting to look at how much monetary, physical and time flows are triggered per unit change of a particular activity. This allows us to compare activities in terms of their environmental and socio-economic impact. In input-output analysis this approach goes under the name of *multiplier analysis*. In our discussion we concentrate again on the physical multipliers.



Flow	Unit	HPROD	DIY	COM	VW	EDU	PR	SOC	LEIS	CARE	RES
	109 DM	224.21	26.36	28.73	2.65	14.20	336.43	39.91	157.36	11.527	56.49
	%	24.97	2.94	3.20	0.29	1.58	37.47	4.45	17.53	1.28	6.29
	109 DM	401.57	43.62	54.34	4.42	23.91	572.11	60.80	252.05	17.96	91.60
	%	26.38	2.87	3.57	0.29	1.57	37.58	3.99	16.56	1.18	6.02
	109 hours	64.23	6.15	12.26	3.13	15.43	265.58	33.55	94.54	8.81	4.168
	%	12.65	1.21	2.41	0.62	3.04	52.30	6.61	18.62	1.73	0.82
	106 tons	721.602	74.951	105.250	14.925	42.150	1241.236	190.058	783.820	85.769	140.087
	%	21.22	2.20	3.10	0.44	1.24	36.51	5.59	23.05	2.52	4.12
	106 tons	10,312.51	918.74	732.07	93.27	366.84	11,506.59	1,216.21	6,026.00	515.29	147.61
	%	33.83	3.08	2.45	0.31	1.23	37.11	4.06	19.73	1.73	4.94
	109 hours	4.020	0.399	0.439	0.031	0.241	5.605	0.472	2.063	0.112	1.130
	%	27.70	2.75	3.02	0.22	1.66	38.62	3.26	14.22	0.77	7.79

Table 5.7 – Money, time and resource flows by household activities

Units	HP	DIY	COM	VW	EDU	PR	SOC	LEIS	CFO
tons/DM	43.02	32.14	22.02	29.75	23.06	30.64	25.85	33.40	37.46
rk	9	6	1	4	2	5	3	7	8
tons/hour	141.32	129.35	49.84	24.96	20.90	38.01	30.32	54.40	48.36
rk	9	8	6	2	1	4	3	7	5
DM/hour	3.49	4.29	2.34	0.85	0.92	1.27	1.19	1.66	1.31
rk	8	9	7	1	2	4	3	6	5

Table 5.8 – Resource Intensities by Household Activities

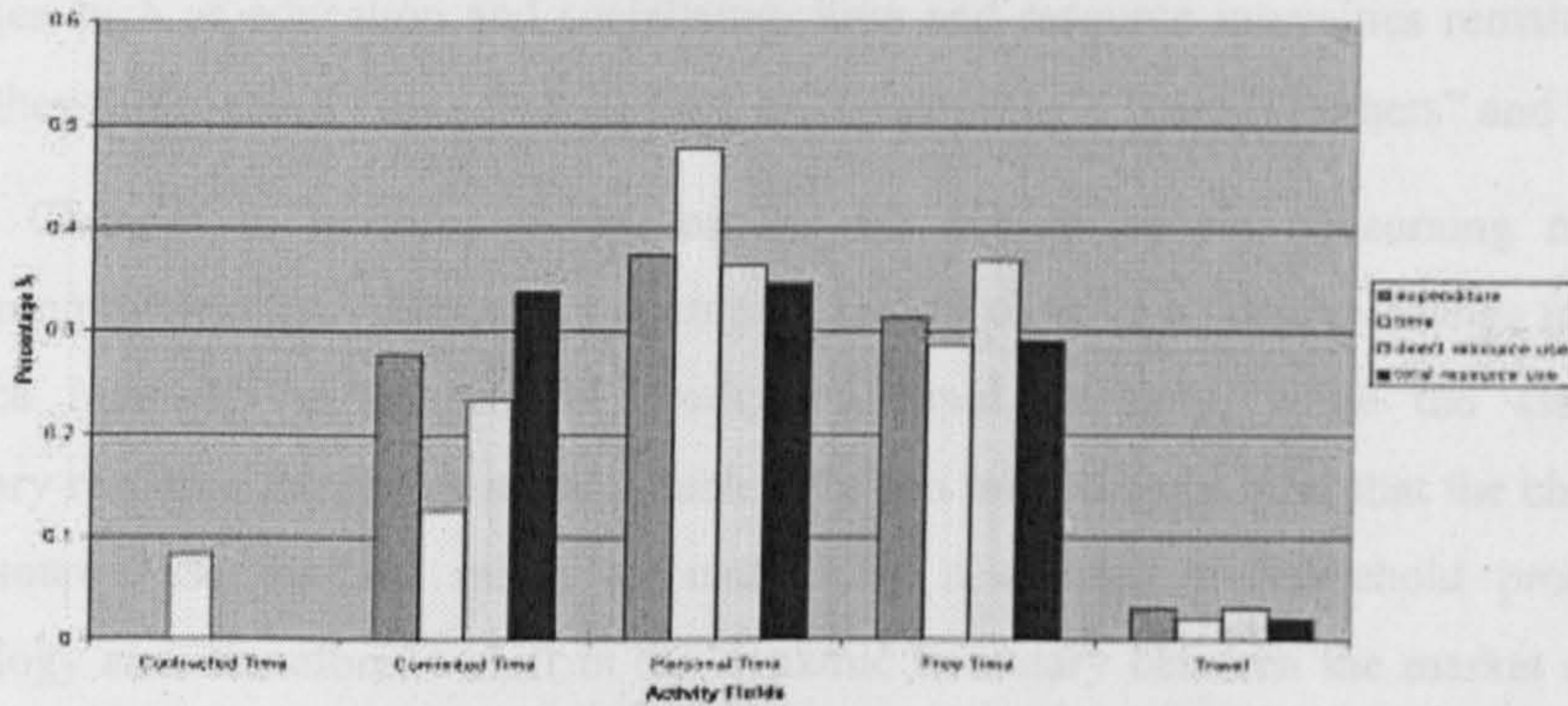


Figure 5.5 - Interrelation between expenditure, time and resource use by activity field

Usually, material intensities are related to the total amount of money spent during a given reporting period. We will henceforth call them “monetary material intensities” (see Equation 5.6). Once time use data is introduced into the framework, we can also express material usage per unit of time spent on a particular activity within the given reporting period – henceforth “time material intensities” (see Equation 5.7). This puts resource usage in close relationship to *activity performance* and provides a new, useful perspective to policy makers (see Schipper et al., 1989; Jalas, 2002a; Jalas, 2002b; Van der Werft, 2002; Hofstetter and Madjar, 2003).

It is important to regard monetary and time material intensities as complements rather than substitutes, because they relate resource use triggered by different activities to the two basic inputs of household production processes. To complete the picture, it is also advisable to relate these two inputs to each other by expressing consumption expenditure per unit of time or vice versa. We will henceforth call these coefficients *household production input intensities*, denoted by  $\epsilon_{hpi}^{act}$ .

Table 5.8 presents monetary and time material intensities together with household production input intensities. The Table shows that monetary and time resource intensities vary considerably across activities. This variation is not only expected (see, Table 5.7 and Figure 5.5), but desirable, as it provides the additional information necessary for identifying richer integrated models. Note that, because time inputs in the household production function are numerically smaller than consumption expenditures, the time resource intensity coefficients have a larger magnitude than the monetary resource intensities. As we would expect from the previous discussion, household production is the most resource-intensive activity, in terms of both money and time. In contrast, for

activities such as education and socialising, time and resource intensities remain small, while they differ greatly for activities such as “commuting”, “care for others” and “DIY”.

Changes in resource intensities can be due to people consuming more or consuming differently. Assume, for example, that we observe a positive change in a time resource intensity and household production input intensity, while the associated monetary resource intensities remain stable. We can immediately infer that the change in the resource use patterns might be caused by a change in household production technology and, therefore, a shift in the dynamic boundary between the market and the non-market spheres. In other words, we are confronted with a social re-structuring of a household consumption process and can start searching for the causes of this shift.

### 5.8.2 Some further extensions of the consumer-lifestyle approach

By going back to Figure 5.5 we can extend our analysis further and try to answer the question *why* we might observe certain patterns of time, money and material use. As an example, consider the pattern for the activity field “committed time.” Compared with expenditure and triggered resource flows, a relatively small share of the time budget was allocated to this activity. Though it might well be in the nature of activities such as household work or do-it-yourself (DIY) activities that they require relatively more money than time inputs compared with other activities, there might be other reasons for the discrepancy between time use and expenditure and material flows across activity fields. Input-output models are not of great use themselves in explaining these discrepancies, because of their restricted production technology. An econometric approach based on a more flexible production functional form, which allows for substitutability among inputs to household production processes, might be more promising. However, what we can do here is apply theoretical or empirical models for explaining the outcomes of input-output calculations.

An obvious candidate to do so would be the household production model itself. However, to make a case for the increased potentials of interdisciplinary research created by time use data, we apply a theory derived from an applied model in the sociological literature. Authors in these fields have worked a great deal with activity-specific enjoyment ratings to understand time patterns of a population. The related literature on people’s subjective well-being is a large research area in itself. It is therefore important to highlight the exemplary nature of the following remarks, which will not be able to fully

do justice to this important research, which has also become increasingly important in the study of resource flows. Robinson and Godbey (1997, p.249) find in their analysis of enjoyment ratings, in combination with time allocation data spanning the time period from 1965 to 1995 that there is striking evidence for the long-disputed assumption that there *is* a relationship between people's attitudes and their behaviour. In the course of daily life people *do* engage in activities that bring them greater enjoyment.

This *hedonistic model* can, for example, explain many of the major shifts in activity patterns in the U.S. between 1965 and 1995.<sup>10</sup> Table 5.9 shows such ratings provided on a scale between 0 (dislike) and 10 (like a lot), aggregated into our four main activity yields for the year 1985.

Activities	Rating	Smallest	Biggest	n
Contracted time	6.7	6.3	7.0	2
Committed time	6.1	4.9	8.8	8
Personal time	7.6	6.5	8.5	3
Free time	7.9	6.0	9.2	10

5.9 Subjective enjoyment ratings for the four main activities

And indeed, people seem to enjoy the activity field “committed time” least. This is mainly driven by low ratings for typical housework activities, such as cleaning or ironing. This low rating of (most) activities associated with the category “committed time” can be found for all different years (see, Robinson and Godbey, 1997). Once we assume that this is a general pattern, which also holds for Germany,<sup>11</sup> this would provide another explanation of why the time input into housework activities might be so low. The high expenditure might then be interpreted as an indication that people have tried to “save” time by increasing the capital intensity of housework processes by buying dishwashers, vacuum cleaners, washing automates or coffee machines, or by substituting activities like eating out for preparing the meal at home and having to do the washing-up afterwards.

<sup>10</sup> Interestingly, one of the big exceptions is “watching television”. Even though people seem to enjoy it less and less, they do it more and more. All increases in free time in the U.S. between 1965 and 1985 were completely re-invested into watching television!

<sup>11</sup> Clearly, this data is for the U.S. and cannot be just applied to Germany, where people might have very different attitudes towards activities. However, there might be good reasons to believe that Germany shows similar trends. If we assume that the hedonistic model also applies to other countries, there are good reasons to believe that similar low enjoyment ratings would be given in Germany, as a comparison of the time use for housework between 1992 and 2000 shows that the absolute amount of time invested into this kind of activities has declined despite an increase in the population (Statistisches Bundesamt, 2003, p.11).

Scholars in the environmental debate have argued that this continuous investment into time saving technology is another important factor in explaining the high level of resource use of housework (Binswanger, 2001; J alas, 2002). Hence, we have built a little theory explaining the outcomes of our input-output model, that is why money and resource use are comparatively high and time use is comparatively low for this activity field.

Finally, we would like to briefly sketch how input-output models can be used to disentangle the relationship between well-being and resource use. This has not been comprehensively attempted so far by input-output practitioners. In Section 5.6 it was already highlighted that productive non-market activities significantly contribute in building up the material foundations for the creation of well-being. From an accounting perspective we can only speak about economic welfare in any meaningful way if these activities are included. Calculating the resource use associated with the different productive market and non-market activities and relating them to their “welfare contribution” would already mark a first step into this direction.

However, there is a long line of criticism of monetary welfare measures from other social sciences and within the economic literature itself. Monetary welfare measures do not only leave out the great bunch of unproductive non-market activities, which can be assumed to play a major role in the creation of human well-being as explained earlier. They are generally too narrow and measure at best only the material foundations of the welfare creation process. To overcome this we can incorporate activity-specific enjoyment ratings into the input-output framework in order to model life enjoyment as an indicator of well-being associated with a particular lifestyle. This certainly is another, more far-reaching step on the way to disclosing the relationship between the material foundations of well-being (provision of goods and services), resource use and well-being itself. Thereby, not only the enjoyment of different activities can be compared, but also indices for the average life enjoyment of a lifestyle group can be calculated. The latter is shown in Table 5-10, which again combines data from Germany and the U.S..

	∅	<12	12<65, nw,std	12<65, nw	12<65, w, std	12<65, av	>65
Average Enjoyment	7.36	7.65	7.51	7.25	7.39	7.30	7.36

Table 5.10 – Enjoyment associated with activity patterns of different socio-economic groups

It should be clear that we assume that there are no meaningful differences in enjoyment ratings across socio-economic groups: indices for all different groups are calculated from enjoyment ratings of the average population. This is clearly not the case, as shown by various authors (see Frank, 1997). Enjoyment ratings differ significantly across socio-demographic groups with characteristics such as income, employment status, age etc. However, as most groups seem to like similar types of activities more or less (see, Robinson and Godbey, 1997), we should be able to get a good picture about more or less desirable activity patterns in general even though we cannot be confident about the absolute level of enjoyment. It is not surprising that children are perceived to have the most enjoyable time patterns, because of their larger amount of personal and free times and their little engagement in activities associated with “committed time”. And in fact, the appreciation of this life period is often expressed by people when they speak about their “easy and carefree childhood”. It is also not surprising that the activity pattern associated with the lifestyle of students, who are not enrolled in the labour market, comes second. The category comprising unemployed people and housewives shows the least desired activity pattern, and old people live what might be called an “average life”.

## **5.9 Conclusion**

In this chapter we have proposed the integration of time use data into monetary-physical data frameworks. The appeal of time use data relates to four major capabilities, which allow to represent social and behavioural issues in quantitative frameworks much more comprehensively. First, time use data allows for extending the scope of quantitative models to cover all human activities. Second, it helps in understanding and modelling economic decisions in a much wider social context. Third, the unique information carried by time use data allows for representing patterns of social life quantitatively. Fourth, time use data can serve as a very powerful “anchor” to incorporate other models and data into quantitative frameworks. Integrated data frameworks in monetary, physical, and time units therefore can cover all dimensions of sustainability comprehensively and appear as a good platform for sustainability research.

In an empirical application we have demonstrated how lifestyle analysis can benefit from the introduction of time use data through the adoption of a household production view on the meso-level, and we have demonstrated how this can be achieved in an input-output context. Such a productive view of household activities corresponds much better with the basic intuition of the Industrial Ecology approach, as it allows for analysing the production and consumption ends of the economy within one coherent framework and for providing a large array of new and interdisciplinary research options. The empirical analysis has been restricted by the available data. However, the results from our simple application have hopefully provided a flavour of how much further sustainability inquiries can go once monetary, physical and time use data have been integrated. So far our interdisciplinary journey into the time use literature has been very exciting and interesting and we sincerely hope that we have provided some inspiration to other researchers interested in the sustainability issue to join in.

# **6 . DISCUSSION AND CONCLUSION**



## **6.1 INTRODUCTION**

In this PhD thesis new German data developments have been used to explore new opportunities for quantitative Sustainable Consumption (SC) research. The first two main chapters have addressed the issue of how the representation of technology in environmental input-output models can be improved, while the later two have directed the attention towards the representation of lifestyles. In the following a discussion of some of the core issues is provided. It is structured into three parts. Section 6.2 summarises and discusses the findings of the discussion on monetary and physical input-output analysis before Section 6.3 deals with the lifestyles issues. Finally, Section 6.4 frames the discussion in a broader context and concludes.

## **6.2 MONETARY AND PHYSICAL INPUT-OUTPUT ANALYSIS**

The first two chapters focussed on the adequate representation of technology in environmental input-output models given the availability of monetary (MIOT) and physical (PIOT) input-output tables. Chapter 2 clarified some misperceptions associated with the construction of the German PIOT, developed the full implications of a conceptual model for analysing the relationship between monetary and physical input-output analysis initially proposed by Weisz and Duchin (2006) and highlighted the need to shift the debate on the appropriate specification of environmental input-output models to an empirical level. Chapter 3 provided a first empirical analysis of the production structures as represented in MIOT and PIOT using the visual capabilities of qualitative (input-output) methods.

In the course of these analyses it was not difficult to demonstrate the value and shortcoming of PIOTs in the context of environmental input-output modelling. On the one hand, physical measurement in weight units is incapable of representing immaterial service outputs (Dietzenbacher, 2005): the outputs of service industries are only depicted in terms of residual outputs. As a direct consequence, environmental input-output models based on purely physical production structures will fail to 'correctly' calculate environmental factor embodiments of given final demands because not all supply chain

links are adequately captured quantitatively. This finding is strikingly supported by the results from the model comparison in Chapter 2.

However, the analysis also highlighted that some of the information contained in PIOTs can be used to improve technological representations of environmental input-output models based on production structures purely specified in monetary units: this is due to PIOTs in contrast to MIOTs providing a full coverage of environmental service activities such as recycling and waste treatment. In this sense, the first two chapters stressed the potential value of the integration of data in multi-unit data frameworks for informing SC policy.

While clear recommendations for the model specification could be derived for tertiary and environmental service sectors, this was not possible for the representation of the remaining primary and secondary sectors. Even though the qualitative methods used in this thesis seemed able to contribute to a more informed decision in the specification process, they clearly remained limited and left room for quantitative methods to contribute to this process.

The work presented suggests the importance of further pursuing the empirical study of the differences in monetary and physical input-output analysis started in Chapter 3 of this PhD thesis. Three lines of research seem to be particularly important:

- *Firstly*, there is a need for a discussion of the computational aspects of physical and hybrid input-output analysis arising from the almost perfect concentration of physical flows in the PIOT. In this context some lessons can be learned from similar discussions in the lifecycle analysis (Suh, 2006).
- *Secondly*, the qualitative comparison presented here needs to be followed by a quantitative analysis of the differences between monetary and physical input-output analysis. On the one hand, this thesis suggests the particular importance of methodologies which help to identify where differences in the monetary and physical input-output analyses arise in the supply chain. In this context, structural path analysis seems to provide a suitable framework (Defourney and Thorbecke, 1984). On the other hand, error propagation methods (Bullard and Sebald, 1998; Schintke and Stäglin, 1988) to control for the potential large influence of individual elements in the direct coefficient matrix derived from physical input-output tables might turn out to be helpful for the specification of hybrid input-output models.

- *Thirdly*, there is further room for an accounting discussion on the merits of assigning the secondary products of an establishment to its principal output, or to the industry where it is principal output, in the light of the separation of products and immaterial services in the production structure.

While these qualitative and quantitative methods are important for informing the specification of an environmental input-output model based on production structures in mixed units, the ultimate decision will never be taken away from the researcher and will depend on various factors such as the particular environmental factor or the particular policy question under consideration. Therefore, it will be equally important to apply environmental input-output methods with hybrid production structures to different policy questions and compare the results.

Currently, such research is under way framed into the policy context of the European Commission's "Thematic Strategy on the Use of Natural Resources" (EC, 2005). The strategy's overall objective is to reduce the negative environmental impacts generated by the use of natural resources. For policies to be most effective, it suggests a strategic approach, which first tackles resource flows with high environmental impacts.

Nathani (2006) introduced an energy-economic model to prioritise materials in terms of their climate change impacts throughout the economy. In this context it is important to separate material goods and immaterial services, which is achieved by decomposing the supply chain layer-wise. However, the research in this thesis shows that material groups such as iron, copper or aluminium as represented in the sector breakdown of the German MIOT also contain a (potentially large) immaterial service component. The model proposed by Nathani is therefore juxtaposed with an alternative model specification, where the various material groups are represented with information from the PIOT. The discussion then tackles various of the 'practical' and research-specific specification issues.

Finally, it should be mentioned that the specification of the production structure in terms of measurement units is certainly not the only issue associated with the most adequate representation of technology for SC research. The other major issue is the representation of foreign technology used for producing the import goods. Usually environmental input-output models assume that the production of an imported good triggers the same amount of emissions as if it was produced at home. Other research carried out as part of this thesis (see Appendices C and D) has shown that this can lead to substantial under-estimations of emissions as, for example production processes in low-

income countries often tend to be much more inefficient than in a high income country such as Germany. The more frequent use of multi-regional input-output models therefore seems to be the other useful addition for improving the technological representation in environmental input-output models.

### **6.3 LIFESTYLE ANALYSIS**

Chapters 4 and 5 on lifestyle analysis focussed on issues of consumption. They highlighted the importance for policy decisions to be based not only on technological issues and the production of goods, but also on social and behavioural issues associated with the consumption side of the economy. Both chapters aimed to contribute to the literature using some unique data sources from Germany's socio-economic reporting system.

Chapter 4 used the conventional framework of lifestyle analysis as traditionally applied in the input-output literature, in which consumption expenditure patterns are seen as a manifestation of a lifestyle. It linked detailed data on income, expenditure, employment and demographics to the environmental input-output model to analyse the development in GHG emissions of 41 socio-economic groups in Germany between 1991-2002. The interest was in the 'hidden' social information and its potential to inform climate change policy. Structural decomposition and regression analyses were used to reveal this information.

Methodological contributions to the literature could be made due to the richness of the data: the application of structural decomposition analysis could be extended to include detailed demographic variables, while a full panel data approach was applied for the first time controlling for time and group specific effects. While the results from the decomposition analysis seemed useful for informing policy making, the insights gained from the regression were rather slim considering the large amount of data work involved.

The main limitations were associated with the small number and type of regression variables available as well as the definitions of the lifestyle groups. In a different piece of research carried out in the course of this project, data from a commercial lifestyle database for marketing purposes were used in a panel regression analysis over household groups and types to determine social factors driving CO<sub>2</sub> emissions in the UK (see Appendix B), as recommended by Duchin (1998). The main

advantage of such an approach is not only the larger number and more interesting nature of the regression variables, but also the spatial rooting of the socio-economic classification system.

Such data sources have the general advantage that once a specific target group is identified by the analysis, certain spatial entities can be specifically addressed by policy. Exploiting the spatial information content embodied in these data systems more rigorously is part of current research efforts. In this sense the national accounting system used in the thesis are very limited. Nevertheless it is likely that adding additional lifestyle variables to the data could substantially increase the analytical value.

Chapter 5 criticised such a purely expenditure driven lifestyle approach and argued that environmental input-output models will remain very limited in terms of a more comprehensive representation of social issues. A more appropriate lifestyle concept is based on people's activity pattern reflecting what they do rather solely on what they spend. Time use data was introduced as a way of representing all human – rather than only market – activities side-by-side with the idea of an integrated data framework in monetary, physical and time units as an adequate platform for SC research. Here, economic, environmental and social aspects were represented in one basic measurement unit each.

The conceptual arguments proposed for the inclusion of time-use data in such an integrated framework seemed convincing. However, the demonstration of all its merits with the available data was more problematic. While the uniqueness of the 'Magic Triangle' data of the German socio-economic reporting system allowed the demonstration of a first methodological implementation of such a hybrid environmental input-output model in mixed monetary, physical and time units and some other extensions, the absence of detailed data for different lifestyle groups was a drawback.

However, it seems that the 'whole package' of conceptual argument and empirical example provide enough reasons to motivate more detailed future research. The main task in this context would be to estimate household activity-specific consumption expenditure and time use matrices for different lifestyle groups. How this can be achieved has been indicated in Chapter 5 and is documented, for example, in Brodersen (1990) or INSTRAW (1996).

The initial interest for SC research would be to see how different socio-economic group combine money and time in different 'consumption technologies' to achieve a particular consumption target and what the associated environmental impacts are. There

is a considerable interest in the literature on this issue. Do people consume differently when they have more time at their disposal? Is the environmental impact of such lifestyles really lower? How do we substitute time and capital? Moreover, the activity classification would allow the linking of many interesting data sources into such models as, for example, information about people's health status, their exercise routines or enjoyment of activities.

## 6.4 BROADENING THE VIEW

Overall it might be concluded that this thesis has at least conceptually established the value of integrated data framework in monetary, physical and time units for SC research. However, particularly in the case of the lifestyle analysis these merits could not always be fully demonstrated with the data obtained from the socio-economic reporting system.

It needs to be stressed that data frameworks in monetary, physical and time units can only be a starting point for comprehensive SC analysis. It might be the biggest limitation of this thesis in the context of SC that it largely fails to deal with any wider welfare issues comprehensively. These play a key role for policy formation. In chapter 4, for example, evidence was provided for a macro-rebound effect showing that 117Mt of GHG emission savings between 1991 and 2002 from energy efficiency improvements in the German economy were 'eaten-up' by increases in final consumption. Whether or not these 117Mt are something, which should be tackled by policy through curbing consumption can only be seriously discussed, if information about the development in well-being are available.

The thesis has arrived back at the opening discussion: in the introduction we have presented some evidence that increases in final consumption do not or hesitantly translate into increases in well-being in industrialised countries. By doing so, it has been suggested that *consuming less* might be a serious policy option neglecting all the institutional barriers, which would certainly emerge. In Chapter 5 some extended measures of welfare have been presented as well as activity specific enjoyment ratings. However, the accounting literature has suggested that all these measures are partial and societal well-being needs to be measured in a wider set of indicators (e.g. Juster et al., 1981). In this sense only the development of a comprehensive welfare module for the German socio-

economic welfare system in multiple units and multiple classifications, as for example the SESAME framework (see Keuning, 1994; Keuning 2000) would allow quantitative SC research to inform policy comprehensively in the full spirit of the Rio mandate.

However, whether or not *consuming less* is a serious option for individuals will depend on the alternatives they are presented with. This is often neglected by authors. Particularly the socio-anthropological literature has highlighted that consumer goods are an integral part of the culture in a consumer society. They are used for creating identity, to reflect a social position or to communicate with others and cannot just be taken away from people (e.g. Douglas, 1976; Douglas and Isherwood, 1979). Talk about reductions in consumption therefore need to be accompanied by visions of alternative ways of living, which are appealing to people. Some other research carried out in the course of this PhD project (see Minx et al., 2006; Minx and Tschochohei, 2006) has therefore been interested in the concept of the ‘part-time society’ developed by Carsten Stahmer (Stahmer, 2003).

The work associated with the part-time society starts from the idea that it might be most promising, if decision-making directed towards more sustainable lifestyles is guided by a vision of society. In this vision the structural problems industrialised countries like Germany typically suffer from such as the problems on the labour market, the ageing demographic structure of society, the unresolved issue of gender equality, the highly level of public debt, increasing levels of inequality, the deterioration of the welfare state or the detrimental environmental impacts of the current lifestyle are reconciled and embedded in a new model of welfare generation. The central lever to such a re-organisation of society is a radical re-distribution of work between the formal and informal sector. A reduction in market times of the current work force allows for an equal participation in market work processes. In return all members of society also participate in the informal work and help to put strain off the public purse and social security systems, whilst strengthening social cohesion.

It is beyond the scope to introduce these ideas more comprehensively. However, beside all discussion about improving data frameworks and models for informing policy, we should not forget to implement the policies required to move towards more sustainable lifestyles. Integrated data frameworks need to be accompanied by an integrated policy approach.

## References

- Alcantara, V. and Duarte, R., 2004, Comparison of Energy Intensities in European Union Countries: Results of a Structural Decomposition Analysis, *Energy Policy* 32: 177-189.
- Aroche-Reyes, F., 1996, Important Coefficients and Structural Change: A Multilayer Approach, *Economic Systems Research* 8: 235-246.
- Aroche-Reyes, F., 2002, Structural Transformation and Important Coefficients in North American Economies, *Economic Systems Research* 14(3): 235-246.
- Atkinson, G., 1997, *Measuring Sustainable Development*, Edward Elgar Publishing, Cheltenham.
- Ayres, R.U., 1989, Industrial Metabolism, in: Ausubel, J.H. and Sladovich, H.E. (eds), *Technology and Environment*, National Academy Press, Washington DC.
- Baas, L., Hofman, H., Huisingh, D.V., Huisingh, J., Koppert, P. and Neumann, F., 1990, *Protection of the North Sea: Time for Clean Production*, Rotterdam, Erasmus Centre for Environmental Studies, Erasmus University.
- Bacharach, M., 1970. *Bi-Proportional Matrices and Input-Output Change*. Cambridge University Press, Cambridge, UK.
- Bailey, R.R., 2000, *Input-Output Modelling of Material Flows in Industry*, Phd Thesis, Georgia Institute of Technology, Georgia.
- Barth, F., 1967, On the Study of Social Change, *American Anthropologist* 69(6): 661-669.
- Becker, G., 1965, A theory about the allocation of time, *Economic Journal* 75(299): 493-517.
- Beckerman, W., 1995, *Small is Stupid. Blowing the Whistle on the Greens*, Duckworth, London.
- Bellet, M., Lalic, S. and Vincent, M., 1989, Clusters, Production Routes and Industrial Complexes in the Production System, Paper presented at the 9<sup>th</sup> International Conference on Input-Output Techniques, Keszthely, Hungary.
- Beutel, J. and Stahmer, C., 1982, Input-Output Analyse der Energieströme 1980, *Allgemeines Statistisches Archiv* 3: 209-239.
- Betts, J.R., 1989, Two Exact, Non-Arbitrary and General Methods of Decomposing Temporal Change, *Economic Letters* 30: 151-156.
- Bin, S. and Dowlatabadi, H., 2005, Consumer Lifestyle Approach to US Energy Use and the Related CO<sub>2</sub> Emissions, *Energy Policy* 33(2), pp.197-208
- Binswanger, M., 2001, Technological Progress and Sustainable Development. What About the Rebound Effect?, *Ecological Economics* 36: 119-132.
- Binswanger, M., 2002, Time-Saving Innovations and Their Impact on Energy Use: Some Lessons from a Household-Production-Function Approach, Discussion Paper 2002-W01, Solothurn University of Applied Sciences and Northwestern Switzerland.
- Bishop, R. C., 1978, Endangered Species and Uncertainty. The Economics of a Safe Minimum Standard, *American Journal of Agricultural Economics* 61(5): 926-930.
- Bon, R., 1989, Qualitative Input-Output Analysis, in: Miller, R.E., Polenske, K. and Rose, A.Z.(eds), *Frontiers in Input-Output Analysis*, Oxford University Press, Oxford: 222-231.
- Brach, D., Grubb. M. and Vronlijk, C., 1999, *The Kyoto Protocol: A Guide and Assessment*, Earthscan, London.
- Bullard, C.W and Herendeen, R.A., 1974, The Energy Costs of Goods and Services, *Energy Policy* 1(4): 268-277.
- Bullard, C.W. and Sebald, A.V., 1977, Effects of Parametric Uncertainty and Technological Change on Input-Output Models, *Review of Economics and Statistics* 59: 75-81.
- Bullard, C.W., Penner, P. and Pilati, D., 1978, Net Energy Analysis, *Resources and Energy* 1(3): 267-313.
- Bundesministerium für Umwelt; Naturschutz und Reaktorsicherheit (BMU), 2005, Nationales Klimaschutzprogramm 2005. Sechster Bericht der Interministeriellen Arbeitsgruppe "CO<sub>2</sub>-Reduktion", BMU, Berlin.



- Bundesministerium für Umwelt; Naturschutz und Reaktorsicherheit (BMU), 2006, Demonstrable Progress Report: 2006 Report under the United Nations Framework Convention on Climate Change, BMU, Berlin.
- Boulding, K.E., 1966, The Economics of the Coming Spaceship Earth, in: Resources for the Future (eds.), *Environmental Quality in a Growing Economy*, John Hopkins University Press, New York.
- Brodersen, S., 1990, Time and Consumption, Denmark Statistics.
- Cairncross, A.K., 1958, Economic Schizophrenia, *Scottish Journal of Political Economy*, February: 15-21.
- Carlstein, T., Parks, D. and Thrift, N. (eds.), 1978a, *Timing Space and Spacing Time*, Volume 1: Making Sense of Time, Edward Arnold Ltd, London.
- Carlstein, T., Parks, D. and Thrift, N. (eds.), 1978b, *Timing Space and Spacing Time*, Volume 2: Human Activity and Time Geography, Edward Arnold Ltd, London.
- Carlstein, T., Parks, D. and Thrift, N. (eds.), 1978c, *Timing Space and Spacing Time*, Volume 3: Time and Regional Dynamics, Edward Arnold Ltd, London.
- Chang, Y.F. and Lin, S.J., 1998, Structural Decomposition of Industrial CO<sub>2</sub> Emissions in Taiwan: An Input-Output Approach, *Energy Policy* 26(1): 5-12.
- Charkiewicz, E., van Bennekom, S. and Young, A., 2001, Transitions to Sustainable Production and Consumption - Concepts, Policies and Actions, Shaker Publishing, Maastricht.
- Ciriacy-Wantrup, S.V., 1952, Resource Conservation: Economics and Policies. University of California Press, Berkeley.
- Cleveland, C.J., and Ruth M., 1997, When, Where and How Much Do Bio-physical Limits Constrain the Economic Process?, *Ecological Economics* 22: 203-223.
- Cogoy, M., 1995, Market and Non-Market Determinants of Private Consumption and Their Impacts on the Environment, *Ecological Economics* 13:169-180.
- Cogoy, M., 1999, The Consumer as a Social Actor, *Ecological Economics* 28: 365-398.
- Cogoy, M., 2000, Ecological Efficiency, Economic Efficiency and Time Efficiency in Private Consumption, *Journal of Interdisciplinary Economics* 8: 97-111.
- Cohen, C., Lenzen, M. and Schaeffer, R., 2005, Energy Requirements of Households in Brazil, *Energy Policy* 33(4), pp. 555-562.
- Cohen, M and Murphy, J, 2001, Exploring Sustainable Consumption - Environmental Policy and the Social Sciences, Pergamon Press, Oxford.
- Common, M.S. and Salma, U., 1992, Accounting for Changes in Australian Carbon Dioxide Emissions, *Energy Economics* 14(3), pp. 217-225.
- Commoner, B., 1972, The Environmental Cost of Economic Growth, in: Ridker, R.G. (ed.): *Population, Resources and the Environment*, US Government Printing Office: 339-363.
- Daly, H., 1989, For the Common Good. Redirecting the Economy Towards Community, the Environment and Sustainable Development, Green Print, London.
- Daly, H.E., 1992, Is the Entropy Law Relevant to the Economics of Natural Resource Scarcity? Yes - Of Course It is, *Journal of Environmental Economics and Management*: 91-95.
- DeSerpa, A.C., 1971, A Theory of the Economics of Time, *Economic Journal* 81(324): 828-846.
- Dietzenbacher, E. and Lahr, M.L. (eds), 2001, *Input-Output Analysis: Frontiers and Extensions*, Palgrave, Basingstoke: 1-31.
- Dietzenbacher, E., 2005, Waste Treatment in Physical Input-Output Analysis, *Ecological Economics* 55(1): 11-23.
- Dietzenbacher, E. and Stage, J., 2006, Mixing Oil and Water? Using Hybrid Input-Output Tables in a Structural Decomposition Analysis, *Economic Systems Research* 18(1): 85-95.
- Dietzenbacher, E., Glijum, S., Hubacek, K. and Suh, S., 2007, Physical Input-Output Analysis and Disposals to Nature, Handbook of Input-Output Economics for Industrial Ecology, Springer, Dordrecht, The Netherlands, forthcoming.
- Dodds, S., 1997, Towards a Science of Sustainability: Improving the Way Ecological Economics Understands Human Well-Being, *Ecological Economics* 23(2): 95-111.
- Douglas, M., *Relative Poverty, Relative Communication*, in: Hasley, A. (ed.), *Traditions of Social Policy*, Blackwell, Oxford.
- Douglas, M., and Isherwood, B., 1979, *The World of Goods*, Basic Books, New York.

- Duchin, F., 1998, *Structural Economics: Measuring Change in Technology, Lifestyle and the Environment*, Island Press, New York.
- Duchin, F. and Hubacek, K., 2003, Linking Social Expenditures to Household Lifestyles, *Futures* 35: 61-74.
- Easterlin, R., 1974, Does Economic Growth Improve the Human Lot? Some Empirical Evidence, in: David,
- Easterlin, R., 2000, The Worldwide Standard of Living Since 1800, *Journal of Economic Perspectives* 14(1): 7-26.
- Easterlin, R., 2001, Income and Happiness: Towards a Unified Theory, *Economic Journal* 111: 465-84.
- Ehling, M., 1999, The German Time Use Survey. Methods and Results, in: Merz, J. and Ehling, M. (eds.), *Time Use - Research, Data, and Policy*, Nomos, Baden-Baden.
- Ehrlich, P.R. and Holdren, J.P., 1971, The Impact of Population Growth, *Science* 171(3977): 1212-1217.
- Ekins, P., 1993, Limits to Growth and Sustainable Development. Grappling with Realities, *Ecological Economics* 8: 269-288.
- Ekins, P., Simon, S., Deutsch, L., Folke, K., De Groot, R., 2003, A Framework for the Practical Application of the Concepts of Critical Natural Capital and Strong Sustainability, *Ecological Economics* 44: 165-185.
- Elgin, D., 1993, *Voluntary Simplicity*, William Morrow Publishing, New York.
- Eisner, R., 19/-88, Extended Accounts for National Income and Product, *Journal of Economic Literature*- 26(4): 1611-1684.
- Erkman, S., 1997, Industrial Ecology: An Historical View, *Journal of Cleaner Production* 5(1-2): 1-10.
- Eurostat, 2000, Survey on Time Use. Activity Coding List, Final Draft, DOC E2/TUS/5/00, Luxembourg.
- Federal Statistical Office of Germany, 2001, A Physical Input-Output Table for Germany 1995, Endbericht zum Projekt 98/559/ 3040/B4/MM, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2002, Input-Output Tabellen – in Preisen von 1995 – 1991-2000, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2004a, Input-Output Tabellen – in jeweiligen Preisen – 2000, Fachserie 18, Reihe 2, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2004b, Verkehr und Umwelt, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2005a, Konsumverflechtungstabellen 1991-2003, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2005b, Sozio-Ökonomische Entwicklung: Zeitreihen zu Erwerbstätigkeit, Einkommen und Konsum, Schriftenreihe Sozio-Ökonomisches Berichtssystem für eine Nachhaltige Gesellschaft, Band 7, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006a, Input-Output Tabellen – in jeweiligen Preisen – 2000: Ergebnisse nach Revision 2005, Fachserie 18, Reihe 2, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006b, Input-Output Tabellen – in jeweiligen Preisen – 2001: Ergebnisse nach Revision 2005, Fachserie 18, Reihe 2, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006c, Input-Output Tabellen – in jeweiligen Preisen – 2002: Ergebnisse nach Revision 2005, Fachserie 18, Reihe 2, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006d, Input-Output Tabellen – in jeweiligen Preisen – 2002: Ergebnisse nach Revision 2005, Fachserie 18, Reihe 2, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006e, Die Nutzung von Umweltressourcen durch die Konsumaktivitäten der Privaten Haushalte, Statistisches Bundesamt, Wiesbaden.
- Federal Statistical Office of Germany, 2006f, Input-Output Tabellen – in jeweiligen Preisen – 1991-2000, Statistisches Bundesamt, Wiesbaden.
- Ferng, J.J., 2003, Allocating the Responsibility of CO<sub>2</sub> Over-Emission from the Perspectives of Benefit Principle and Ecological Deficit, *Ecological Economics* 46: 121-141.

- Foran, B., Lenzen, M. and Dey, C., 2005a, Balancing Act – A Triple Bottom Line Account of the Australian Economy, Canberra, ACT, Australia.
- Foran, B., Lenzen, M., Dey, C. and Bilek, M., Integrating Sustainable Chain Management with Triple Bottom Line Reporting, *Ecological Economics* 52(2):143-157.
- Frank, R.W., 1997, The Frame of Reference as a Public Good, *Economic Journal* 107(445): 1832-1847.
- Frey, B.S. and Stutzer, A., 2002, What Can Economics Learn from Happiness Research?, *Journal of Economic Literature* 40: 402-435.
- Frosch, R.A. and Gallopoulos, N., 1989, Strategies for Manufacturing, *Scientific American* 261(3): 94-102.
- Gallego, B. and Lenzen, M., 2005, A Consistent Formulation of Consumer and Producer Responsibility, *Economic Systems Research* 17(4): 365-391.
- Gatersleben, B., 2000, Sustainable Household Consumption and Quality of Life: The Acceptability of Sustainable Consumption Patterns and Consumer Policy Strategies, *International Journal of Environment and Pollution* 15(2): 200-216.
- Gay, P.W. and Proops, J.L.R., 1993, Carbon-Dioxide Production by the UK Economy. An Input-Output Assessment, *Applied Energy* 44(2), pp. 113-130.
- German Advisory Council on the Environment (SRU), 2006, National Implementation of the EU Emissions Trading Scheme: Market-Based Climate Change Mitigation or The Continuation of Energy Subsidies by Other Means, Statement, Berlin.
- German Advisory Council on Global Change (WGBU), 2007, New Impetus for Climate Change Policy: Making the Most of Germany's Dual Presidency, *Policy Paper No. 5*, Berlin.
- Gershuny, J., 1987, Time Use and the Dynamics of the Service Sector, *The Service Industry Journal* 7 (4): 56-72.
- Georgescu-Roegen, N., 1971, The Entropy Law and the Economic Process, Harvard University Press, Cambridge, Massachusetts.
- Gigantes, T., 1970. The representation of technology in input-output systems. In: Carter, A.C. and Bródy, A. (eds.), Contributions to Input-Output Analysis: Fourth International Conference on Input-Output Techniques. North Holland Publishing, Amsterdam.
- Ghosh, S. and Roy, J., 1998, Qualitative Input-Output Analysis of the Indian Economic Structure, *Economic Systems Research* 10(3): 263-273.
- Giljum, S. and Hubacek, K., 2007, Conceptual Foundations and Applications of Physical Input-Output Tables (PIOTs), Handbook of Input-Output Economics for Industrial Ecology, Springer, Dordrecht, The Netherlands, forthcoming.
- Giljum, S. and Hubacek, K., 2004, Alternative Approaches of Physical Input-Output Analysis to Estimate Primary Material Inputs of Production and Consumption Activities, *Economic Systems Research* 16(3): 301-310.
- Giljum, S., Hubacek, K. and Sun, L., 2004, Beyond the Simple Material Balance: A Reply to Sangwon Suh's Note on Physical Input-Output Analysis, *Ecological Economics* 48(1): 19-22.
- Global Commons Institute, 2007, <http://www.gci.org.uk>
- Gowdy, J.M. and Miller, J.L., 1987, Technological and Demand Change in Energy Use: An Input-Output Analysis, *Environment and Planning A* 19: 1387-1398.
- Gravgaard-Pedersen, O., 1998, Physical Input-Output Tables for Denmark 1990, Denmark Statistics, Copenhagen.
- Greening, L.A., Greene, D.L. and Difiglio, C., 2000, Energy Efficiency and Consumption – The Rebound Effect – A Survey, *Energy Policy* 28: 389-401.
- Gross, D.R., 1984, Time Allocation: A Tool for the Study of Cultural Behavior, *Annual Review of Anthropology* 13: 519-558.
- Guan, D., Hubacek, K., Weber, C., Peters, G. and Reiner, D., 2008, The drivers of China's CO<sub>2</sub> emissions from 1980 to 2030. Global Environmental Changes: Human and Policy Dimension, *paper submitted*.
- Hannon, B., Blaszcsek T., Kennedy, D., and Illyes, R., 1984, A Comparison of Energy Intensities: 1963, 1967 and 1972, *Resources and Energy* 5(1): 83-102.
- Haq, G., Minx, J., Whitelegg, J. and Owen, A., 2007, Greening the Greys. Climate Change and the Over 50s, Stockholm Environment Institute, York.
- Harary, F., Norman, R.Z. and Cartwright, D., 1965, Structural Models: An Introduction to the Theory of Directed Graphs, Oxford University Press, Oxford.
- Hardin, G., 1986, The Tragedy of the Commons, *Science* 162: 1245-1248.

- Hawrylyshyn, O., 1977, Towards a Definition of Non-Market Activities, *Review of Income and Wealth* 23(1): 79-96.
- Hayden, A., 1999, *Sharing the Work, Sparing the Planet: Work Time, Consumption and Ecology*, Zed Books, London.
- Heinze, A., 2007, Personal Communication, 27.01.2007.
- Hendrickson, C., Horvath, A., Joshi, S. and Lave, L., 1998, Economic Input-Output Models for Environmental Life Cycle Assessment, *Environmental Science & Technology* 32(7):184A-191A.
- Herendeen, R.A. and Bullard, C.W., 1974, Energy Costs of Goods and Services, *CAC Working Paper No. 140*, Centre for Advanced Computation, Illinois.
- Herendeen, R.A. and Tanaka, J., 1976, The Energy Cost of Living, *Energy* 1: 165-178.
- Herendeen, R.A., Total Energy Costs of Household Consumption in Norway, 1973, *Energy* 3: 615-630.
- Herendeen, R.A., Ford, C., and Hannon, B., 1981, The Energy Cost of Living: 1972-73, *Energy* 6(12): 1433-1450.
- Hertwich, E. and Katzmayer, M., 2004, Examples of Sustainable Consumption: Review, Classification and Analysis, *Report and Communications Series from the Industrial Ecology Programme of Norwegian University for Science and Technology* 5/2004, Trondheim.
- Hertwich, E., 2005, Consumption and the Rebound Effect: An Industrial Ecology Perspective, *Journal of Industrial Ecology* 9(1-2): 85-98.
- Hertwich, E., 2006, Accounting for Sustainable Consumption: A Review of Studies of the Environmental Impact of Households, in: Jackson, T (ed.), *The Earthscan Reader in Sustainable Consumption*, Earthscan, London.
- Hetherington, R., 1996, An Input-Output Analysis of Carbon Dioxide Emissions for the UK, *Energy Conversion Management* 37(6-8): 979-984.
- Hill, P.T., 1979, Do-It-Yourself and GDP, *Review of Income and Wealth* 31(1): 31-49.
- Hirsch, F., 1977, *Social Limits to Growth*, Routledge, London.
- Helliwell, J., 2001, How's Life? Combining Individual and National Variables to Explain Subjective Well-Being, Mimeo, University of British Columbia.
- Hoekstra, R. and Van Den Bergh, J.C.J.M., 2002, Structural Decomposition Analysis of Physical Flows in the Economy, *Environmental and Resource Economics* 23: 357-378.
- Hoekstra, R. and Van Den Bergh, J.C.J.M., 2003, Comparing Structural and Index Decomposition Analysis, *Energy Economics* 25: 39-64.
- Hoekstra, R. and Van den Bergh, J.C.J.M., Constructing Physical Input-Output Tables for Environmental Modeling and Accounting: Framework and Illustrations, *Ecological Economics*, in press.
- Hofstetter, P. and Madjar, M., 2003, Linking Changes in Happiness, Time use, Sustainable Consumption, and Environmental Impacts. An Attempt to Understand Time-Rebound Effects, Final Project Report, Büro für Analyse & Ökologie, Zürich.
- Holling, C. S., 1986, *The Resilience of Terrestrial Ecosystems. Local Surprise and Global Change. Sustainable Development in the Biosphere*. W. C. a. M. Clark, R.E. Cambridge, Cambridge University Press.
- Holub, H.W., Schnabl, H., and Tappeiner, G., 1985, Qualitative Input-Output Analysis with Variable Filer, *Zeitschrift für die Gesamte Staatswissenschaft* 141: 282-300.
- Holub, H.W. and Schnabl, H., 1985, Qualitative Input-Output Analysis and Structural Information, *Economic Modelling* 2: 67-74.
- Holub, H.W. and Tappeiner, G., 1987, Die Beurteilung von RAS und MODOP mittels qualitativer Verfahren, *Allgemeines Statistisches Archiv* 71: 234-244.
- Holub, H.W. and Tappeiner, G., 1988, A General Technique for the Comparison of Economic Structures, *Quality and Quantity* 22: 293-310.
- Hubacek, K., and Giljum, S., 2003, Applying Physical Input-Output Analysis to Estimate Land Appropriation (Ecological Footprints) of International Trade Activities, *Ecological Economics* 44(1), 137-151.
- INSTRAW, 1996, *Valuation of Household Production and the Satellite Accounts*, United Nations, Santo Domingo.
- IPCC, 2007, *Climate Change 2007: The Physical Science Basis – Summary for Policy Makers*, IPCC Secretariat, Geneva.
- Jackson, T. and Marks, N., 1999, Consumption, Sustainable Welfare and Human Needs - With Reference to UK Expenditure between 1954 and 1994, *Ecological Economics* 28: 421-441.

- Jackson, T. and Michaelis, L., 2003, Policies for Sustainable Consumption, Report prepared to the Sustainable Development Commission, London.
- Jackson, T., Jager, W., and Stagl, S., 2004, Beyond Insatiability: Needs Theory, Consumption and Sustainability, ESRC Working Paper 2004/2, Swindon.
- Jackson, T., 2004, Models of Mammon - a cross-disciplinary survey in the pursuit of the 'sustainable consumer', ESRC Working Paper 2004/1, Swindon.
- Jackson, T., 2005, Motivating Sustainable Consumption. A Review of Evidence on Consumer Behaviour and Behavioural Change, Report to the Sustainable Development Research Network, University of Surrey, Guildford.
- Jalas, M., 2002, A Time Use Perspective of the Material Intensity of Consumption, *Ecological Economics* 41: 109-123.
- Jalas, M., 2005, The Everyday Life Context of Increasing Energy Demands. Time Use Survey Data in a Decomposition Analysis, *Journal of Industrial Ecology* 9(1-2): 129-145.
- Jänicke M., 1988, Ökologische Modernisierung. Optionen und Restriktionen präventiver Umweltpolitik, in: Simonis, U. (ed.), *Präventive Umweltpolitik*, Campus, Frankfurt am Main: 13-26.
- Juster, F.T., Courant, P.N., and Dow, G.K., 1981, A Theoretical Framework for the Measurement of Well-Being, *Review of Income and Wealth* 27(1):1-32.
- Juster, F.T. and Stafford, F.P., 1991, The Allocation of Time: Empirical Findings, Behavioral Models, and Problems of Measurement, *Journal of Economic Literature* 29(2): 471-522.
- Kratena, K., Chovanec, A. and Konechy, R., 1992, Eine Ökologische Volkswirtschaftliche Gesamtrechnung für Österreich. Die Umwelt Input-Output Tabelle 1983, Institut für sozial-, wirtschafts- und umweltpolitische Forschung, Wien.
- Kratterl, A. and Kratena, K., 1990, Reale Input-Output Tabelle und Ökologischer Kreislauf, Physica Verlag, Heidelberg.
- Kazemier, B., Keuning, S. and Van De Ven, P., 1999, Measuring Well-Being with an Integrated System of Economic and Social Accountants. An Application of the SESAME Approach to the Netherlands, Discussion Paper P-30/1999-2, Statistics Netherlands, Voorburg.
- Kendrick, J.W. (ed.), 1996, *The New System of National Accounts*, Kluwer Academic Publishing, London.
- Keuning, S.J., 1994, The SAM and Beyond: Open SESAME!, *Economic Systems Research* 6(1): 21-50.
- Keuning, S.J., 2000, Accounting for Welfare with SESAME, in: United Nations, *Handbook of National Accounting. Household Accounting, Experience in Concepts and Compilation*, Vol. 2, Studies in Methods F, No. 75, New York: 273-307.
- Kim, J.H., 2002, Changes in Consumption Patterns and Environmental Degradation in Korea, *Structural Change and Economic Dynamics* 13, pp. 1-48.
- Kleine, E. and Meyer, B., 1981, Qualitative oder Quantitative Input-Output Analyse für die Konjunkturpolitik?, *Zeitschrift für die Gesamte Staatswissenschaft* 138: 129-145.
- Klevermarken, A., 1999, Microeconomic Analysis of Time use Data. Did We Reach the Promised Land?, in: Merz, J. And Ehling, M. (eds.), *Time use – Research, Data, Policy*, Nomos, Baden-Baden: 423-456.
- Kondo, Y., 2006, Environmental Impacts of Consumers' Time Use: Consumption Technologies and the Waste Input-Output Model, Paper presented at the Conference of the International Society for Industrial Ecology.
- Konijn, P., Bour, S. de, and Dalen, J. van, 1997, Input-Output Analysis of Material Flows with Application to Iron, Steel and Zinc, *Structural Change and Economic Dynamics* 8: 129-153.
- Kurz, H.D., Dietzenbacher, E. and Lager, C., 1998, *Input-Output Analysis*, Volume III, Edward Elgar, Cheltenham: Chapter 1 – Introduction.
- Lenzen, M., 2003, Environmentally Important Paths, Linkages and Key Sectors in the Australian Economy, *Structural Change and Economic Dynamics* 14: 1-34.
- Lenzen, M., Dey, C., and Foran, B., 2004, Energy Requirements of Sydney Households, *Ecological Economics* 49: 375-399.
- Lenzen, M., Pade, L.-L., and Munksgaard, J. (2004), CO<sub>2</sub> Multipliers in Multi-Region Input-Output Models, *Economic Systems Research* 16(4): 391-412.

- Lenzen, M., Cohen, M., Hayami, H., Pachauri, S. and Schaeffer, R., 2006, A Comparative Multivariate Analysis of Household Energy Requirements in Australia, Brazil, Denmark, India, and Japan, *Energy* 31: 181-207.
- Lenzen, M., Murray, J., Sack, F., and Wiedmann, T., 2007, Shared Consumer and Producer Responsibility – Theory and Practice, *Ecological Economics* 61: 27-42.
- Leontief, W., 1970, Environmental Repercussions and the Economic Structure: An Input-Output Approach, *Review of Economics and Statistics* 52(3): 262-271.
- Leontief, W. and Ford, D., 1971, Air pollution and the Economic Structure: empirical results of input-output calculations, Fifth International Conference on Input-Output Techniques, North Holland, Geneva, Switzerland: 9-30.
- Lin, X. and Polenske, K., 1995, Input-Output Anatomy of China's Energy Use in the 1980s, *Economic Systems Research* 7: 67-84.
- Lintott, J., 1997, Beyond the Economics of More: The Place of Consumption in Ecological Economics, *Ecological Economics* 25: 239-248.
- Llop, M., 2007, Economic Structure and Pollution Intensity Within the Environmental Input-Output Framework, *Energy Policy*, forthcoming.
- Lützel, H., 1989, Household Production and National Accounts, *Statistical Journal of the United Nations ECE* 6: 337-348.
- Maaß, S., 1980, Die Reagibilität von Prognosen mittels Input-Output Modellen auf Fehler im Datenmaterial, Athenäum Verlag, Berlin.
- Madlener, R. and Stagl, S., 2001, Sozio-Ökologisch-Ökonomische Beurteilung Handelbarer Zertifikate und Garantierter Einspeisetarife für Ökostrom (Socio-Ecological-Economic Evaluation of Tradable Certificates and Guaranteed Feed-in Tariffs for Green Electricity), *Zeitschrift für Energiewirtschaft* 1: 53-66.
- Mäenpää, I. and Muukonen, J., 2001, Physical Input-Output in Finland: Methods, Preliminary Results and Tasks Ahead, Paper presented at Workshop on Economic Growth, Material Flows and Environmental Pressure, 25<sup>th</sup>-27<sup>th</sup> April, Stockholm, Sweden.
- Manoochehri, J., 2002, Post-Rio 'Sustainable Consumption': Establishing Coherence and a Common Platform, *Development* 45(3): 51-57.
- Manoochehri, J., 2005, Sustainable Consumption: A Short 'History', submitted to *Global Environmental Politics*
- Max-Neef, M.A., 1991, Human Scale Development, Conception, Application and Further Reflections. Apex Press, London.
- Max-Neef, M.A., 1995, Economic Growth and Quality of Life: A Threshold Hypothesis, *Ecological Economics* 15: 115-118.
- McDonald, G., Patterson, M. and Willcox, M., 2006, Towards a Physical Input-Output Table of the New Zealand Economy, Paper presented at the Intermediate Input-Output Meeting on Sustainability, Trade and Productivity, Sendai, Japan.
- Meadows, D.H., Meadows, D.L., Randers, J. and Behrens, W.W., 1972, The Limits to Growth, Universe Books, New York.
- Merz J. and Ehling, M. (eds), 1999, *Time use. Research, Data and Policy*, Nomos, Baden-Baden.
- Mesnard, L. de, 1995, A Note on Qualitative Input-Output Analysis, *Economic Systems Research* 7(4). 439-445.
- Mesnard, L. de, 2001, On Boolean Topological Methods of Structural Analysis, in: Lahr and Dietzenbacher (eds.), *Input-Output Analysis: Frontiers and Extensions*, Palgrave, Chippenham.
- Meyer, C.D., 2000, *Matrix Analysis and Applied Linear Algebra*, SIAM, Philadelphia
- Miller, R.E. and Blair, P.D., 1985, *Input-Output Analysis. Foundations and Extensions*, Prentice Hall, Englewood Cliffs, NJ.
- Minx, J.C., 2002, Towards Sustainable Household Consumption Patterns in the UK, MSc Dissertation, Environment Department, University of York.
- Minx, J.C. and Tschochohei, H., 2005, Towards a Comprehensive Concept of Space for Sustainability Analysis, Paper presented at the 7<sup>th</sup> Weimarer Kolloquium, November, Weimar.
- Minx, J.C. and Tschochohei, H., 2006, Die Bedeutung des Flächenverbrauchs für die Halbtagsgesellschaft, in: Harthard, S., Schaffer, A. and Stahmer, C. (eds.), *Die Halbtagsgesellschaft: Konkrete Utopie für eine Zukunftsfähige Gesellschaft*, Nomos, Baden-Baden: 153-165.

- Minx, J.C., Schaffer, A., Stahmer, C. and Tschochohei, H., 2006, New Ways of Integrated Accounting for Sustainable Development Research: Socio-Economic Input-Output Tables for Germany, Paper presented at the Intermediate Input-Output Meeting on Sustainability, Trade and Productivity, Sendai, Japan.
- Minx, J.C. and Baiocchi, G., 2007, Time Use and Sustainability, in: Suh, S., *Handbook of Input-Output Methods for Industrial Ecology*, Springer, Dordrecht, forthcoming: included as chapter 5 of this thesis.
- Minx, J.C., Baiocchi, G., Hubacek, K. and Barrett, J., 2007, On Flaws and Features of Physical Input-Output Tables: A Comment on the Physical Input-Output Debate with Some Analysis, draft paper to be submitted to *Ecological Economics*: included as chapter 2 of this thesis.
- Minx, J.C., 2007b, An Assessment of the Different Methodological Variants of Qualitative Input-Output Analysis, Mimeo, York.
- Minx, J.C., Baiocchi, G., Hubacek, K., Wiedmann, T. and Barrett, J., 2007c, Revealing Structures: Empirical Differences between Monetary and Physical Input-Output Models and their Implications for Environmental Economic Analysis, Abstract submitted for the International Conference on Input-Output Techniques, Istanbul, July.
- Minx, J.C., Wiedmann, T., Barrett, J. And Suh, S., 2008, Methods Review to Support the PAS Process for the Calculation of the Greenhouse Gas Emissions Embodied in Goods and Services, DEFRA, London, UK.
- Moll, H.C., Noorman, K.J., Kok, R., Engström, R., Throne-Holst, H. and Clark, C., 2005, Bringing About More Sustainable Consumption Patterns: Analyzing and Evaluating Household Metabolism in European Countries and Cities, *Journal of Industrial Ecology* 9: 259-176.
- Mukhopadhyay, K. and Chakraborty, D. (1999) India's energy consumption changes during 1973/74 to 1991/92, *Economic Systems Research* 11: 423-438.
- Mukhopadhyay, K. and Forssell, O., 2005, An Empirical Investigation of Air Pollution from Fossil Fuel Combustion and its impact on health in India during 1973-1974 to 1996-1997, *Ecological Economics* 55: 235-250.
- Morioka, T. and Yoshida, N., 1995, Comparison of Carbon Dioxide Emission Patterns due to Consumer Expenditure in UK and Japan, *Journal of Global Environmental Engineering* 1: 59-78.
- Morioka, T. and Yoshida, N., 1997, Carbon Dioxide Emission Patterns Due to Consumer Expenditure in Life Stages and Life Styles, *Journal of Environmental Systems and Engineering* 559: 91-101.
- Munksgaard, J., Pedersen, K.A., and Wier, M., 2000, Impact of Household Consumption on CO<sub>2</sub> Emissions, *Energy Economics* 22: 423-440.
- Munksgaard, J. and Pedersen, K., 2001, CO<sub>2</sub> Accounts for Open Economies. Producer or Consumer Responsibility?, *Energy Policy* 29, pp. 327-334.
- Munksgaard, J., Paade, L.-L., Minx, J. and Lenzen, M., 2005, Influence of Trade on National CO<sub>2</sub> Emissions, *International Journal of Global Energy Issues* 23(4): 324-336.
- Munksgaard, J., Minx, J.C., Christoffersen, L., and Pade, L.-L., 2007, Models for National CO<sub>2</sub> Accounting, in: Suh, S.; *Handbook of Input-Output Methods for Industrial Ecology*, Springer, Dordrecht, forthcoming
- Nebbia, 2000, Contabilita Monetaria e Conatibilita Ambientale, Estratto da "Economia Publica".
- Nooij, M. de, Soest, P. van, Kruk, R. van der, Hoen, A.R., 2006, International Comparison of Energy Use: The Usefulness of Structural Decomposition Analysis Across Countries, *Paper presented atr*
- Osborn, F., 1953, *The Limits of the Earth*, Little, Brown & Co, Boston.
- Oswald, A.J., 1997, Happiness and Economic Performance, *Economic Journal* 107(445): 1815-1831.
- Pachauri, S. and Spreng, D. (2002), Direct and Indirect Energy Requirements of Households in India, *Energy Policy* 30, pp. 511-523
- Pachauri, S., 2004, An Analysis of Cross-Sectional Variations in Total Household Energy Requirements in India Using Micro Survey Data, *Energy Policy* 32: 1723-1735.
- Packard, V., 1960, *The Waste Makers*, David McKay Company Inc, New York.
- Pasinetti, L.L., 1977, *Lectures on the Theory of Production*, Macmillan, New York.
- Pearce, D. (ed.), 1998, *Economics and Environment, Essays on Ecological Economics and Sustainable Development*, Edward Elgar Publishing, Cheltenham.

- Peet, N.J., Carter, A.J. and Baines, J.T., 1985, Energy in New Zealand Households: 1974-1980, *Energy* 32, 1723-1735.
- Perrings, C., 1987, Economy and Environment. A Theoretical Essay on the Interdependence of Economic and Environmental Systems, Cambridge University Press, New York.
- Perrings, C. and Walker, B., 1997, Biodiversity, Resilience and the Control of Ecological-Economic Systems. The Case of Fire-Driven Rangelands, *Ecological Economics* 22: 73-83.
- Peters, G. and Hertwich, E., 2006, The Importance of Imports for Household Environmental Impacts, *Journal for Industrial Ecology*.
- Peters, G. and Hertwich, E., 2006, Structural Analysis of International Trade: Environmental Impacts of Norway, *Economic Systems Research* 18(2):155-181.
- Pollak, R.A. and Wachter, M.L., 1975, The Relevance of the Household Production Function and its Implication for the Allocation of Time, *Journal of Political Economy* 83(2): 255-278.
- Princen, T., 1999, Consumption and the Environment, *Ecological Economics* 31(3): 347-363.
- Proops, J.L., 1977, Input-Output Analysis and Energy Intensities: A Comparison of Some Methodologies, *Applied Mathematical Modelling* 1(4): 181-188.
- Proops, J.L.R., Faber, M. and Wagenhals, G., 1992, Reducing CO<sub>2</sub> Emissions: A Comparative Input-Output Study for Germany and the UK, Springer, Heidelberg.
- Pyatt, G., 1990, Accounting for Time use, *Review of Income and Wealth* 36(1): 33-52.
- Reid, M.G., 1934, *Economics of Household Production*, John Wiley and Sons, New York.
- Reinders, A.H.M.E, Vringer, K. and Blok K., 2003, The Direct and Indirect Energy Requirements of Households in the European Union, *Energy Policy* 31: 139-151.
- Roberts, S. and Thumin, J., 2006, A Rough Guide to Individual Carbon Trading, Report to DEFRA, Centre for Sustainable Energy, London.
- Robinson, J.P. and Godbey, G., 1997, *Time for Life. The Surprising Ways Americans Use Their Time*, Pennsylvania State University Press, Pennsylvania.
- Rosenstein-Rodan, P.N., 1934, The Role of Time in Economic Theory, *Economica* 1(1): 77-97.
- Sanchez-Choliz, J. and Duarte, R., 2004, CO<sub>2</sub> Emissions Embodied in International Trade: Evidence for Spain, *Energy Policy*...
- Schaffer, A., 2003, Zeitprismen nach Hägerstrand und Ihre Verknüpfung mit Sozio-Ökonomischen Input-Output Tabellen, paper presented at the 5th Weimarer Kolloquium of the Association for Ecological Economics Germany, Weimar, 10-12 September.
- Schaffer, A. and Stahmer, C., 2005, Die Halbtagsgesellschaft – Ein Konzept für Nachhaltige Produktions- und Konsummuster, *GAIA* 14(3): 229-239.
- Schintke, J., 1976, Sensitivitätsanalysen im Statistischen Offenen Leontief Modell, *DIW Beiträge zur Strukturforchung*, No.42, DIW, Berlin.
- Schintke, J. and Stäglin, R., 1988, Important Coefficients in Market Transaction Tables and Production Flow Tables, in: Ciaschini, M. (ed.), *Input-Output Analysis: Current Developments*, Chapman & Hall, London.
- Schipper, L., Bartlett, S., Hawk, D., and Vine, E., 1989, Linking Life-Styles and Energy Use: A Matter of Time?, *Annual Review of Energy* 14: 273-320.
- Schipper, L., 1997, Energy and Lifestyles, Daedalus.
- Schmid, W., 1998, Philosophie der Lebenskunst. Eine Grundlegung, Suhrkamp, Frankfurt a.M..
- Schnabl, H. and Holub, H.W., 1979, Qualitative und Quantitative Aspekte der Input-Output Analyse, *Zeitschrift für die Gesamte Staatswissenschaft* 135: 657-678.
- Schnabl, H., 1994, The Evolution of Production Structures Analysed by a Multi-Layer Procedure, *Economic Systems Research* 6(1): 51-68.
- Schnabl, H., 1995, The Subsystem-MFA: A Qualitative Method for Analysing National Innovation Systems – The Case of Germany, *Economic Systems Research* 7: 51-68.
- Schnabl, H., 2000, Strukturpolitik: Innovation, Technologieverflechtung und sektoraler Strukturwandel, Oldenbourg Verlag, München.
- Schnabl, H., 2003, The ECA Method for Identifying Sensitive Reactions with an IO Context, *Economic Systems Research* 15(4): 495-504.



- Schor, J. B., 1998, A New Critique of Consumer Society, in: D. A. Crocker and T. Linden: *Ethics of Consumption. The Good Life, Justice and Global Stewardship*, Rowman & Littlefields Publishers Inc., Oxford, 131-138.
- Schor, J.B., 2005, Sustainable Consumption and Worktime Reduction, *Journal of Industrial Ecology* 9(1-2): 37-50.
- Schumacher, E., 1974, *Small is Beautiful*, Abracus, London.
- Scitovsky, T., 1976, *The Joyless Economy, The Psychology of Human Satisfaction*, Revised Edition, Oxford University Press, Oxford.
- Seibel, S., 2003, Decomposition of Carbon-Dioxide-Emission Changes in Germany – Conceptual Framework and Empirical Results, *Eurostat Working Paper Series*, 2003 Edition, Office for Official Publications of the European Communities, Luxembourg.
- Shannon, C.E. and Weaver, W., 1962, *The Mathematical Theory of Communication*, University of Illinois Press, Urbana.
- Sharp, C., 1981, *The Economics of Time*, Martin Robertson & Company, Oxford.
- Sherman, J. and Morrison, W., 1950, Adjustment of an Inverse Matrix Corresponding to a Change in One Element of a Given Matrix, *Annals of Mathematical Statistics* 17: 124- 127.
- Skolka, J., Important Input Coefficients in Austrian Input-Output Tables for 1964 and 1976, in: Smyshlyaev, A. (ed.), *Proceedings of the Fourth IIASA Task Force Meeting on the IO-Model*, Laxenburg.
- Smith, R.H., Diener, E. and Wedell, D.H, 1989, Intrapersonal and Social Comparison Determinants of Happiness: A Range Frequency Analysis, *Journal of Personality and Social Psychology* 56(3), 317:325.
- Sraffa, P., 1960, *Production of Commodities by Means of Commodities*, Cambridge University Press, Cambridge.
- Stäglich, R. and Schintke, J., 2002, Analytische Auswertung von Physischen, Monetären und Zeit-Input-Output Tabellen. Nutzungsmöglichkeiten für Wirtschafts-, Umwelt- und Beschäftigungspolitik, Endbericht zum Auftrag von EUROSTAT, Grant Agreement 200041200003, Deutsches Institut für Wirtschaftsforschung, Berlin.
- Stahmer, C., 1991, Vom Bruttosozialprodukt zum Ökosozialprodukt? Umweltberichterstatterung im Rahmen der Volkswirtschaftlichen Gesamtrechnungen, in Diefenbacher, H. and Habicht-Erenler, S. (eds.), *Wachstum und Wohlstand*, Marburg.
- Stahmer, C., 1995, Satellitensystem für Aktivitäten der Privaten Haushalte, in: Seel, B. and Stahmer, C. (eds), *Haushaltsproduktion und Umweltbelastung. Ansätze einer Ökobilanzierung für den Privaten Haushalt*, Frankfurt a.M., New York: 60-111.
- Stahmer, C., Kuhn, M., and Braun, N., 1998, Physical Input-Output Tables for Germany 1990, Eurostat Working Paper No2/1998/B/1, European Commission, Luxembourg.
- Stahmer, C., 2000, The magic triangle of input-output, Paper presented at the XIII International Conference on Input-Output Techniques, 21-25 August, Macerata, Italy.
- Stahmer, 2003, Halbtagsgesellschaft, *Zeitschrift für Zukunftsgestaltung und Vernetztes Denken* 44: 34-37.
- Stahmer, C., Ewerhart, G. and Herrchen, I., 2003a, Monetäre, Physische und Zeit-Input-Output-Tabellen, Teil 1: Konzepte und Beispiele, Schriftenreihe Sozio-ökonomisches Berichtssystem für eine Nachhaltige Gesellschaft, Band 1, Statistisches Bundesamt, Wiesbaden.
- Stahmer, C., Ewerhart, G. and Herrchen, I., 2003b, Monetäre, Physische und Zeit-Input-Output-Tabellen, Teil 1: Konzepte und Beispiele, Materialband zu Band 1 der Schriftenreihe Sozio-ökonomisches Berichtssystem für eine Nachhaltige Gesellschaft, Statistisches Bundesamt, Wiesbaden.
- Stahmer, C., Mecke, I. and Herrchen, I., 2003c, Zeit für Kinder. Betreuung und Ausbildung von Kindern und Jugendlichen, Teil 3 der Schriftenreihe Sozio-ökonomisches Berichtssystem für eine Nachhaltige Gesellschaft, Statistisches Bundesamt, Wiesbaden.
- Stahmer, C., Herrchen, I. and Schaffer, A., 2004, Sozio-Oekonomische Input-Output Rechnung 1998, Schriftenreihe Sozio-ökonomisches Berichtssystem für eine Nachhaltige Gesellschaft, Band 4, Statistisches Bundesamt, Wiesbaden.
- Suh, S., Huppés, G., de Haes, H.U., 2002, Environmental Impacts of Domestic and Imported Commodities in U.S. Economy, Paper presented at the 14th International Conference on Input-Output Techniques, October 10-15, Montreal.

- Stahmer, C., 2004, Social Accounting Matrices and Extended Input-Output Tables, in: OECD (ed.), *Measuring Sustainable Development: Integrated Economic, Environmental and Social Frameworks*, OECD, Paris.
- Stahmer, C., 2004b, Aufbau eines Sozio-Ökonomischen Berichtssystems für eine Nachhaltige Gesellschaft, *Vierteljahreshefte zur Wirtschaftsforschung* 73: 77-95.
- Stahmer, C., 2006, Personal Communication.
- Stern, N., 2006, *The Stern Review: The Economics of Climate Change*, HM Treasury, London.
- Stone, R., 1961, Input-Output and National Accounts, OECD, Paris.
- Suh, S., 2004. A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities. *Ecological Economics* 48(1): 9–17.
- Suh, S., 2004, Material and Energy Flows in Industry and Ecosystem Networks, PhD thesis, Institute of Environmental Sciences, Leiden University, Netherlands.
- Suh, S. and Huppes, G., 2005, Methods for Life Cycle Inventory of a Product, *Journal of Cleaner Production* 13(7):687.
- Sustainable Consumption Roundtable, 2006, I Will if You Will. Towards Sustainable Consumption, National Consumer Council and Sustainable Development Commission, London.
- Szalai, A. (ed), *The Use of Time. Daily Activities of Urban and Suburban Populations in Twelve Countries*, Mouton, The Hague, Paris.
- Takase, K., Kondo, Y., and Wishizu, A., 2005, An Analysis of Sustainable Consumption by the Waste Input-Output Model, *Journal of Industrial Ecology* 9(1-2): 201-220.
- Takayama, A., 1985, *Mathematical Economics*, Cambridge University Press, Cambridge.
- Taracon, M.A. and Rio, P. del, 2005, Projection of Input-Output Tables by Means of Mathematical Programming Based on the Hypothesis of Stable Structural Evolution, *Economic Systems Research* 17(1): 1-23.
- Todd, S., Lawson, R. and Faris, F., XXXX, A Lifestyle Analysis of New Zealand Consumers, *Asia Pacific Journal of Marketing and Logistics*
- Torre, A., 1989, Technical Change and Technological Complementarities: In Search of New Tools, Paper presented at the 9<sup>th</sup> International Conference on Input-Output Techniques, Keszthely, Hungary.
- Tukker, A. et al., 2006, Environmental of Products – Analysis of the life cycle environmental impacts related to final consumption in the EU-25, *Technical Report Series of the Institute for Prospective Technological Studies EUR 22284 EN*, European Commission.
- Tversky, A. and Griffin, D., 1991, Endowment and Contrasts in Judgement of Well-Being, in: Zeckhauser, R.J. (ed.), *Strategy and Choice*, MIT Press, London: 297-318.
- UNCED, 1992, Agenda 21, United Nations Division for Sustainable Development, New York.
- United Nations, 1975, Towards a System of Social and Demographic Statistics, *Studies in Methods*, Series F, No. 18, New York.
- United Nations, 1993a, *Systems of National Accounts*, New York.
- United Nations, 1993b, *Integrated Environmental and Economic Accounting*, *Studies in Methods*, Series F, No. 61, New York.
- United Nations Environment Programme (UNEP), 2002, *Sustainable Consumption: A Global Status Report*, Division of Technology, Industry and Economics, United Nations, Geneva.
- United Nations Statistics Division (UNST), 2004, *Draft International Classification of Activities for Time use*, United Nations Publication Board, New York, [www.unstats.un.org/unsd/methods/timeuse/tuaaclass.htm](http://www.unstats.un.org/unsd/methods/timeuse/tuaaclass.htm).
- Veblen, T., 1898, *The Theory of the Leisure Class*, Prometheus Books, London.
- Victor, P.A., 1972, *Pollution: Economy and Environment*, George Allen and Unwin Ltd., Oxford.
- Vringer, K. and Blok, K., 1995, The Direct and Indirect Energy Requirements of Households in the Netherlands, *Energy Policy* 23(10), pp. 893-910.
- Wackernagel, M. and Rees, W., 1996, *Our Ecological Footprint. Reducing Human Impact on the Earth*, Gabriola Island, New Society Publishers.
- Waugh, F.V., 1950, Inversion of the Leontief Matrix by Power Series, *Econometrica* 18(2): 142-154.

- Weizsäcker, E.U. von, Lovins, A. and Lovins, H., 1995, Faktor 4 - Doppelter Wohlstand und Halbierter Ressourcenverbrauch, Droemer Knauer Verlag, München.
- Weber, C. and Perrels, A., 2000, Modelling Lifestyle Effects on Energy Demand and Related Emissions, *Energy Policy* 28: 549-566.
- Weber, C. and Schnabl, H., 1998, Environmentally Important Intersectoral Flows: Insights from Main Contributions Identification and Minimal Flow Analysis, *Economic Systems Research* 10(4): 337-355.
- Weisz, H., 2000, Accounting for Economy-Wide Material Flows: Highly Aggregated Physical Input-Output Tables for Austria, Wien.
- Weisz, H., Schandl, H. and Fischer-Kowalski, M., 1999, OMEN – An Operating Matrix for Material Interrelations Between the Economy and Nature. How to Make Material Balances Consistent, in: Kleijn, R., Fischer-Kowalski, M. and Palm, V., *Ecologizing Societal Metabolism: Designing Scenarios for Sustainable Material Management*, Leiden.
- Weisz, H. and Duchin, F., 2006, Physical and Monetary Input-Output Analysis: What makes the difference?, *Ecological Economics* 57(3): 534-541.
- Werf, P van der., 2002, Tijdbesteding en Energiegebruik, IVEM-doctoraalsverslag Nr.149, Groningen (in Dutch).
- Wiedmann, T., Lenzen, M., Turner, K. and Barrett, J., 2007a, Examining the Global Environmental Impact of Regional Consumption Activities, Part 2 of Review of Input-Output Models for the Assessment of Environmental Impacts Embodied in Trade, *Ecological Economics* 61: 15-26.
- Wiedmann, T., Wood, R., Lenzen, M., Minx, J.C., Guan, D. and Barrett, J., 2007b, Development of an Embedded Carbon Indicator, DEFRA, London, UK.
- Wiedmann, T., Minx, J.C., Barrett, J., and Wackernagel, M., 2006a, Allocating ecological footprints to final consumption categories with input-output analysis. *Ecological Economics*, 56(1):28-48.
- Wiedmann, T., Minx, J.C., Barrett, J., Vanner, R. and Ekins, P., 2006b, Sustainable Consumption and Production - Development of an Evidence Base: Resource Flows, DEFRA, London, UK.
- Wier, M., Lenzen, M., Munksgaard, J. and Smed, S., Effects of Household Consumption Patterns on CO<sub>2</sub> Requirements, *Economic Systems Research* 13: 259-274.
- WCED, 1987, Our Common Future, The Brundtland Report, Oxford University Press, Oxford.
- Yan, C.-S. and Ames, E., 1965, Economic Interrelatedness, *The Review of Economic Studies* 32(4), 299-310.

# A Allocating Ecological Footprints to Final Consumption Categories With Input-Output Analysis<sup>1</sup>

**Abstract:** We present and discuss a method that allows the disaggregation of national Ecological Footprints by economic sector, detailed final demand category, sub-national area or socio-economic group. This is done by combining existing National Footprint Accounts with input-output analysis. Calculations in the empirical part are carried out by using supply and use tables for the United Kingdom, covering the reporting period 2000. Ecological Footprints are allocated to detailed household consumption activities following the COICOP classification system and to a detailed breakdown of capital investment. The method presented enables the calculation of comparable Ecological Footprints on all sub-national levels and for different socio-economic groups.

The novelty of the approach lies in the use of input-output analysis to re-allocate existing Footprint accounts, in the detail of disaggregation by consumption category and in the expanded use of household expenditure data. This extends the potential for applications of the Ecological Footprint concept and helps to inform scenarios, policies and strategies on sustainable consumption. The method described in this paper can be applied to every country for which a National Footprint Account exists and where appropriate economic and environmental accounts are available. The approach helps to save time in data collection and improves the consistency between Ecological Footprint estimates for a particular human society from different researchers. For these reasons, the suggested methodology includes crucial steps on the way towards a standardisation of Ecological Footprint accounts.

---

<sup>1</sup> This Appendix is a re-production of: Wiedmann, T., Minx, J., Barrett, J., and Wackernagel, M., 2006. Allocating ecological footprints to final consumption categories with input-output analysis. *Ecological Economics*, 56(1):28-48.

## **A.1 INTRODUCTION**

### **A.1.1 The need for a combined footprint approach**

#### **A.1.1.1 Current Ecological Footprint accounting and some of its deficiencies**

The Ecological Footprint measures human demand on nature by assessing how much biologically productive land and sea area is necessary to maintain a given consumption pattern. This can then be compared to available biocapacity, also expressed in land and sea areas. If global demand on area exceeds global supply of biologically productive area, this would indicate overshoot, which is a core concern for sustainability. While initially introduced in the 1990s (Wackernagel and Rees, 1996), the method has been further developed and has been used in numerous studies in recent years (e.g. Wackernagel et al., 1999; Simmons et al., 2000; Barrett, 2001; Lenzen and Murray, 2001 and 2003; Lewan and Simmons, 2001; Barrett and Scott, 2003; Stöglehner, 2003; Wood and Lenzen, 2003; McDonald and Patterson, 2003 and 2004; Erb, 2004; Haberl et al., 2004; Monfreda et al., 2004; Nijkamp et al., 2004; Wackernagel et al., 2004a; Aall and Norland, 2005; Barrett et al., 2005; van Vuuren and Bouwman, 2005). In 2004, a new set of Ecological Footprints for 149 countries of the world has been calculated and published in the Living Planet Report 2004 (WWF, 2004). The Ecological Footprint has been adopted by a growing number of government authorities, agencies, organisations and communities as a metric of ecological performance (e.g. Environment Waikato, 2003; EPA Victoria, 2003; James and Desai, 2003; WSP Environmental and Natural Strategies, 2003a and 2003b; NAFW, 2004; NRG4SD, 2004).

Despite its success and popularity, the Ecological Footprint concept has been criticised for, amongst other issues, not accurately reflecting the impacts of consumption (van den Bergh and Verbruggen, 1999; Lenzen and Murray, 2001; Ferng, 2002), not correctly allocating responsibilities (Herendeen, 2000; McGregor et al., 2004a) and not being useful for policy development (van den Bergh and Verbruggen, 1999; Ayres, 2000; Moffatt, 2000; Ferng, 2002). Most concerns are rooted in the EF's nature as an index combining actual land-use with a notion of "hypothetical" energy land. The conversion of carbon impacts from energy use into land units cannot be done in a non-arbitrary way. While often discussed as a comprehensive measure of environmental sustainability, it

therefore rather arbitrarily mixes up land-use and climate change issues in a not very meaningful way and wraps the whole thing into a notion of Carrying Capacity providing a seemingly intuitive measure of what one planet living might be.

It is important to recognise these limitations and restrict EF applications to communicative purposes. However, to serve different user groups and circumstances it might be helpful to slice the indicator in different ways depending on the application. In particular, the current National Footprint Account (NFA) method which is based on resource balance accounting on a national scale (Monfreda et al., 2004) neither provides a breakdown by economic sector nor by final demand category or detailed consumption activity. Although based on a comprehensive account of resource flows, it does not depend on consumption statistics by economic sector and hence fails to depict the mutual interrelationships of economic activities and to assign indirect environmental burden arising out of inter-industrial dependencies. For example, the NFA method does not provide Ecological Footprints for services that often use a very small amount of resource inputs directly. However, services trigger resource flows indirectly, because they use numerous intermediate products from other industries for their service provision. Rosenblum et al. (2000) and Suh (2004a) for example show that those indirect requirements account for the majority of resource use of services.

Furthermore, two specific problems arise when one tries to generate Ecological Footprints for use in decision-making by local or regional governments and authorities:

- lack of data: the smaller the area and population under investigation the more difficult it becomes generally to obtain accurate data on resource consumption. Detailed information on the consumption volumes of materials and products is usually only held at national level (in databases such as PRODCOM<sup>2</sup> or UN Comtrade<sup>3</sup>). At local authority level only few data are available; examples for the UK being the consumption of electricity and natural gas (DTI, 2004) or municipal waste arisings (DEFRA, 2004).
- comparability of results: numerous Footprint studies for sub-national geographical areas in recent years have used different methods and data sets and have produced results that are not directly comparable with each other. Initial recommendations to tackle this problem were drawn from an

---

<sup>2</sup> Products of the European Community, Eurostat, [http://epp.eurostat.ec.eu.int/portal/page?\\_pageid=1090.1137397&\\_dad=portal&\\_schema=PORTAL](http://epp.eurostat.ec.eu.int/portal/page?_pageid=1090.1137397&_dad=portal&_schema=PORTAL)

<sup>3</sup> UN Commodity Trade Statistics Database, UN Statistics Division, <http://unstats.un.org/unsd/comtrade>

international workshop in the European Common Indicators Project (Lewan and Simmons, 2001). However, no commonly accepted procedure of calculating sub-national Footprints is yet available. This is of concern for decision-makers who might want to adopt the Ecological Footprint as a performance indicator, suggesting a need for a standardised methodology for Footprint accounting at both national and sub-national level (GFN, 2004a).

While these problems are of a methodological nature, lacking policy relevance is another perceived weakness of the Ecological Footprint. Generally, the Ecological Footprint is used to merely describe the human demand on nature. The underlying dynamics leading to this resource consumption however, are usually not explored. A UK Government report (DEFRA/DTI, 2003) acknowledges that the drivers behind the environmental impacts of consumption are less well understood than those behind the environmental impacts of production. So far, no existing model offers satisfactory explanations of the environmental impacts of different consumer lifestyles and socio-economic groups although first attempts have been made to explore this application potential for the Ecological Footprint (Lenzen and Murray, 2001 and 2003).

#### **A.1.1.2 The combined approach**

In order to provide meaningful analyses for policy-makers at all levels it is vital that future Ecological Footprint studies address the insufficiencies mentioned above. In this paper we present a methodology based on input-output analysis that allows the disaggregation of existing national Footprint estimates by economic sector, final demand category, sub-national area or socio-economic group, whilst ensuring full comparability of results. Taking the existing National Footprint Accounts (NFA) provided by the Global Footprint Network (GFN, 2004b) as a starting point, we then disaggregate the total Footprint of the United Kingdom, for the year 2000, by using input-output analysis based on economic supply and use tables. With this method it is possible to:

... allocate the existing and commonly accepted national Footprint estimates to detailed final consumption categories. The breakdown is based on expenditure data and includes a detailed disaggregation of household consumption activity by standard classification and of capital investment (gross fixed capital formation). Thus, the mutual interrelationships among economic sectors are taken into account and direct as well as indirect Ecological Footprints are assigned to

consumer activities that are relevant for sustainable consumption policies. The approach also allows the clustering of detailed consumption categories to policy areas such as food, energy, housing, transport, household consumption, services etc.

... generate comparable sub-national Footprint accounts, based on detailed expenditure data in the area under investigation. This enables the direct comparison of results on different spatial scales. A first study employing the presented approach has been undertaken in Wales (Barrett et al., 2005).

... calculate Ecological Footprints of socio-economic groups, based on the spending behaviour of 55 different socio-economic types. Such an analysis informs about typical consumption patterns and helps to formulate policy strategies on sustainable consumption (Birch et al., 2004).

... bring Footprint analysis into the scope of ecological-economic modelling frameworks and to enable scenario analysis, which is at the heart of today's sustainability approaches.

The proposed procedure builds on and contributes to existing research (see below for a more detailed review of recent studies). It links existing National Footprint Accounts to standardised, national environmental-economic accounting and therefore builds on two consistent data sets that are produced annually. Economic national accounts are generated and made available by government statistical offices. Although several studies have applied input-output analysis to modify Ecological Footprint calculations before (Bicknell et al., 1998; Lenzen and Murray, 2001; McDonald and Patterson, 2003 and 2004), this is the first time that an existing National Footprint Account (NFA) – in this case for the UK in 2000 – has been linked to and disaggregated by means of input-output analysis. Rather than using actual land use or land disturbance as input data, the method uses the NFA data based on bioproductivity as a starting point for calculations.

Ecological Footprints of expenditure and socio-demographic patterns have also been explored before (Lenzen and Murray, 2001 and 2003). Again, the novelty of our approach lies in the application for the UK and the possibility that all results can be directly compared to existing National Footprint Accounts.

This type of analysis is possible if detailed and adequate data for expenditure on final consumption is available, which was the case for household expenditure in this study. Thus, with this method Footprint analyses can be carried out which – due to a lack



of consumption related data – would either not have been possible before or would have required substantially more time and effort.

For these reasons, the method proposed helps to increase the policy relevance of Footprint accounts and ensures consistency and comparability of results between different spatial levels and across countries. This becomes even more important once a common standard for Footprint accounting is achieved.

### **A.1.2 Input-output analysis and the Ecological Footprint – a short review**

Environmental extended input-output analysis (Leontief and Ford, 1970; Victor, 1972; Miller and Blair, 1985) is a well established approach that allows resource flows and environmental impacts to be assigned to categories of final consumption. Some more recent examples of the use of environmental input-output analysis include analyses of international trade (Proops et al., 1999; Ahmad and Wyckoff, 2003; Meyer et al., 2003; Ferguson et al., 2004; Peters and Hertwich, 2004), estimation of land use changes in China (Hubacek and Sun, 2001) as well as pollution attribution and calculation of regionally specific fuel use (McGregor et al., 2001; Turner, 2003) Further applications assess the environmental impacts of spending options (Lenzen and Dey, 2002) and explore the interdependence of industries in terms of environmental pressure and resource depletion (Lenzen, 2003). Material flow calculations at the national and international level (Moll et al., 1999 and 2002; Hinterberger and Giljum, 2003; Giljum and Hubacek, 2004; Suh, 2004a) and Life Cycle Assessments (LCA) have also been combined with input-output analysis (Hendrickson et al., 1998; Joshi, 1999; Lenzen, 2002; Suh and Huppes, 2002; Suh, 2004b; Suh et al. 2004).

Bicknell et al. (1998) were the first to present a way of calculating Ecological Footprints by using an input-output methodology. The total Ecological Footprint of New Zealand is derived by using real land use data and by incorporating embodied energy multipliers in an 80 sector input-output framework. Ferng (2001) identifies some shortcomings in Bicknell et al.'s estimation procedure and provides the necessary corrections in the methodology. Most importantly, Ferng uses a composition of land multipliers instead of aggregated land multipliers to estimate the Ecological Footprint associated with production activities and demonstrates that significantly different results are obtained by the two methods.

Bicknell et al.'s methodology has recently been updated and improved by McDonald and Patterson (2003 and 2004) in a multi-regional input-output framework for New Zealand. They generate regional input-output tables and a regional land appropriation model to calculate the Ecological Footprints and interdependencies of 16 regions in New Zealand. The results are disaggregated by land type and economic sector.

As proposed by van den Bergh and Verbruggen (1999), Lenzen and Murray (2001) apply input-output analysis to base Footprint estimates on actual – instead of hypothetical – land use and land disturbance in Australia. They also take into account greenhouse gases other than CO<sub>2</sub> and emission sources other than energy use and introduce a new land type category called 'emissions land'. Hence, those Footprint estimates cover a scope that is different to that of the National Footprint Accounts. However, Lenzen and Wackernagel et al. are currently working together on a project in Victoria which focuses on ways to align the two methods (Lenzen et al., forthcoming).

Lenzen and Murray (2003) also demonstrate how their input-output based approach can be used to create national, regional and individual Ecological Footprint accounts, to decompose Footprint accounts in production layers and structural paths and to demonstrate the relationship between socio-economic (e.g. household expenditure) and demographic factors and the Ecological Footprint.

Ferng (2002) improves the methodology for the energy component of the Footprint by using a standard input-output approach for the calculation of embodied energy. Ferng is the first to apply a standard economic scenario approach based on a computable general equilibrium model to assess the impact of different policies on the Footprint. This helps to reconcile economic and environmental policies in the future.

Wood and Lenzen (2003) demonstrate how input-output analysis can be used to produce holistic Ecological Footprint accounts for institutions. In addition to direct (on-site) land requirements and emissions, their analysis covers all higher-order requirements based on the institutions' annual operating costs and factor multipliers from a generalised input-output analysis. Wood and Lenzen also show that the proportion of upstream impacts is significant and cannot be neglected; their comparison shows that previous Footprint studies that do not apply input-output analysis produce considerable lower results. They also explore a further potential of the input-output framework by breaking down the Ecological Footprint totals into detailed contributing paths which in turn enables the use of the results in policy formulation.

Hubacek and Giljum (2003) first applied physical input-output analysis to estimate land Footprints (land appropriation) for the production of exports from Europe, arguing that physical multipliers for this kind of calculation would be more appropriate, as the most land intensive sectors are also the sectors with the highest amounts of material flows. In his reply to this paper however, Suh (2004c) shows that the results may vary significantly when using physical input-output tables (PIOT) depending on crucial issues like double counting, the treatment of wastes and the effect of closing the system toward direct material inputs. Giljum and Hubacek themselves demonstrate that results differ when using physical input-output tables, depending on whether waste is seen as a final demand category or as a by-product in intermediate production (Giljum and Hubacek, 2004).

McGregor et al. (2004a, 2004b) present input-output analysis as an alternative to Ecological Footprint calculations. In their applications to the Jersey and Scottish economy however, they only attribute CO<sub>2</sub> and pollutant emissions to elements of final demand and do not calculate any land use quantities. In order to account for pollution generation and resource use within the geographical boundaries of Jersey and Scotland, the authors endogenise trade in the input-output system. This procedure, in essence, allocates pro rata the pollution of production for exports to the sectors and final demand uses that import. By doing so, the responsibility for regional pollution is reallocated to the consumption of the population living in those regions. A critique of this approach can be found in Moffatt et al., 2005.

In conclusion, a number of research studies have been undertaken in recent years to explore the potential of input-output analysis to calculate Ecological Footprints. All of these approaches focus on different research questions, geographical areas and applications and all are based on different assumptions and data sets. As a result none of the studies are directly comparable and in most cases it would be difficult to adapt the methods to different areas or applications.

The method presented in this paper takes the available National Footprint Accounts (NFA) (GFN, 2004b) as a basis and uses monetary input-output analysis to establish a link with detailed national expenditure data. We do not offer an alternative to the NFA approach as such nor does our method update the NFA results. The novelty of our approach rather lies in the combination of the two methods, the comparability of results on any spatial scale, the detailed disaggregation of national totals and hence in a vastly extended range of potential applications. We hope that the method presented helps

with both the process of standardisation of Footprint results and the exploration of new fields of application in the context of sustainable consumption policies.

The rest of the paper is structured as follows. Details of the calculation method are presented in the next Section. Results for the UK are presented and discussed in Section A.3. This is followed by a description of possible applications of the method in Section A.4, illustrating its potential usefulness. Finally, Section A.5 concludes the findings.

## **A.2 Methodological approach**

The method described in this paper applies input-output analysis in a supply and use table framework (SUT) as originally proposed by Gigantes (1970). Miller and Blair (1985) provide a comprehensive and reader-friendly introduction. Similar procedures have been applied in the environmental field by, for example, Vaze (1997) and Lenzen (2001).

Besides the higher level of control and flexibility provided by such a procedure, the choice for a SUT framework was triggered by the unavailability of analytical tables for recent years. The latest analytical input-output table for the United Kingdom – which are supposed to be produced every five years – would have been from the year 1995. Supply and use tables in contrast are available on an annual basis. For an up-to-date policy relevant analysis, the intention of this work was to combine the most recent UK industrial transaction tables from the year 2000 (ONS, 2003) with the latest National Footprint Accounts (WWF, 2004).

The SUT framework represents a complete picture of the UK economy showing all inputs (domestically produced goods and imports) and all outputs (domestic final consumption and exports) in monetary terms. Table 1 provides an overview of the supply and use table framework used. Note that the system we use is closed with respect to imports and exports, i.e. imports are included in the combined supply matrix  $V$ , the combined use matrix  $U$  and – in the form of direct imports – the final demand matrix  $Y^{com}$ . Exports are included in the final demand matrix  $Y^{com}$ . Hence, the terms ‘commodities’ and ‘industries’ in Table 1 refer to both domestic and foreign markets. Total industry and commodity outputs include imports, which in this approach are treated as competitive and – with respect to imports for intermediate demand – as endogenous.

	Commodities	Industries	Final Demand	Total Output
Commodities		$U_{m \times n}$	$Y_{m \times o}^{com}$	$q$
Industries	$V_{m \times m}$			$x$
Value Added		$W$		
Total Input	$q$	$x$		$\Sigma$

with:

$V$  = combined matrix for the supply of commodities (m) by industries (n); including imports

$U$  = combined matrix for the use of commodities (m) by industries (n) = intermediate flows; including imports

$Y^{com}$  = combined matrix for the final demands (o) for commodities (m), including direct imports and exports.

$q$  = commodity output vector, including imports

$x$  = industry output vector, including imports

$W$  = value added / primary input matrix

Table A.1 - Overview of the monetary supply and use table framework used in this work

All calculations have been carried out on a 76x76 sector level imposed by the aggregation level of the UK Environmental Accounts (ONS, 2004).

The method applied involves the following seven steps<sup>4</sup>:

- Step 1: associate NFA Ecological Footprints of production and imports with industrial sectors
- Step 2: prepare combined supply matrix (76x76)
- Step 3: prepare combined use matrix (76x76) in basic prices
- Step 4: calculate direct and indirect requirement matrix (76x76)
- Step 5: calculate direct and indirect intensity vectors (7x76)
- Step 6: calculate Ecological Footprints of final demand categories
- Step 7: disaggregate final demand categories

<sup>4</sup> Technical note: All calculations were performed on a desktop PC with Microsoft® Excel®. Specific add-in programmes – 'Matrix15.xla' and 'BigMatrix.xla' (Volpi, 2003) – were used to enable calculations with big matrices in Excel®.

### Step 1: associate NFA Ecological Footprints of production and imports with industrial sectors

The National Footprint Accounts (NFA) constitute the underlying methodology with which Ecological Footprints have been calculated for 149 countries (GFN, 2004b; WWF, 2004). Using UN statistics on production, import, export and yields for a number of resource and product categories, the accounts estimate the apparent net consumption of a nation. Estimates for the embodied energies of secondary products inform the trade balance. The method distinguishes between national conversion efficiency for domestically produced products and global conversion efficiency for imports. Based on the resource balance, the 'global hectares' necessary to satisfy the national demand are calculated. One global hectare (gha) reflects the productivity of a world average bioproductive hectare. A detailed description of the NFA method can be found in Monfreda et al. (2004) as well as a methodology paper from the Global Footprint Network (Wackernagel et al., 2004b).

According to the NFA, the per capita Ecological Footprint of the United Kingdom for the year 2000 amounts to 5.31 gha/cap (Moran, 2004). Table A.2 shows a breakdown of this total. In the following we present a methodology to relate these NFA figures to economic sectors in order to provide a basis for input-output calculations.

Land type	Domestic production (P)	Imports (I)	Stock changes (SC)	Total use (TU=P+I+SC)	Exports (E)	Apparent consumption (TU-E)
Energy (fossil fuels)	2.50	1.29	-	3.80	0.78	3.02
Energy (nuclear)	0.29	-	-	0.29	-	0.29
Crop land	0.44	0.40	0.01	0.86	0.20	0.66
Pasture	0.23	0.10	0.001	0.33	0.03	0.30
Built land	0.38	-	-	0.38	-	0.38
Sea	0.17	0.20	-0.002	0.37	0.12	0.24
Forest	0.09	0.36	-	0.45	0.03	0.42
<b>Total Ecological Footprint (gha/cap)</b>	<b>4.10</b>	<b>2.36</b>	<b>0.01</b>	<b>6.47</b>	<b>1.16</b>	<b>5.31</b>

**Table A.2 - Summary of the National Footprint Account for the United Kingdom in 2000**  
(Data from the Global Footprint Network; Moran, 2004. All numbers in global hectares per capita. Figures may not add up to the stated totals due to rounding.)

The Ecological Footprint for the total use of resources (6.47 gha/cap) represents the total land requirements of all inputs to the UK economy. It includes the Footprint for production, imports and stock changes and can be seen as the total demand on nature that

is required to produce the total output of the UK economy, including the production of exports.

The total use Footprint acts as a starting point for input-output calculations in our model. In a first step, it is redistributed to 76 industrial sectors as well as direct household consumption in order to obtain specific input data for the input-output analysis. Direct consumption of private households has to be accounted for separately because it is not represented in the inter-industrial transactions described in input-output tables. Two categories were considered here, a) the direct usage of fuels in households as well as consumed land in the form of residences and b) direct emissions from private vehicles as well as road space used by private cars (the refining and distributing of the fuels however is attributed to the respective intermediate industries).

The redistribution of the total use Footprint was done separately for the seven land types shown in Table 2 as follows:

- The domestic production energy Footprint for fossil fuels (2.50 gha/cap) was assigned to the 76 industrial sectors and the two direct household consumption categories (domestic consumption of fuels and private transport) by using the respective carbon dioxide emissions from UK Environmental Accounts (ONS, 2004). These cover the total terrestrial emissions of CO<sub>2</sub> in the United Kingdom.
- The fossil fuel energy Footprint of imports (1.29 gha/cap) was redistributed to UK industrial sectors by using an allocation matrix that matches the 64 categories of materials and products used by the National Footprint Accounts with the 76 economic sectors of the input-output framework. By assigning the NFA Footprints of imports to the respective UK industries, consistency with the monetary supply and use table framework is established that combines inputs from domestic industries and imports in both the supply and the use matrix. However, a differentiation is made between the energy Footprint of domestic production and imports. While the National Footprint Accounts use territorial CO<sub>2</sub> emissions of a nation to calculate the energy Footprint of domestic production, they use world-average embodied energy data to convert quantities of imported agricultural and manufactured goods into their energy equivalents (Monfreda et al., 2004). These values are then converted to CO<sub>2</sub> emissions and corresponding energy Footprints, assuming a world

average fuel mix. Imports of services are not explicitly addressed in the NFA method.

- The Footprint for nuclear energy (0.29 gha/cap) was attributed to one industrial sector only – electricity production and distribution – representing the main user of nuclear material (Footprint calculations usually do not account for the military use of nuclear material).
- The Footprints for cropland and pasture (total use of 0.86 and 0.33 gha/cap, respectively) were assigned completely to the agricultural sector.
- The Ecological Footprint for built land (0.38 gha/cap) includes area for hydro-power and was attributed to industrial and domestic sectors by using real land requirements for non-domestic premises, based on research undertaken by Bruhns et al. (2000), as well as land area occupied by transport infrastructure and domestic buildings (DTLR, 1999).
- The Footprints for fishery (marine and inland water, 0.37 gha/cap for total use) and forest area (0.45 gha/cap) were assigned to the fishing and the forestry sector, respectively. An estimated forest Footprint of 0.002 gha/cap was directly allocated to domestic fuel consumption in order to account for the domestic use of fuel wood for heating which is not valued in economic terms.

The results of Step 1 basically constitute an expansion of national environmental accounts with Ecological Footprints. The Ecological Footprints derived in that way represent the direct ecological requirements of the 76+2 economic sectors, i.e. the environmental pressure caused by land appropriation and CO<sub>2</sub> emissions of UK production activities and imports.

However, such an account does not yet show the affiliation of Ecological Footprints with consumption activities. Input-output analysis is therefore used to allocate Footprints to final consumption categories as outlined in the following steps.

### Step 2: prepare combined supply matrix (76x76)

A supply table shows the commodities supplied by (domestic) industries for a particular year. Principal products are recorded on the principal diagonal, while secondary products are shown as the off-diagonal elements of the matrix. The recent publications of supply tables by the UK Office for National Statistics (ONS) include the two vectors of



industrial and commodity output as well as the supply matrix in summary form only because of disclosure rules prohibiting the publication of data that may be traced to a single contributor from ONS inquiries (ONS, 2003). However, earlier versions of environmental accounts include complete supply matrices, with 1998 being the most recent year available (ONS, 1999). In order to update the complete supply table with recent information for the year 2000, the RAS procedure was applied (Bacharach, 1970; Allen, 1975; Miller and Blair, 1985). The RAS method allows the updating of the  $n^2$  elements of the supply table with  $2n$  pieces of new information. These are the vectors of total commodity output  $q^{new}$  and total industry output  $x^{new}$ , which are provided in the SUT publication (ONS, 2003).

Imports were included in the re-estimation of the supply table due to the lack of availability of separate information on the industrial use of imports. Hence, in this combined supply table, imported commodities are treated as competitive to domestic products. As mentioned above however, the National Footprint Accounts use world-average conversion factors for the imports of secondary products, whereas national conversion factors are used for domestically produced secondary products (Monfreda et al., 2004).

### Step 3: prepare combined use matrix (76x76) in basic prices

The industrial dimension of the combined use matrix shows, for each industry, the total costs incurred in the production process as intermediate consumption, including the costs for imported intermediate products and services. The product dimension of the use matrix shows intermediate consumption and final demand by product and is valued at purchasers' prices. Again, both intermediate and final demand estimates include goods and services both domestically produced and imported.

The officially published use tables are only available in a mixed price system (ONS, 2003) rendering it unsuitable for immediate application. In order to make the use table consistent with the supply table, the intermediate flow matrix needs to be transformed from purchasers' into basic prices. In particular, this requires the exclusion of direct taxes and re-distribution of trade margins (Ruiz, 2002). A use matrix in basic prices for the year 2000 was courteously provided by Cambridge Econometrics (Lewney, 2004) and integrated with the available ONS data.

**Step 4: calculate direct and indirect requirement matrix (76x76)**

Similar to the  $A$  matrix of the standard input-output model (Leontief and Ford, 1970) a technical coefficient matrix  $B$  with generic elements  $b_{ij}$  can be derived from the use matrix (Miller and Blair, 1985).

$$B = [b_{ij}] = \left[ \frac{U_{ij}}{X_j} \right] \quad (\text{A.1})$$

where:  $U_{ij}$  = use of commodity  $i$  by industry  $j$  and  $X_j$  = total output of industry  $j$  including imports. Each element  $b_{ij}$  represents the amount of commodity  $i$  required to produce one unit of the output of industry  $j$ . Therefore, the input-output systems can be written as:

$$q = Bx + y^{com} \quad (\text{A.2})$$

where:  $q$  = commodity output vector (including imports);  $B$  = technical coefficient matrix;  $x$  = industry output vector and  $y^{com}$  = vector of the final demand for commodities. To derive the direct and indirect requirement matrix (generally known as the 'Leontief Inverse' in the standard input-output model), information on primary and secondary production needs to be added to the framework. For this, a matrix  $D$  can be defined whose individual coefficients  $d_{ji}$  are often referred to as commodity output proportions.

$$D = [d_{ji}] = \left[ \frac{V_{ji}}{q_i} \right] \quad (\text{A.3})$$

where:  $V_{ji}$  = supply of commodity  $i$  by industry  $j$  and  $q_i$  = total (domestic + imported) supply of commodity  $i$ .

Matrix  $D$  can be used to 'weight' the technical coefficient matrix  $B$  and assign all secondary products to the industry where they have been originally produced. This implies that we treat all secondary products as by-products being manufactured with the same technology as the principal product of this industry (industry based technology assumption). Alternatively, we could have considered secondary products as subsidiary and assigned them to the industry, where they constitute the principal product. We opted for the industry based assumption as it appeared reasonable to link secondary production

to the Ecological Footprint of the respective industry as assigned in (Step 1). The only superior treatment would have been to apply the best suited assumption for each individual industry in a hybrid technology system as done by Vaze (1997). However, the required information for such a procedure was not available.

A symmetric (industry-by-industry) input-output framework can then be constructed in the following way:

$$x = [(I - DB)^{-1} \cdot D] \cdot y^{com} \quad (A.4)$$

where:  $x$  = industry output vector;  $I$  = identity matrix;  $D$  = industry-based technology coefficient matrix;  $B$  = technical coefficient matrix and  $y^{com}$  = vector of the total final demand for commodities. The bracketed term  $[(I-DB)^{-1}D]$  represents the direct and indirect requirement matrix (the ‘Leontief Inverse’) of the SUT framework.

#### Step 5: calculate direct and indirect intensity vectors (7x76)

The Ecological Footprints per industrial sector from Step 1 are then divided by the total output of these industries at basic prices including imports. The result is a 7x76 matrix – 7 Footprint land types and 76 industries – for Ecological Footprints per industry output (in gha/cap/M£), called the direct intensity matrix  $EF^{dir}$ . It expresses the Ecological Footprints that are directly associated with the production activities of industrial sectors per million £ of their product output.

Postmultiplying  $EF^{dir}$  with the direct and indirect requirement matrix results in the total intensity matrix  $EF^{tot}$  which represents the total (direct and indirect) Ecological Footprints of industrial activities arising through the entire industrial supply chain to provide one unit of product to final demand (unit gha/cap/M£).

$$EF^{tot} = EF^{dir} \cdot [(I - DB)^{-1} \cdot D] \quad (A.6)$$

$EF^{tot}$  is also referred to as the multiplier matrix. Equation (A.5) enables the Footprints of production activities to be assigned to final demand sectors – as is done in the next step – and thereby accounts for all mutual interdependencies of industrial sectors.

#### Step 6: calculate Ecological Footprints of final demand categories

This step allocates Ecological Footprints to final demand categories. This is done by postmultiplying the total intensity matrix  $EF^{tot}$  with the final demand matrix  $Y^{com}$ .

This results in the matrix  $EF^{FD}$  which shows the individual Ecological Footprints  $ef_{lo}$  of final demand category  $o$  per land type  $l$  (unit gha/cap):

$$EF^{tot} \cdot Y^{com} = EF^{FD} = [ef_{lo}] \quad (A.7)$$

A further insight in the detailed make-up of each Ecological Footprint  $ef_{lo}$  can be obtained if the corresponding final demand vector  $Y_o^{com}$  is diagonalised and the resulting matrix  $\hat{Y}_o^{com}$  is premultiplied with  $EF^{tot}$ . This results in a breakdown of the Footprint of any chosen final demand category into the direct and indirect contributions of all of the 76 industrial sectors.

### Step 7: disaggregate final demand categories

Any disaggregation of final demand can be applied to the model. A detailed breakdown of both final household demand and capital investment is provided by the UK Office for National Statistics with the publication of supply and use tables (ONS, 2003). The private household demand vector of the use table is disaggregated according to the COICOP classification (Classification of Individual Consumption According to Purpose). COICOP was jointly developed by the statistical office of the OECD and Eurostat and was first published in 1999. It covers all areas of individual consumption. The intuition behind it is that usually multiple market goods are required to satisfy a certain consumption activity. Therefore, only the combination of market goods in ‘consumptive systems’ represented by the COICOP columns of the household demand matrix allows thorough examination of household expenditure patterns and resulting environmental implications. Total expenditure by COICOP headings as well as associated Ecological Footprints are shown in Table A.3.

The same holds true for capital investment represented in the final demand category ‘Gross Fixed Capital Formation’. Here, a breakdown is provided into 39 economic sectors where capital is invested (see also Table A.4). All figures for final demand sub-categories have been converted from purchasers’ prices to basic prices by assuming the same ratio as for the total final demand vectors of households and capital investment.

## **A.3 Results and Discussion**

### **A.3.1 Results from the allocation of Ecological Footprints to detailed consumption categories**

An overview of the results of the input-output calculations is presented in Table A.3. The three final demand categories with the highest Footprint are household consumption (3.84 gha/cap), capital investment (0.69 gha/cap) and exports (1.51 gha/cap). These categories will be discussed in detail in the following. Total household consumption includes the direct consumption of built land and fuels for housing (0.50 gha/cap), built land and fuels for private transport (0.28 gha/cap) and all other consumption by private households (3.06 gha/cap). The last one is by far the largest contributor to the total Footprint and comprises the consumption of food, consumable and durable items as well as services.

A detailed breakdown by COICOP classification of this household consumption is shown in Table A.4. The five consumption activities with the highest total Footprint per capita are food (0.68 gha/cap), electricity and gas distribution (0.39 gha/cap), catering services (0.35 gha/cap), transport services (0.18 gha/cap) and other recreational items and equipment (0.18 gha/cap). In these categories we also find the highest energy Footprint (electricity and gas distribution with 0.39 gha/cap), the highest real land Footprint (food consumption with 0.58 gha/cap) and the highest Footprint per M£ spent (electricity and gas distribution with 2.84E-05 gha/cap/M£, followed by food, 2.32E-05 gha/cap/M£ and other recreational items and equipment, 2.10E-05 gha/cap/M£).

The expenditure breakdown by COICOP includes all consumption activities of households that are valued in monetary terms. This also includes expenditure on services and hence the presented method allows the calculation of total (direct plus indirect) Ecological Footprints for service activities. Service industries are at the end of the value-added chain and they require a variety of resources from the secondary and primary sector, many of which have a substantial Ecological Footprint. This can be demonstrated by looking at the per capita Footprint of food consumption in households (0.68 gha/cap) and catering services (0.35 gha/cap). If this is compared with the amount of food in 2000 that was eaten in households (0.570 t/cap) and that was eaten out (0.069 t/cap) (ONS, 2001) it becomes obvious that the Ecological Footprint per tonne of food eaten is significantly higher when the food is provided by a catering service (1.2 gha/t for eating in versus 5.1 gha/t for eating out).

Land type	Total household consumption				Government	Gross fixed capital formation	Other final demand <sup>b)</sup>	Exports goods	Exports of services <sup>c)</sup>	Total final demand	Final national demand
	Domestic fuel and land consumption <sup>a)</sup>	Private transport <sup>a)</sup>	Other household consumption	(capital investment)							
Energy (fossil fuels)	0.358	0.252	1.43	0.250	0.471	0.045	0.757	0.233	3.80	2.80	
Energy (nuclear)	-	-	0.193	0.022	0.027	0.006	0.029	0.016	0.293	0.247	
Crop land	-	-	0.684	0.019	0.036	-0.0002	0.086	0.032	0.858	0.739	
Pasture	-	-	0.259	0.007	0.014	-0.0001	0.033	0.012	0.325	0.280	
Built land	0.141	0.026	0.102	0.031	0.020	0.013	0.025	0.020	0.378	0.332	
Sea	-	-	0.214	0.008	0.004	-0.003	0.115	0.029	0.367	0.223	
Forest	0.002	-	0.181	0.034	0.120	0.003	0.091	0.022	0.454	0.340	
<b>Total EF (gha/cap)</b>	<b>0.50</b>	<b>0.28</b>	<b>3.06</b>	<b>0.37</b>	<b>0.69</b>	<b>0.06</b>	<b>1.14</b>	<b>0.37</b>	<b>6.47</b>	<b>4.97</b>	
<b>Normalised total EF (gha/cap) (see text for details)</b>	<b>0.55</b>	<b>0.30</b>	<b>3.23</b>	<b>0.41</b>	<b>0.76</b>	<b>0.07</b>	<b>-</b>	<b>-</b>	<b>-</b>	<b>5.31</b>	

a) These Footprints have been allocated directly – not using input-output analysis – as described above in Step 1

b) Includes non-profit institutions serving households, changes in inventories and valuables

c) These are sales of services to the rest of the world by UK corporations and households as measured on a balance of payments basis. Top service exporting sectors in the UK are business services, such as advertising, market research, technical, legal and management consultancy and other financial services.

**Table A.3 – Total Ecological Footprint (EF) of the United Kingdom in 2000 allocated to final demand categories using input-output analysis (all numbers in global hectares per capita)**

Appendix A – Allocating Ecological Footprints to final consumption categories

COICOP number	Household consumption involving intermediates	Total expenditure (basic prices)	Energy Footprint	Real land Footprint	Total Ecological Footprint	Total Ecological Footprint per expenditure (×1,000,000)
		M£	gha/cap	gha/cap	gha/cap	gha/cap/M£ (×1,000,000)
01.1	Food	29,347	0.102	0.579	0.681	23.2
01.2	Non-alcoholic beverages	3,390	0.010	0.030	0.040	11.8
02.1	Alcoholic beverages	5,241	0.016	0.046	0.062	11.8
02.2	Tobacco	2,826	0.004	0.019	0.023	8.2
03.1	Clothing	13,715	0.020	0.004	0.024	1.8
03.2	Footwear	4,288	0.006	0.004	0.010	2.3
04.1	Actual rentals for housing	23,715	0.017	0.015	0.031	1.3
04.2	Imputed rentals for housing	54,008	0.037	0.034	0.071	1.3
04.3	Maintenance and repair of the dwelling	9,979	0.035	0.030	0.064	6.5
04.4	Water supply and misc. dwelling services	5,073	0.014	0.002	0.017	3.3
04.5	Electricity and gas distribution	13,874	0.389	0.005	0.394	28.4
05.1	Furniture, furnishings, carpets etc.	4,836	0.039	0.011	0.050	10.3
05.2	Household textiles	3,044	0.009	0.002	0.011	3.6
05.3	Household appliances	34,323	0.061	0.038	0.099	2.9
05.4	Glassware, tableware and hh utensils	1,793	0.009	0.001	0.011	6.0
05.5	Tools and equipment for house and garden	2,367	0.010	0.005	0.016	6.6
05.6	Goods and services for hh maintenance	4,402	0.007	0.002	0.009	2.0
06.1	Medical products, appliances and equipment	2,924	0.007	0.002	0.009	3.2
06.2	Out-patient services	2,688	0.004	0.002	0.006	2.1
06.3	Hospital services	1,910	0.003	0.001	0.004	2.0
07.1	Purchase of vehicles	22,397	0.090	0.011	0.101	4.5
07.2	Operation of personal transport equipment	27,502	0.074	0.014	0.088	3.2
07.3	Transport services	24,644	0.155	0.024	0.179	7.3
08.1	Postal Services	936	0.001	0.0003	0.002	1.6
08.2	Telephone and telefax equipment	243	0.0004	0.0001	0.0005	2.0
08.3	Telephone and telefax services	12,734	0.017	0.004	0.021	1.6
09.1	Audio-visual, photo and similar equipment	21,095	0.043	0.020	0.063	3.0
09.2	Other major durables for recreation and culture	3,657	0.011	0.008	0.018	5.1
09.3	Other recreational items and equipment	8,421	0.052	0.125	0.177	21.0
09.4	Recreational and cultural services	20,686	0.024	0.016	0.039	1.9
09.5	Newspapers, books and stationery	5,942	0.019	0.008	0.026	4.5
10.	Education	10,382	0.015	0.009	0.023	2.2
11.1	Catering services	54,951	0.118	0.231	0.349	6.4
11.2	Accommodation services	8,901	0.019	0.037	0.057	6.4
12.1	Personal care	7,387	0.024	0.004	0.028	3.8
12.3	Personal effects	34,215	0.061	0.047	0.107	3.1
12.4	Social protection	10,649	0.014	0.008	0.022	2.1
12.5	Insurance	23,430	0.033	0.011	0.044	1.9
12.6	Financial services	9,270	0.025	0.008	0.032	3.5
12.7	Other services	9,870	0.013	0.008	0.021	2.1
	Non-resident household expenditure in UK	- 11,629	- 0.030 <sup>e)</sup>	- 0.046 <sup>e)</sup>	- 0.076 <sup>e)</sup>	6.5
	UK resident holidays abroad	17,557	0.045	0.064	0.109	6.2
	Total	546,981	1.62	1.44	3.06	

Table A.4 - Expenditure and Ecological Footprints of household consumption involving Intermediates, allocated using input-output analysis; UK, 2000

Capital investment or Gross Fixed Capital Formation (GFCF) relates principally to investment in tangible fixed assets such as plant and machinery, transport equipment, dwellings and other buildings and structures. Unlike other authors (Lenzen and Murray, 2001; McGregor et al., 2004a) we do not endogenise capital investment into the input-output tables (which would be a 'partial closure' of the input-output system). Instead we deliberately retain GFCF as a final demand category, thus allowing explicit demonstration of the Ecological Footprint of infrastructure and machinery. Table A.5 shows a detailed breakdown of capital investment following information on expenditure provided by the official tables for final demand (ONS, 2003).

The following five investment categories show the highest Footprint per capita: dwellings (0.113 gha/cap), real estate activities (0.086 gha/cap), retail trade (0.040 gha/cap), post and telecommunications (0.038 gha/cap) and wholesale trade (0.035 gha/cap). Most of the capital invested in 2000 was in four of these five categories: M£24,555 in dwellings, M£18,273 in real estate activities, M£11,910 in post and telecommunications and M£8,550 in wholesale trade. Investment in dwellings is also responsible for both the highest energy Footprint (0.071 gha/cap) and the highest real land Footprint (0.043 gha/cap). Investment in agriculture, forestry and fishing – which ranks sixth in terms of Footprint per capita (0.032 gha/cap) – shows by far the highest Footprint per money invested, with 2.01E-5 gha/cap/M£.

As can be seen in Table A.3, exports account for the second highest Ecological Footprint of all final demand categories (1.51 gha/cap). This figure is substantially higher than the one calculated by the National Footprint Accounts (1.16 gha/cap, see Table A.2). Obviously, the indirect Ecological Footprint of economic activities are weighted differently by the two methods which becomes most apparent in the Footprint for exports. This can be demonstrated by looking at the different ways the Footprint of exports is calculated.



Appendix A – Allocating Ecological Footprints to final consumption categories

Standard Industrial Classification, SIC(92)	Capital investment (gross fixed capital formation)	Total expenditure (basic prices)	Energy Footprint	Real land Footprint	Total Ecological Footprint	Total Ecological Footprint per expenditure (×1,000,000)
		M£	gha/cap	gha/cap	gha/cap	gha/cap/M£ (×1,000,000)
01, 02, 05	Agriculture, forestry and fishing	1,585	0.007	0.025	0.032	20.1
11	Extraction of oil and gas	2,973	0.013	0.003	0.016	5.4
10, 12 - 14	Other mining and quarrying	277	0.001	0.0002	0.001	5.3
23	Solid and nuclear fuels, oil refining	670	0.002	0.001	0.003	4.8
24	Chemicals and man-made fibres	2,470	0.010	0.002	0.012	4.9
26	Other non-metallic minerals	556	0.003	0.0005	0.003	5.9
27 - 28	Basic metals and metal products	1,066	0.005	0.0007	0.005	5.0
29	Machinery and equipment	823	0.004	0.0007	0.004	5.2
30 - 33	Electrical and optical equipment	2,036	0.008	0.001	0.009	4.5
34 - 35	Transport equipment	2,354	0.010	0.002	0.012	5.2
15 - 16	Food, beverages, tobacco	2,102	0.009	0.002	0.012	5.5
17 - 19	Textile and leather products	313	0.001	0.0002	0.002	5.1
21 - 22	Pulp and paper, printing and publishing	1,914	0.008	0.003	0.011	5.5
20, 25, 36, 37	Other manufacturing	1,429	0.007	0.001	0.008	5.5
40.1	Electricity	2,884	0.013	0.002	0.015	5.2
40.2, 40.3	Gas	634	0.002	0.0003	0.003	4.4
41	Water	1,323	0.004	0.002	0.006	4.8
45	Construction	1,826	0.008	0.001	0.009	5.2
50	Motor vehicles sales and repairs	4,130	0.011	0.002	0.014	3.3
51	Wholesale trade	8,550	0.027	0.008	0.035	4.1
52	Retail trade	6,165	0.030	0.011	0.040	6.6
55	Hotels and restaurants	3,847	0.017	0.006	0.023	6.0
60.1	Rail transport	129	0.0005	0.0001	0.001	4.2
60.2, 60.3	Other land transport	2,224	0.009	0.002	0.011	4.9
61	Water transport	586	0.002	0.0002	0.002	3.2
62	Air transport	3,189	0.007	0.001	0.008	2.6
63	Other transport services	4,062	0.012	0.006	0.017	4.3
64	Post and telecommunications	11,910	0.033	0.006	0.038	3.2
65 - 67	Financial intermediation	6,144	0.018	0.006	0.023	3.8
70 - 74	Real estate activities	18,273	0.067	0.019	0.086	4.7
75	Public administration etc.	4,527	0.012	0.006	0.018	4.0
	Roads	1,745	0.004	0.003	0.007	4.1
80	Education	2,926	0.008	0.004	0.012	4.1
85	Health and social work	3,241	0.009	0.004	0.013	3.9
90	Sewage and refuse disposal	2,930	0.010	0.004	0.014	4.9
91 - 93	Other services	6,279	0.021	0.007	0.028	4.5
	Dwellings	24,555	0.071	0.043	0.113	4.6
	Transfer costs for land, etc.	8,436	0.013	0.009	0.022	2.6
	Valuables	315	0.002	0.0002	0.002	6.2
	Total	151,398	0.50	0.19	0.69	

Table A.5 - Expenditure and Ecological Footprints of capital investment, allocated using input-output analysis, UK, 2000

In order to account for embodied energy in traded goods the National Footprint Accounts (NFA) convert quantities of agricultural and manufactured goods into their energy equivalents, using the best available data on energy intensity of goods (Monfreda et al., 2004, Wackernagel et al., 2004b). In the current accounts, the same energy intensities for imports and exports are used and they are the same for each country. These values are then assigned CO<sub>2</sub> equivalents and subsequently energy Footprints. For imports this is done by using a world average carbon dioxide intensity of production; for exports the average carbon dioxide intensity of the primary energy production of the exporting country is used. The NFA do not take into account imports and exports of services.

In contrast, the method presented in this paper starts from the Footprints for domestic production in the UK and imports to the UK and uses input-output calculations to re-allocate the total to final demand categories, including exports. This automatically assigns specific energy intensities and carbon dioxide intensities to the production of exports with all upstream effects of the national economy taken into account. Also, the export of services is considered separately, again with all indirect impacts included. If one looks at the Ecological Footprint of exports of goods alone, the figures generated by the two methods do not differ much (1.16 gha/cap with the NFA method versus 1.14 gha/cap with the input-output method; compare Tables A.2 and A.3).

From this it may be concluded that the use of generic embodied energies in the NFA method results in a fairly accurate estimation of the Footprint for exported goods but that the omission of exports of services leads to an underestimation of the total Footprint of exports. This in turn leads to an overestimation of the Footprint for consumption. While the Footprint for apparent consumption in the NFA method amounts to 5.31 gha/cap (Table A.2) the input-output calculations suggest 4.97 gha/cap for final national consumption (Table A.3).

In order to make the results derived from the two methods comparable we therefore suggest a simple normalising procedure. After the deduction of exports the resulting final national demand Footprints for each land type (last column in Table A.3) are recalibrated to match the total consumption Footprints from the NFA method (last column in Table A.2). This is done for all land types separately and the recalibration factors for each land type are then applied throughout the final demand categories,

excluding exports. This results in slightly higher values of final demand Footprints (compare the two bottom rows in Table A.3).

By applying this normalising procedure, the difference in Ecological Footprint totals of the two methods (mainly stemming from the different treatment of service exports) is re-allocated evenly to all consumption activities within the UK. This ensures absolute comparability with results from the National Footprint Accounts, even if sub-national accounts and Footprints for socio-economic groups are calculated as described in the application examples below. This procedure also leaves room for improvements in the National Footprint Accounts. If future versions of the NFA method were to take into account exports of services, for example, the differences between the two methods would become smaller and would ultimately vanish if the same data sets, assumptions and calculations were used.

### **A.3.2 Assumptions and limitations of the methodology presented**

In the following section we focus on the critical assumptions that are specific to the method employed in this paper. A general and detailed discussion of input-output analysis and Ecological Footprints can be found in Bicknell et al. (1998, p. 157) and to some extent in McDonald and Patterson (2004, p. 56). For the assumptions and limitations of general input-output analysis we refer to Dorfman et al. (1958), Victor (1972), and Miller and Blair (1985).

Two assumptions relate to the treatment of imports in the model. Firstly, in the combined supply table, imported commodities are treated as competitive to domestic products, i.e. the monetary value of imports is assigned to industries in exactly same way as the domestic supply of products. This was done because of a lack of data and if input-output tables for imports are made available in the future<sup>5</sup> the model can be adapted to account for imports separately.

Secondly, by adopting the National Footprint Account totals the assumption was inherited that all imported goods were produced with a world-average carbon dioxide intensity, not distinguishing between different origins of the products. This assumption could only be relaxed by building up a multi-regional or international input-output model

---

<sup>5</sup> Note that analytical input-output tables usually provide this information. The most recent analytical tables for the UK for example show imports for intermediate and final demand in monetary terms in a 138 sector breakdown for the year 1995.

(Furukawa, 1986; Lenzen et al., 2004; Peters and Hertwich, 2004). However, besides being an extremely labour intensive task (essentially all trading partners or regions should be present in such a model), there are still many methodological problems in the practical implementation as outlined by Lenzen et al. (2004), associated with the required reconciliation of many different data sources from different countries and the lack of data in specific areas (e.g. trade in services).

Further assumptions are associated with the use of the RAS procedure for obtaining an up-to-date supply table. Miller and Blair (1985) point out that differences in estimates of total output obtained with and without the RAS estimation are small. The method should be even less restrictive in the employed supply and use setting. Firstly, there was up-to-date information on the allocation of primary products that account for 92 percent of the total industry output (ONS, 2003). Therefore, uncertainty is only associated with the allocation of the eight percent of secondary products represented in the off-diagonal elements of the supply table. Secondly, the information in the use table remains unaffected by the RAS procedure.

The assignment of secondary products according to the industry-based technology assumption – even though frequently applied in practice (e.g. Lenzen et al., 2004) – is certainly a limiting factor as it introduces error into the analysis. However, this error is comparably small as it only affects the eight percent of industrial output the secondary products account for. We think that this assumption is less restrictive than using the outdated technological information from the 1995 analytical table. Moreover, supply and use tables are published as a time-series and are being up-dated every year, which opens a greater potential for research and applications.

The model presented is based on static input-output calculations for one year which means that it should not be used as a forecasting tool straight away as it is unlikely that coefficients remain unchanged over the forecast time period. This is clearly a limitation if the model is to explore different policy scenarios over time. However, dynamic input-output models can help to relax the strong assumption of a fixed production technology. The required time series for both the National Footprint Accounts as well as supply and use tables are available for several past decades. Moreover, by using structural decomposition analysis (e.g. Betts, 1989; Munksgaard et al., 2000) it would also be possible to identify the underlying causes for changes in environmental pressures.

It could be argued that the use of monetary information to model land appropriation is inadequate and that physical input-output tables (PIOT) should be used instead. Apart from specific problems when using physical tables – we refer to the ongoing discussion on physical versus monetary input-output analysis in the literature (compare Hubacek and Giljum, 2003; Suh, 2004c; Giljum and Hubacek, 2004) – it is the non-existence of PIOTs for most countries, let alone PIOT time series that makes their practical application virtually impossible. The excellent availability of monetary supply and use tables on the other hand opens up a great potential for practical applications of the presented model.

Finally it should be mentioned that the method presented implicitly adopts all assumptions and limitations of the National Footprint Account methodology, a detailed description of which is given elsewhere (Monfreda et al., 2004; Wackernagel et al., 2004b and 2004c). However, these limitations are not inherent to the approach presented in this paper as it can re-allocate any alternative or improved national Footprint. In this respect the method presented is independent of the National Footprint Accounts but relies on them as the best available and most comprehensive Footprint data at national level to date.

With the proposed methodology a vast range of practical applications is conceivable. Some examples are listed below. However, for lack of space they have not been elaborated further.

### Example 1

Ecological Footprints of any sub-national area (region, local authority area, city, district, borough, etc.) can be calculated, provided that suitable expenditure data is available for this area. The method is based on detailed household expenditure data by socio-economic group, COICOP classification and local area. This data is then compiled and treated as a final demand category in the input-output calculus, resulting in Footprints for household consumption that are comparable on any spatial level. A real data analysis was undertaken (Barrett et al., 2005) that calculated the Ecological Footprints in 2000 of Wales (5.25 gha/cap), the city of Cardiff (5.59 gha/cap) and the local authority area of Gwynedd in North Wales (5.28 gha/cap), which can be directly compared with the Footprint of the UK (5.31 gha/cap).

## Example 2

Ecological Footprints of different socio-economic groups in a society can be calculated. Estimates of annual expenditure by socio-economic group and COICOP can be used to create highly detailed consumption profiles that act as final demand category in input-output calculations. In a real data assessment of UK socio-economic groups (Birch et al., 2004) some of the authors involved in this article used the ACORN system (A Classification Of Residential Neighbourhoods) to produce 55 types of consumption profiles and corresponding Ecological Footprints. These cover the entire spectrum of household expenditure and provide a robust pattern of consumption behaviour, whilst being consistent with Government national statistics on household expenditure.

The variation in the overall Ecological Footprint of ACORN types is substantial. The greatest extreme is an Ecological Footprint of 6.61 gha/cap for ACORN Type 21 (“Prosperous Enclaves, Highly Qualified Executives”) compared with 4.09 gha/cap for ACORN Type 50 (“Council Areas, High Unemployment, Lone Parents”). The results of this study (presented in Birch et al., 2004 and Barrett et al., 2005) also support the findings by Lenzen and Murray (2001) who established a relatively strong correlation between per capita expenditure and the Footprint ( $R^2 = 0.82$ ). We found a similar correlation of  $R^2 = 0.76$  as illustrated in Figure 5.1.

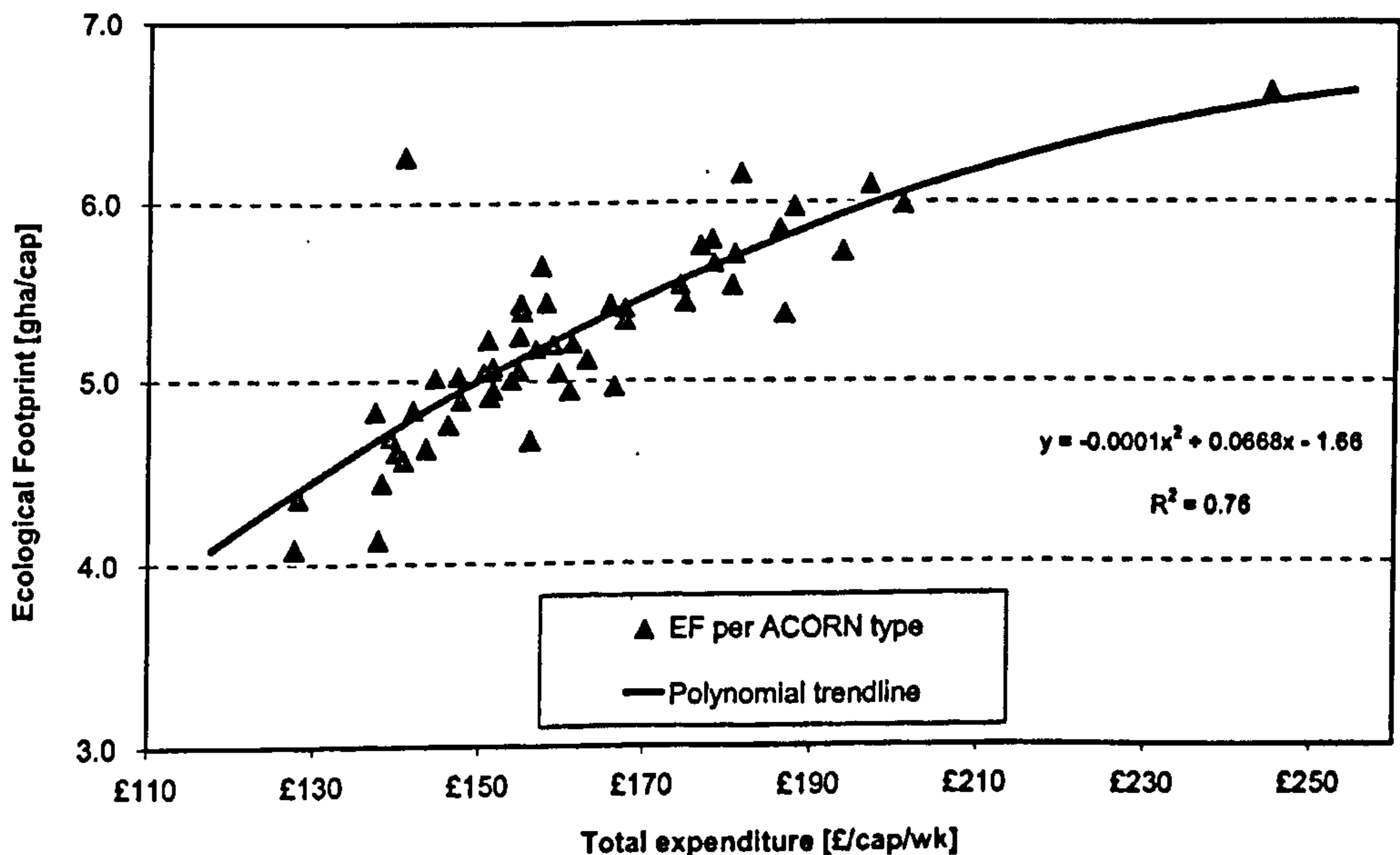


Figure A.1 - Correlation (elasticity) between Ecological Footprint (EF) and per capita expenditure of socio-economic types (data from Barrett et al., 2005)

### **Example 3**

The method presented allows exploration of the impacts of tourism by using expenditure data for foreign or domestic tourism in a country. As an example we employ our approach to estimate the average Ecological Footprint of overseas visitors to the UK, reflecting the resulting environmental impact during the length of their stay. The comprehensive expenditure pattern of foreign visitors – which includes all tourist activities with monetary transactions – can be found under “Non-resident household expenditure in UK” in the COICOP breakdown of final household consumption (ONS, 2003; see also Table A.4). Applying the input-output analysis as described above and expressing the result as an absolute figure, not on a per capita basis, results in a Footprint of 4.7 million gha in 2000. In order to derive a per person number, total overseas ‘visitor years’ can be used which are calculated by multiplying the total number of visitors in one year with the average length of their stay.

The result is a figure of 8.5 gha/person. This suggests that the impact of a visitor’s ‘lifestyle’ – whilst they are staying in the UK and not including ongoing consumption in their country of origin – is considerably higher than that of a UK resident for which the Ecological Footprint is 5.3 gha/cap. The reason for this significant difference is likely to be due to tourists consuming more services and travelling more than residents.

## **A.4 Conclusions**

The method presented in this paper employs a hybrid analysis by combining Ecological Footprint accounting with monetary input-output analysis, thus vastly expanding the range of applications with consistent and comparable Footprint results. The consistent disaggregation of national Footprints by economic sector, final consumption category, sub-national area or socio-economic group offers various advantages:

- By taking into account Ecological Footprints of upstream production processes, the ultimate responsibility for specific consumption activities can be assigned, including the utilisation of services. It could be shown that this leads to a slightly higher Footprint of UK export activities compared to the National Footprint Account method.
- The procedure enables comparable numbers to be produced, which is particularly relevant if Footprint results from different spatial levels need to be evaluated.

- Standardised economic national accounts provide a reliable basis for input-output calculations. The proposed method is applicable in all countries for which supply and use tables or analytical input-output tables, Environmental Accounts and National Footprint Accounts exist.<sup>6</sup>
- The integration of Footprint accounting into standard economic models allows a systematic evaluation of policy options as extensive scenario analysis becomes possible.

Furthermore, the method presented shows a way towards a standardisation of Footprint estimates. Defining a standard accounting procedure will be an ongoing, elaborate and long-lasting process. We hope that the work described in this paper makes an essential contribution to this process.

All these issues become relevant in the context of the current debate on Sustainable Consumption and Production (see e.g. OECD, 2002; UNEP, 2002). In order to enable the implementation of appropriate policies it is crucial to understand the environmental impacts of resource consumption at global, regional and local level and amongst different socio-economic groups, and to identify underlying causes of consumption. This helps to formulate tailor-made policies and to ensure that strategies towards achieving sustainable consumption are coherent.

---

<sup>6</sup> The United Nations database on National Accounts Statistics contains a complete and consistent set of time series from 1970 onwards of main national accounts aggregates for all UN Members States and all other countries and areas in the world (<http://unstats.un.org/unsd/snaama/Introduction.asp>).



## A.5 Literature

- Aall, C. and Norland, I.T., 2005. The Use of the Ecological Footprint in Local Politics and Administration: Results and Implications from Norway. *Local Environment*, 10:159–172.
- Ahmad, N., Wyckoff, A., 2003. Carbon dioxide emissions embodied in international trade. DSTI/DOC(2003)15, Organisation for Economic Co-operation and Development (OECD).
- Allen, R.I.G., 1975. Estimating and Projecting Input-Output Coefficients. Input-Output Publishing, London.
- Ayres, R.U., 2000. Commentary on the utility of the Ecological Footprint concept. *Ecological Economics*, 32:347–349.
- Bacharach, M., 1970. Bi-Proportional Matrices and Input-Output Change. Cambridge University Press, Cambridge, UK.
- Barrett, J. and Scott, A., 2003. The Application of the Ecological Footprint: a case of passenger transport in Merseyside. *Local Environment*, 8:167-183.
- Barrett, J., 2001. Component ecological footprint: developing sustainable scenarios. *Impact Assessment and Project Appraisal*, 19:107-108.
- Barrett, J., Birch, R., Cherrett, N., Wiedmann, T., 2005. Reducing Wales' Ecological Footprint – Main Report. Stockholm Environment Institute, University of York; published by WWF Cymru, Cardiff, UK; March 2005. <http://www.walesfootprint.org>.
- Betts, J., 1989. Two Exact, Non-Arbitrary and General Methods of Decomposing Temporal Change, *Economic Letters*, 30:151-156.
- Bicknell, K.B., Ball, R.J., Cullen, R. and Bigsby, H.R., 1998. New methodology for the Ecological Footprint with an application to the New Zealand economy. *Ecological Economics*, 27:149-160.
- Birch, R., Barrett, J. and Wiedmann, T., 2004. Exploring the consumption and related environmental impacts of socio-economic groups within the UK. International Workshop on Sustainable Consumption, School of the Environment, University of Leeds, 5/6 March 2004. <http://www.env.leeds.ac.uk/~hubacek/leeds04/call.htm>.
- Bruhns, H., Steadman, P., Herring, H., Moss, S. and Rickaby, P., 2000. Types, numbers and floor areas of non-domestic premises in England and Wales, classified by activity. *Environment and Planning B: Planning and Design*, 27:641-665.
- DEFRA, 2004. Municipal Waste Management Survey 2002/03. Department for Environment, Food and Rural Affairs, London.
- DEFRA/DTI, 2003. Changing Patterns – UK Government Framework for Sustainable Consumption and Production. Department for Environment, Food and Rural Affairs, London.
- Dorfman, R., Samuelson, P.A. and Solow, R.M., 1958. Linear Programming and Economic Analysis, McGraw-Hill, New York.
- DTI, 2004. Energy Trends. Regional and local gas consumption statistics for 2003, pp. 18; Experimental regional and local electricity consumption statistics for 2003, pp. 27; Department of Trade and Industry, London.
- DTLR, 1999. Land Use Change in England, DTLR Statistical Bulletin No. 16. Department for Transport, Local Government and Regions, London.
- Environment Waikato, 2003. Regional Ecological Footprint. Waikato Regional Council, Hamilton East, New Zealand. <http://www.ew.govt.nz/enviroinfo/indicators/community/sustainability/ecofoot/keypoints.htm>.
- EPA Victoria, 2003. EPA Victoria and Eco-footprint. Environment Protection Authority, Victoria, Australia. <http://www.epa.vic.gov.au/eco-footprint>
- Erb, K.H.K., 2004. Actual land demand of Austria 1926-2000: a variation on Ecological Footprint assessments. *Land Use Policy*, 21:247-259.
- Ferguson, L., McGregor, P.G., Swales, J.K. and Turner, K.R., 2004. The environmental 'trade balance' between Scotland and the rest of the UK. Scotcon, University of Stirling.
- Ferng, J.J., 2001. Using composition of land multiplier to estimate Ecological Footprints associated with production activity. *Ecological Economics*, 37:159-172.

- Ferng, J.J., 2002. Toward a scenario analysis framework for energy footprints. *Ecological Economics*, 40:53-69.
- Furukawa, S., 1986. *International Input-Output Analysis. Compilation and case studies of interaction between ASEAN, Korea, Japan and the United States, 1975*; IDE Occasional Paper Series 21. Institute of Developing Economies, Tokyo.
- GFN, 2004a. Charter for Global Footprint Network Committees, Global Footprint Network, Oakland CA. [http://www.footprintnetwork.org/gfn\\_sub.php?content=standards](http://www.footprintnetwork.org/gfn_sub.php?content=standards).
- GFN, 2004b. National Footprint and Biocapacity Accounts, Global Footprint Network, Oakland CA. [http://www.footprintnetwork.org/gfn\\_sub.php?content=nrb](http://www.footprintnetwork.org/gfn_sub.php?content=nrb).
- Gigantes, T., 1970. The representation of technology in input-output systems. In: Carter, A.C. and Bródy, A. (eds.), *Contributions to Input-Output Analysis: Fourth International Conference on Input-Output Techniques*. North Holland Publishing, Amsterdam.
- Giljum, S. and Hubacek, K., 2004. Alternative Approaches of Physical Input-Output Analysis to Estimate Primary Material Inputs of Production and Consumption Activities. *Economic Systems Research*, 16:301-310.
- Haberl, H., Wackernagel, M. and Wrbka, T., 2004. Land use and sustainability indicators. An introduction. *Land Use Policy*, 21:193-198.
- Hendrickson, C., Horvath, A., Joshi, S. and Lave, L.B., 1998. Economic Models for Input-Output Lifecycle Analysis. *Environmental Science and Technology* 29:184A-191A.
- Herendeen, R.A., 2000. Ecological footprint is a vivid indicator of indirect effects. *Ecological Economics*, 32:357-358.
- Hinterberger, F. and Giljum, S., 2003. Modelling global resource use: MFA, land use and input-output models; Paper prepared for presentation at the workshop "Quo vadis, MFA?", Wuppertal Institute, 9-10 October 2003. Sustainable Europe Research Institute (SERI), Vienna
- Hubacek, K. and Giljum, S., 2003. Applying physical input-output analysis to estimate land appropriation (Ecological Footprints) of international trade activities. *Ecological Economics*, 44:137-151.
- Hubacek, K. and Sun, L., 2001. A scenario analysis of China's land use and land cover change: incorporating biophysical information into input-output modeling. *Structural Change and Economic Dynamics*, 12:367-397.
- James, N. and Desai, P., 2003. *One Planet Living in the Thames Gateway – A WWF-UK One Million Sustainable Homes Campaign Report*; BioRegional Development Group, Surrey, UK, June 2003. <http://www.wwf.org.uk/filelibrary/pdf/thamesgateway.pdf>.
- Joshi, S., 1999. Product Environmental Life Cycle Assessment Using Input-Output Techniques, *Journal of Industrial Ecology*, 3:95-120.
- Lenzen, M. and Dey, C.J., 2002. Economic, energy and greenhouse emissions impacts of some consumer choice, technology and government outlay options. *Energy Economics*, 24:377-403.
- Lenzen, M. and Murray, S.A., 2001. A modified Ecological Footprint method and its application to Australia. *Ecological Economics*, 37:229-255.
- Lenzen, M. and Murray, S.A., 2003. *The Ecological Footprint – Issues and Trends*, ISA Research Paper 01-03, The University of Sydney
- Lenzen, M., 2001. A generalised input-output multiplier calculus for Australia. *Economic Systems Research*, 13:65-92.
- Lenzen, M., 2002. A guide for compiling inventories in hybrid life-cycle assessments: some Australian results. *Journal of Cleaner Production*, 10:545-572.
- Lenzen, M., 2003. Environmentally important paths, linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics*, 14:1-34.
- Lenzen, M., Deumling, D., Lauck, B., Goldfinger, S. and Wackernagel, M.; forthcoming in 2005. *The Ecological Footprint of the State of Victoria*. University of Sydney, School of Physics, Australia and Global Footprint Network, Oakland, USA.
- Lenzen, M., Pade, L.L. and Munksgaard, J., 2004. CO<sub>2</sub> multipliers in multi-region input-output models. *Economic Systems Research*, 16:391-412
- Leontief, W. and Ford, D., 1970. Environmental repercussions and the economic structure: an input-output approach. *The Review of Economics and Statistics*, 52:262-271.

- Lewan, L. and Simmons, C., 2001. The use of Ecological Footprint and Biocapacity Analyses as Sustainability Indicators for Sub-national Geographical Areas: A Recommended Way Forward. Final Report to the European Common Indicators Project, EURO-CITIES. Prepared for Ambiente Italia, 27<sup>th</sup> August 2001.
- Lewney, R., 2004. Personal communication, Cambridge Econometrics, Cambridge, UK.
- McDonald, G.W. and Patterson, M.G., 2003. Ecological Footprints of New Zealand and its Regions, 1997/98. Technical Paper, Environmental Reporting, Ministry for the Environment, Wellington, New Zealand, September 2003. <http://www.mfe.govt.nz/publications/ser/eco-footprint-sep03/html> or via <http://www.environment.govt.nz>.
- McDonald, G.W. and Patterson, M.G., 2004. Ecological Footprints and interdependencies of New Zealand regions. *Ecological Economics*, 50:49-67.
- McGregor, P.G., McNicoll, I.H., Swales, J.K. and Turner, K.R., 2001. Who Pollutes in Scotland: A Prelude to an Analysis of Sustainability Policies in a Devolved Context, Fraser of Allander Institute, University of Strathclyde, Glasgow. *Quarterly Economic Commentary*, 26:23-32.
- McGregor, P.G., Swales, J.K. and Turner, K.R., 2004a. The impact of Scottish consumption on the local environment: an alternative to the Ecological Footprint? Fraser of Allander Institute, University of Strathclyde, Glasgow. *Quarterly Economic Commentary – Economic Perspectives*, 29:29-34.
- McGregor, P.G., Swales, J.K. and Turner, K.R., 2004b. An Input-Output Based Alternative to "Ecological Footprints" for Tracking Pollution Generation in a Small Open Economy. *Strathclyde Discussion Papers in Economics*, no. 04-04. University of Strathclyde, Glasgow.
- Meyer, B., Lutz, C. and Wolter, M.I., 2003. Global Multisector/Multicountry 3-E Modelling: From COMPASS to GINFORS. Paper presented at the IHDP Conference on Governance for Industrial Transformation, Berlin, 5-6 December 2003.
- Miller, R.E. and Blair, P.D., 1985. *Input-Output Analysis: Foundations and Extensions*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Moffatt, I., 2000. Ecological footprints and sustainable development. *Ecological Economics*, 32:359-362.
- Moffatt, I., Wiedmann, T. and Barrett, J., 2005 accepted. The impact of Scotland's economy on the environment: a note on input-output and Ecological Footprint analyses. *Quarterly Economic Commentary – Economic Perspectives*, forthcoming.
- Moll, S., Bringezu, S., Femia, A. and Hinterberger, F., 2002. Ein Input-Output-Ansatz zur Analyse des stofflichen Ressourcenverbrauchs einer Nationalökonomie: ein Beitrag zur Methodik der volkswirtschaftlichen Materialintensitätsanalyse. In: Hinterberger, Friedrich (Hrsg.): *Arbeit - Umwelt - Wachstum: Nachhaltigkeitsaspekte des sektoralen Strukturwandels*. Norderstedt: Books on Demand, pp. 129-189.
- Moll, S., Hinterberger, F., Femia, A. and Bringezu, S., 1999. An input-output approach to analyse the Total Material Requirement (TMR) of national economies. In: Kleijn, René (Hrsg.): *ConAccount Workshop, Amsterdam, 21<sup>st</sup> November 1998 – Ecologizing societal metabolism: designing scenarios for sustainable materials management*. Centre of Environmental Science (CML), Leiden University, 1999, pp. 39-46.
- Monfreda, C., Wackernagel, M. and Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts. *Land Use Policy*, 21:231-246.
- Moran, D., 2004. Updated version of the National Footprint Account spreadsheet for the United Kingdom in the year 2000. Personal communication, Global Footprint Network, Oakland CA.
- Munksgaard, J., Pedersen, K.A. and Wier, M., 2000. Impact of Household Consumption on CO<sub>2</sub> Emissions. *Energy Economics*, 22:423-440.
- NAfW, 2004. Sustainable Development Indicators for Wales 2004. National Assembly for Wales, Statistical Bulletin 18/2004. <http://www.wales.gov.uk/keypubstatisticsforwalesheadline/content/sustainable/2004/hdw20040323-e.htm>.
- Nijkamp, P., Rossi, E. and Vindigni, G., 2004. Ecological Footprints in Plural: A Meta-analytic Comparison of Empirical Results. *Regional Studies*, 38:747-765.
- NRG4SD, 2004. International Seminar on Sustainable Development Indicators – Bases for developing common indicators at a regional level. Network of Regional Governments for Sustainable Development (NRG4SD), ENCORE, Basque

- Government; Carlton Hotel, Bilbao, Basque Country, November 9-10, 2004. <http://www.nrg4sd.net/ENG/Events/Other/BilbaoNov2004.htm>.
- OECD, 2002. Towards Sustainable Household Consumption? Trends and Policies in OECD Countries; Organisation for Economic Co-operation and Development, Paris.
- ONS, 1999. Environmental Accounts, 1999 edition. Office for National Statistics, London.
- ONS, 2001. National Food Survey 2000. Office for National Statistics, London.
- ONS, 2003. United Kingdom Input-Output Analyses, 2003 Edition. Editor: Sanjiv Mahajan. Office for National Statistics, London. Download of Input-Output Supply and Use Tables at: <http://www.statistics.gov.uk/inputoutput>.
- ONS, 2004. Environmental Accounts, 2004 edition. Office for National Statistics, London.
- Peters, G.P., Hertwich, E., 2004. Production factors and pollution embodied in trade: Theoretical development. Working Paper 5/2004, Industrial Ecology Programme, Norwegian University of Science and Technology. <http://www.indecol.ntnu.no/publications.php>.
- Proops, J., Atkinson, G., v. Schlotheim, B. and Simon, S., 1999. International trade and the sustainability footprint: a practical criterion for its assessment. *Ecological Economics*, 28:75-97.
- Rosenblum, J., Horvard, A. and Hendrickson, C., 2000. Environmental Implications of Service Industries. *Environmental Science and Technology* 34:4669-4676.
- Ruiz, Y., 2002. United Kingdom Input-Output Analytical Tables 1995, 2002 Edition (Web only). Editor: Sanjiv Mahajan. Office for National Statistics, London. <http://www.statistics.gov.uk/inputoutput>.
- Simmons, C., Lewis, K., Barrett, J., 2000. Two feet – two approaches: a component-based model of ecological footprinting. *Ecological Economics*, 32:375-380.
- Stöglhner, G., 2003. Ecological footprint – a tool for assessing sustainable energy supplies. *Journal of Cleaner Production*, 11:267-277.
- Suh, S. and Huppes, G. 2002. Missing inventory estimation tool using extended input-output analysis. *International Journal of Life Cycle Assessment*, 7:134-140
- Suh, S., 2004a. Material and energy flows in industry and ecosystems networks. PhD Thesis, Centre of Environmental Science (CML), Leiden University.
- Suh, S., 2004b. Functions, commodities and environmental impacts in an ecological-economic model. *Ecological Economics*, 48:451-467.
- Suh, S., 2004c. A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities. *Ecological Economics*, 48:9-17.
- Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W. and Moriguchi, Y., 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science and Technology*, 38:657-664.
- Turner, K.R., 2003. The additional precision provided by regional-specific data: the identification of fuel-use and pollution generation coefficients in the Jersey economy. *Strathclyde Discussion Papers in Economics*, no. 03-09. University of Strathclyde, Glasgow.
- UNEP, 2002. Tracking progress: Implementing sustainable consumption policies. A global review of implementation of the United Nations Guidelines for Consumer Protection; UNEP and Consumers International, May 2002. <http://www.unep.org/pc/sustain>, see also: <http://www.unep.org/themes/consumption>.
- van den Bergh, J.C.J.M. and Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the 'Ecological Footprint'. *Ecological Economics*, 29:61-72.
- van Vuuren, D.P. and Bouwman, L.F., 2005. Exploring past and future changes in the ecological footprint for world regions. *Ecological Economics*, 52:43-62.
- Vaze, P., 1997. Environmental input-output tables for the United Kingdom. *Economic Trends*, 527:34-55. Office for National Statistics, London.
- Victor, P.A., 1972. *Pollution, Economy and Environment*. George Allen and Unwin Ltd, London.
- Volpi, L., 2003. Tutorial for BigMatrix.xla – Linear Algebra for Big Matrices. Foxes Team, Rome, Italy. Download at <http://digilander.libero.it/foxes>.

- Wackernagel, M. and Rees, W.E., 1996. *Our Ecological Footprint – Reducing Human Impact on the Earth*. New Society Publishers, Gabriola Island, B.C., Canada.
- Wackernagel, M., Lewan, L. and Hansson, C.B., 1999. Evaluating the use of natural capital with the Ecological Footprint. *Ambio*, 28:604–612.
- Wackernagel, M., Monfreda, C., Erb, K.H., Haberl, H., Schulz, N.B., 2004a. Ecological footprint time series of Austria, the Philippines and South Korea for 1961–1999: comparing the conventional approach to an ‘actual land area’ approach. *Land Use Policy*, 21:261–269.
- Wackernagel, M., Monfreda, C., Moran, D., Goldfinger, S., Deumling, D., Murray, M., 2004b. National Footprint and Biocapacity Accounts 2004: The underlying calculation method. Global Footprint Network, Oakland CA. <http://www.footprintnetwork.org>.
- Wackernagel, M., Monfreda, C., Schulz, N.B., Erb, K.H., Haberl, H. and Krausmann, F., 2004c. Calculating national and global ecological footprint time series: Resolving conceptual challenges. *Land Use Policy*, 21:271–278.
- Wood, R. and Lenzen, M., 2003. An Application of a Modified Ecological Footprint Method and Structural Path Analysis in a Comparative Institutional Study. *Local Environment*, 8:365-386.
- WSP Environmental and Natural Strategies, 2003a. *Towards a Sustainable London – Reducing the Capital's Ecological Footprint. Phase 1 Report: Determining London's Ecological Footprint and Priority Impact Areas for Action*. WSP Environmental Ltd, London and Natural Strategies LLC, Oakland CA. [http://www.londonremade.com/lr\\_footprinting.asp](http://www.londonremade.com/lr_footprinting.asp).
- WSP Environmental and Natural Strategies, 2003b. *Towards a Sustainable London – Reducing the Capital's Ecological Footprint. Phase 2 Report: Proposals to Reduce London's Ecological Footprint*. WSP Environmental Ltd, London and Natural Strategies LLC, Oakland CA. [http://www.londonremade.com/publications\\_research.asp](http://www.londonremade.com/publications_research.asp).
- WWF, 2004. *Living Planet Report 2004*, World-Wide Fund for Nature International (WWF), Global Footprint Network, UNEP World Conservation Monitoring Centre. WWF, Gland, Switzerland. <http://www.panda.org/livingplanet>.

# **B The Impact of Social Factors and Consumer Behavior on the Environment**

## **An Input-Output Approach for the UK**

**Abstract:** This purports to provide some new evidence on the relationship between the level of income and other social factors on some measures of environmental quality. Using detailed from a generalised input-output model for the UK in an econometric panel data approach we provide precise information and an in-depth understanding of the impact of significant social factors and consumer behaviour on CO<sub>2</sub> emissions.

## **B.1 INTRODUCTION**

Evidence increasingly suggests that the human-induced release of greenhouse gases into the atmosphere might pose serious, potentially irreversible changes to the global climate within the next decades. Triggered by deep concerns about detrimental impacts for the human population, the issue has therefore climbed right to the top of the global environmental policy agenda. While an increase in the atmospheric carbon concentration seems unavoidable over the next few decades, decision makers have started to seriously think about how this increase can be slowed and ultimately stopped and reduced through the adoption of policy measures on the global, national and local level (Gay and Proops, 1993).

The UK government has championed climate change on its environmental agenda in the Sustainable Development Strategy (Government, 2005) and committed to a series of targets for reducing greenhouse gas emissions such as:

- the reduction of carbon emissions by 20% from 1990 levels by 2010. This exceeds the UK's international commitments under the Kyoto Protocol;
- the reduction of greenhouse gas emissions by 60% from 1990 levels by 2050.

Greenhouse gas emissions mainly arise from the use of energy/burning of fossil fuels throughout the economy and it has been acknowledged that the achievement of the government's targets requires tackling the issue from the supply as well as from the demand side involving all stakeholders from UK citizens ("the people") to business to government (HM Government, 2006; Roundtable, 2006). A precondition for good demand side management of energy use and carbon production is a sound understanding how energy is used throughout the economy.

'Lifestyle Analysis' has focussed on the relationship between consumer activities and the total greenhouse gas emissions triggered by the direct energy use of households or through their indirect energy use from the production of goods and services they demand. In line with Adam Smith's view that 'consumption is the sole end and purpose of economic activity' authors, therefore, usually argue that most of the climate change impacts can be directly or indirectly traced back to private consumers.

The lifestyle approach is usually distinguished from one with a purely technological focus as it tries to provide a wider picture of the consumer (and required production processes to satisfy his needs and wants) by depicting him in his socio-

economic context. Lifestyles are usually seen to be reflected in the consumption patterns of societal groups with different socio-economic characteristics, but also other elements such as time use, social identity, education, employment, family status (Hertwich & Katzmayer, 2004). This is in line with the new impetus of the Sustainable Consumption and Production (SCP) debate, where the importance of social and behavioural issues is stressed (see, Government, 2005, chapter 3).

With consumer choice prominently back on the environmental agenda, this paper aims to provide a detailed understanding of the social background factors behind household consumption choices and their climate change impacts. Section B.2 provides a review of the input-output literature concerned with lifestyle analysis. Section B.3 outlines the input-output methodology, describes the data sources and discusses the results. This highlights the lack of control for the individual social and behavioural background factors giving rise to the differences in emissions between socio-economic groups. Therefore, Section B.4 proposes different regression models to further analyse the results derived from the input-output estimations and their relationship to individual socio-economic variables before Section B.5 concludes on the usefulness and policy relevance of such an approach.

## ***B.2 Literature Review – Input-Output Data and Lifestyle Analysis***

With the re-fashion of behavioural issues and the recent impetus of the sustainable consumption debate (Princen et al., 2002; Charkiewicz et al., 2001; Lintott, 1998), input output models to assess direct and indirect environmental impacts of household consumption activities have been very popular and widely used in research (e.g. Cohen et al., 2005; Lenzen et al., 2004; Pachauri & Spreng, 2002; Wier et al., 2001; Weber & Perrels, 2000). In these models household consumption expenditure clusters are commonly interpreted as an economic manifestation of a lifestyle (Duchin, 1998). As expenditure clusters of different socio-economic groups trigger different environmental flows, we usually find comparative studies in the literature with the shared motivation to identify consumption categories/ bundles and lifestyle groups with environmental saving potential. Such an analysis that allows the development of a deep understanding of the environmental impact of consumption patterns in direct relation to production activities, is an essential precondition for the design of effective policies directed towards more



environmentally friendly consumption patterns brought by technological and behavioral changes on supply and demand side of the economy.

In the climate change context most attention has been directed towards CO<sub>2</sub> emissions. Studies have, for example, been helpful to understand how CO<sub>2</sub> emissions vary across lifestyle groups and how these relate to their socio-economic profile as well as to spending levels and composition of household consumption baskets (including both the direct expenses for energy as well as all other expenses with indirect CO<sub>2</sub> impacts), what key product groups in the baskets should be targeted by policy or how inequality in income and spending translate into CO<sub>2</sub> impacts. This has helped a great deal to identify effective intervention points for energy conservation and CO<sub>2</sub> mitigation policies.

However, the standard environmental input-output based lifestyle analysis approach can also be challenged on various grounds. Three lines of criticism are briefly summarised here before we will deal with the last one in depth in the rest of this paper: The first line of criticism is directed towards the purely expenditure based conceptualisation of a lifestyle. We will never be able to get a complete picture of people's lifestyles as long as we purely concentrate on what they spend rather than on what they do. Schipper et al. (1989) therefore emphasise the need for a re-definition of lifestyle in terms of activity patterns. On similar lines (Gershuny, 1987, p.55) argues that "[...] if we are to understand the processes of structural change in 'the economy', we need to consider evidence about behaviour outside it: we need to know more about the everyday life." Because monetary data is largely restricted to the market sphere and is unable to comprehensively cover non-market activities, authors have proposed to complement monetary and physical with time use data. We have provided a comprehensive outline of the value of time-use data for the inclusion of social and behavioural issues in sustainability research elsewhere (see Chapter 5 of this thesis).

Therefore, also in the input-output literature people have started to introduce timeuse data. Inspired by some Danish research on the relationship between time and consumption (Brodersen, 1990), Jalas (2002, 2005) was the first to link expenditure and time-use data and analyse energy and resource use in an environmental input-output based lifestyle model. More recently, Kondo (2006) and Minx & Baiocchi (2006) have further added to the literature on similar lines. Stahmer (2004) and later Schaffer and Stahmer (2005) have gone one step further and developed a set of socio-economic input-output tables in monetary, physical and time units mapping not industrial sectors, but socio-economic groups against each other. Their approach, which directly feeds into the

discussion of sustainable consumption and life-work balances, generates a much more complete overview of what people do inside and outside the market, how they consume within their activity activity patterns and what CO<sub>2</sub> emissions are triggered.

The second line of criticism is directed towards the treatment of import related CO<sub>2</sub> emissions. Because lifestyle analysis is interested in all CO<sub>2</sub> emissions triggered by household consumption activities within a (well defined) region, studies conventionally compile emission inventories based on the principle of consumer responsibility (see, Munksgaard and Pedersen, 2001; Munksgaard et al., 2006). These include import related and exclude export related CO<sub>2</sub>. However, because of limited data availability and the work intensity of the task, applied input-output models usually impute import related emissions purely based on the data for the (one) region under investigation based on the assumption that the structure of the economy and the sectoral CO<sub>2</sub> intensities are the same ‘abroad’ as ‘at home’. However, Lenzen et al. (2004) have shown that this can lead to a significant estimation error (also Munksgaard et al., 2006). A more appropriate way of dealing with the issue therefore is to base estimations on a multi-regional input-output model as done for example by Lenzen et al. (2004), Munksgaard et al. (2006) or Peters and Hertwich (2006).

A final line of criticism can be directed towards the lack of exploitation of the social information hidden in the input-output data. While it is interesting to see how groups with different socio-economic characteristics compare in terms of their energy use and CO<sub>2</sub> impacts, it can be argued that it is important to go one step further and develop an understanding how individual characteristics relate to environmental impacts. Does education have a positive or a negative impact on energy use and CO<sub>2</sub> emissions? How does ‘sharing’ change people’s behaviour in the use of fossil fuels? What other characteristics have a significant influence on CO<sub>2</sub> emissions arising from household consumption directly and indirectly?

These are all questions that have been heavily discussed in various strands of the environmental literature. In the literature on green product service systems ‘sharing’, for example, is seen as a key factor for reducing resource consumption and the resulting environmental impacts (Weizscker et al., 1995; Hawken et al., 1999). At the same time there is an extensive discussion surrounding common property resources, where ‘sharing’ in terms of joint/communal ownership and access/use leads to a mis- or overuse of resources (Hardin, 1968). The same argument can be applied to any shared property. Even though shared goods might be better seen as ‘club goods’ for which we pay a

certain (weekly, monthly, yearly, one-off) fee to get access, similar problems in their careful use occur.

A similar diversity in arguments can be found for the environmental merits of increased use of information and communication technologies (ICT), in general, and the internet, in particular. Will this allow households to significantly reduce their environmental impacts? One strand in the literature outlines how service provision through ICT/internet can potentially help to drastically reduce resource use and environmental impacts of (developed economies) (Gay et al., 2005; Alakeson et al., 2003; Wilsdon, 2002). It is highlighted that moving from books to bytes, from compact discs to MP3s or from checkbooks to clicks, producing 'just in time' and 'just enough', and avoiding travel by doing things 'where we are' (e.g. telework, online shopping) might be key to dematerialise, decarbonise and demobilise our economies (Sui and Rejeski, 2002). However, critiques highlight the energy requirements of a digital society and refer to the increased energy use through the spread of information technology in general and computers/internet in particular (Mills, 1999). The Californian energy crisis is an often cited example.<sup>1</sup>

Also the environmental merits of education have been discussed. The green consumerism literature often argues that a higher education level is likely to be associated with greener environmental choices due to the complexity of the issue. "If one seeks to become an effective green consumer, [...] a great amount of learning must be undertaken" (Pettit & Sheppard, 1992, p.340). However, higher education levels are also often associated with a higher income as often assumed in the economic literature.<sup>2</sup> The positive environmental implications of greener choices might therefore be eaten up by the higher levels of consumption.

---

<sup>1</sup> There is a special issue on e-Commerce, the internet and the environment in the *Journal for Industrial Ecology* (2002, Volume 6 No.2). This can be consulted by the reader for further arguments of different positions.

<sup>2</sup> At least up to a certain education level this argument might hold.

This points towards another stream of literature concentrating on finding an inverse U-shaped relationship between income/expenditure and different environmental indicators. This discussion has been commonly referred to as the 'Environmental Kuznets Curve debate'. Four main reasons have been proposed why such a relationship might be observed (Lenzen et al., 2006, p.184):

- environmental quality is a luxury good;
- structural changes in the economy;
- equalising income distribution, democracy and civil rights;
- technological progress.

Authors commonly find that such a relationship is more likely to be found for local pollutants such as SO<sub>2</sub> rather than global pollutants such as CO<sub>2</sub>. Usually EKC studies use time-series data for a particular (or a group of) pollutant(s) and country or cross-sectional data for multiple countries in a single reporting period. Much less evidence has been provided whether or not such a relationship can be observed for certain environmental indicators within a society across socio-economic groups. Instead in the input-output literature usually a general suggestion has been made that even though their marginal impact might be smaller due to the purchase of healthier products and higher quality, richer households tend to pollute more than poor ones due to their higher spending levels.

These types of questions have been largely left unanswered in the input-output based lifestyle literature. The main reason might be that results for answering these questions cannot be obtained anymore in an input-output context. Instead results need to be entered in (econometric) multi-variate regression models, which relax the strong linearity assumption and allow controlling for the influence of a set of (independent) socio-economic variables on (the dependent variable) CO<sub>2</sub> emissions. However, some efforts in the literature have been made into this direction. A whole series of studies has, for example, has calculated the energy and/or CO<sub>2</sub> elasticity of expenditures for different product groups (e.g. Vringer & Blok, 1995; Cohen et al., 2005; Lenzen, 1994). However, comprehensive assessments of the individual influence of socio-economic characteristics on energy use and/or CO<sub>2</sub> emissions have only been undertaken occasionally (e.g. Lenzen et al., 2006; Weber & Perrels, 2000).

This study adds to this line of literature and tries to demonstrate the analytical value of such an approach and its policy implications. Using a panel regression approach

we are able to control for many unobservable factors and estimate the impact of socio-economic factors on CO<sub>2</sub> emission controlling for related and competing factors.

### B.3 CO<sub>2</sub> EMISSIONS OF LIFESTYLE GROUPS

#### B.3.1 Input-Output Model

The estimation of the environmental impacts associated with the household consumption patterns of different lifestyle groups in the UK can be expressed most generally in the following way:

$$p^{hh,tot} = p^{hh,dir} + p^{hh,ind} \quad (B.1)$$

where  $p^{hh,tot}$ ,  $p^{hh,dir}$  and  $p^{hh,ind}$  are vectors of total, direct and indirect CO<sub>2</sub> emissions from household consumption patterns of  $s$  different socio-economic groups.

The direct emissions of households  $p^{hh,dir}$  from domestic energy consumption and private transport can be readily obtained from the environmental accounts. They can be assigned to the various socio-economic groups proportionally to their energy and transport fuel expenditures. The indirect emissions can be calculated by multiplying a vector of total CO<sub>2</sub> intensities  $\varepsilon^{ind}$  of  $n$  different production sectors with a detailed matrix of household consumption expenditure of the  $s$  different socio-economic groups in  $m$  functional spending groups:

$$p^{hh,ind} = (\varepsilon^{ind}) Y^{hh} = (\varepsilon^{ind}) A^{hh} Y^{hh} \quad (B.2)$$

with  $A_{m \times r}^{hh} = [a_{ik}] = y_{ik} / \sum_{j=1}^m y_{jk}$  being a matrix of direct coefficients indicating the proportion of the final household demand for products of the  $n$  different industries in the  $r$  different functional spending categories and  $Y^{hh,soc}$  being a matrix of household consumption expenditures of the  $s$  different socio-economic groups in the  $r$  spending categories. Hence, each row  $Y_{s\cdot}^{hh,soc}$  shows the consumption expenditures across the  $k$

functional spending categories for one of the  $s$  socio-economic groups. Note that the sum of the spending of the different groups in the  $r$  functional spending categories must be equal to the sum of the final product delivered by the  $n$  industrial sectors to the category, that is  $(Y^{hh,soc} \mathbf{1})' = \mathbf{1} Y^{hh}$ , where  $\mathbf{1}$  is a vector of ones of appropriate size.

The vector of total CO<sub>2</sub> intensities  $\boldsymbol{\varepsilon}^{ind}$  from the  $n$  different industrial sectors is derived from input-output analysis in a supply and use table framework. This vector can be estimated by:

$$\boldsymbol{\varepsilon}^{ind} = \mathbf{r}' \left( (\mathbf{I} - \mathbf{B}\mathbf{D})^{-1} \mathbf{D} \right) \quad (\text{B.3})$$

where  $\mathbf{r}$  is a  $n \times 1$  vector of sectoral direct CO<sub>2</sub> intensities indicating the amount of CO<sub>2</sub> emitted per unit of final output of the  $n$  different sectors,  $\mathbf{I}$  is an identity matrix of size  $n \times n$ ,  $\mathbf{D} = [d_{ji}] = \left[ \frac{v_{ji}}{q_i} \right]$  is a coefficient matrix of size  $n \times n$  based on an industry technology assumption indicating the supply  $v_{ji}$  of commodity  $i$  to industry  $j$  per unit of total supply  $q_i$  of commodity  $i$  and  $\mathbf{B} = [b_{ij}] = \left[ \frac{u_{ij}}{x_j} \right]$  is a technical coefficient matrix of size  $n \times n$  providing information about the use  $u_{ij}$  of commodity  $i$  by industry  $j$  per unit of output  $x_j$  of industry  $j$ . The approach is described in detail in Wiedmann et al. (2006).

### B.3.2 Input-Output Data

For the input-output estimation the supply and use table provided by the Office for National Statistics for the year 2000 were used (Office for National Statistics (ONS), 2003) and combined with sectoral CO<sub>2</sub> data from the UK Environmental Accounts for the year 2000. All calculations were carried out at the  $76 \times 76$  sector aggregation level of the Environmental Accounts (Office for National Statistics, 2005).

However, the UK supply and use table publication cannot be immediately applied: the supply table provided is incomplete and only available at a very high sectoral aggregation level. The use table is provided in a mixed price system of purchasers' and basic prices. Therefore, an old supply table from the environmental accounts for the year 1998 (Office for National Statistics, 1999) was updated with 2000 information based on

the RAS procedure. A use table fully converted into basic prices was courteously provided by Cambridge Econometrics. A very detailed description of the preparation of the supply and use tables can be found in Wiedmann et al. (2006: see Appendix A of this thesis).

The household consumption expenditure vector in the use table was broken down according to 39 COICOP spending categories. The required data is included in the supply and use table publication. The breakdown into socio-economic groups was achieved through the use of commercial marketing data from CACI.<sup>3</sup> The data provide expenditure estimates for 56 societal groups in 41 COICOP functional spending categories for the year 2004. The 12 COICOP headline categories are shown in Table B.1. The socio-economic groups are distinguished according to ACORN profiles. ACORN stands for “A Classification of Residential Neighbourhoods”. The classification includes every street in the country and groups spatial areas according to socio-economic profiles of the residents. The underlying assumption of the data collection process is that people with certain socio-economic profiles tend to live in the same area. The classification distinguishes 17 ACORN lifestyle groups, which can be further mapped into 56 ACORN lifestyle types as shown in Table B.2.

Category	Descriptor
1	Food and non-acholic drink
2	Alcoholic drink, tobacco and narcotics
3	Clothing and footwear
4	Housing (net), fuel and power
5	Household goods and services
6	Health
7	Transport
8	Communication
9	Recreation and culture
10	Education
11	Restaurants and hotels
12	Miscellaneous goods and services

**Table B.1– Main COICOP spending categories**

To reconcile the ACORN with the COICOP final demand matrix some of the CACI estimates in the category ‘Purchase of vehicles’ (COICOP 7.2) needed to be adjusted as the provided data on include expenditure estimates for bicycles. Moreover, data gaps for COICOP categories ‘accommodation services’ (COICOP 11.2), ‘social protection’ (COICOP 12.4) as well as ‘insurance’ (COICOP 12.5) needed to be filled by

<sup>3</sup> CACI is a commercial marketing data firm with headquarters in London (see <http://www.caci.co.uk>).

imputation. This was achieved by roughly grouping the 56 Acorn groups into income deciles and using estimates from the the UK's expenditure and food survey (Office for National Statistics, 2005). This is likely to lead to some error as the ACORN groups are less homogenous in their income clusters. However, in the absence of information this appeared as the best way of dealing with the problem.<sup>4</sup> Finally, the spending estimates were all calibrated according to the spending levels of the 2000 use table for each COICOP category. Hence, the estimates reflect the spending levels of the year 2000 and the composition of consumption baskets of the year 2004.

Group	Descriptor	Types
1	Wealthy Executives	4
2	Affluent Greys	4
3	Flourishing Families	4
4	Prosperous Professionals	2
5	Educated Urbanities	4
6	Aspiring Singles	4
7	Starting Out	2
8	Secure Families	6
9	Settled Suburbia	3
10	Prudent Pensioners	2
11	Asian Communities	2
12	Post Industrial Families	2
13	Blue Collar Roots	3
14	Struggling Families	6
15	Burdened Singles	3
16	High Rise Hardship	2
17	Inner City Adversity	3

**Table B.2 – Household classification: 17 ACORN groups**

### **B.3.3 Results**

Table B.3 shows that domestic consumption patterns in the UK have triggered a total of 681.3 million tons of CO<sub>2</sub> in 2000. This figure resembles what has been referred to in the literature as a 'consumer responsibility account'. It excludes the 240.2 million tons of CO<sub>2</sub> associated with exports and includes 306.1 million tons occurring in the production processes elsewhere in the world, which feed the UK's domestic demands. This gives rise to a physical CO<sub>2</sub> trade balance with an import surplus of 65.9 million tons.

<sup>4</sup> It could be considered in the future to derive a weighting scheme, which adjusts the consumption expenditure estimates according the (income) homogeneity of the different ACORN groups. However, additional data would need to be purchased from CACI.



FD Category	Emission (in Mt)
Domestic energy consumption (household direct)	86.2
Private transport (household direct)	61.3
Household consumption (household indirect)	358.0
Government	61.9
Capital Investment	109.3
Other final demand	4.7
<b>Total</b>	<b>681.3</b>

Table B.3 - Total CO<sub>2</sub> Emissions in the UK by Final Demand Categories (in Mt)

75% or 505.5 of the 681.3 million tons of CO<sub>2</sub> from consumption in the UK are directly or indirectly related to private households. This explains much of the attention they have received in the literature. Of these, 70% or 358 million tons occur in the domestic and foreign supply chains for producing the goods and services demanded by domestic households, while the remaining 147.6 million are directly emitted by them - 86.2 million tons of CO<sub>2</sub> through domestic energy use and 61.3 million for fueling private vehicles. The pie chart in Figure B.1 illustrates the relative importance of each category

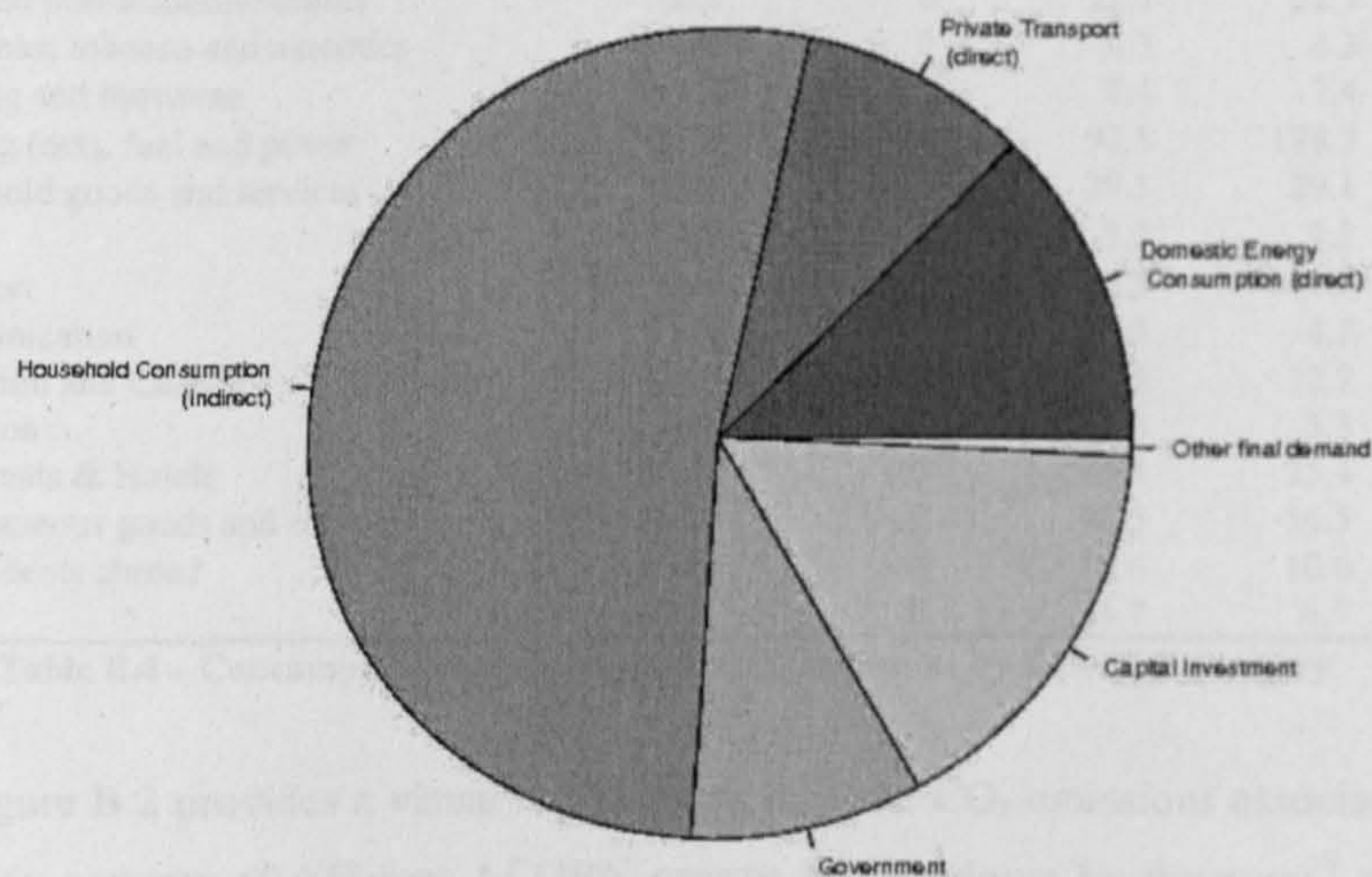


Figure B.1 – Total CO<sub>2</sub> Emissions by Final Demand Categories

Table B.4 takes a closer look at what UK households spend their money on and how these expenses translate into CO<sub>2</sub> emissions. It strikingly highlights the importance of two key areas for climate change policies: housing and transport. While 30% of the household expenditures are directed towards these two functional spending categories, they trigger 60% or 320.2 of the 505.5 million tons of emissions associated with UK

households. This is almost half of the total CO<sub>2</sub> emissions arising from consumption activities in the UK. Each pound currently spent on transport triggers almost 2kg of CO<sub>2</sub>. Similarly each pound spent on housing causes 1.68 kg of CO<sub>2</sub> emissions directly and across the supply chain. In contrast, 'Food and non-alcoholic drinks' as the consumption category has the third highest CO<sub>2</sub> intensity with (only) 0.69 kg per pound spent. To meet the comparatively ambitious reduction targets of the government, it will therefore be key to thoroughly rethink how transportation and housing can be provided in the future in a less carbon intensive way.

With 94.17 billion pounds household direct the largest proportion of expenses towards the functional spending category 12, which mainly comprises services. Even though only about 0.38kg of CO<sub>2</sub> are triggered per monetary unit of final demand in this category, total CO<sub>2</sub> is still third highest due to the high consumption levels.

	Consumption expenditure	Direct emissions	Indirect Emissions	Total emissions	CO <sub>2</sub> Intensity
	m£	kt	kt	kt	t/1000£
1 Food and non-alcoholic drinks	32.3	0	22.3	22.3	0.69
2 Alc drinks, tobacco and narcotics	8	0	4.3	4.3	0.54
3 Clothing and footwear	17.3	0	7.4	7.4	0.43
4 Housing (net), fuel and power	106.2	86.2	92.5	178.7	1.68
5 Household goods and services	50.4	0	29.1	29.1	0.58
6 Health	7.5	0	3.2	3.2	0.44
7 Transport	73.4	61.3	80.3	141.6	1.93
8 Communication	13.7	0	4.3	4.3	0.31
9 Recreation and Culture	59.1	0	32.2	32.2	0.54
10 Education	10.4	0	3.3	3.3	0.31
11 Restaurants & Hotels	57.1	0	25.4	25.4	0.44
12 Miscellaneous goods and services	94.2	0	36.5	36.5	0.39
UK residents abroad	17.6	0	10.6	10.6	0.61
NPISH	22.9	0	6.7	6.7	0.29

Table B.4 – Consumption expenditure and CO<sub>2</sub> emissions by COICOP category

Figure B.2 provides a visual representation of the CO<sub>2</sub> emissions associated with consumption patterns of different ACORN groups broken down by functional spending categories. Moving along the vertical axis outwards ACORN groups as described in Table B.2 tend to be less wealthy and to live increasingly in cities rather than rural areas. The horizontal axis shows the functional spending categories as described in Table B.1. The darker a particular cell in the plot, the higher the CO<sub>2</sub> emissions associated with the spending of a particular ACORN group in a functional spending category. Overall, most CO<sub>2</sub> is triggered by group 7 'Secure Families' across spending categories. However, this is also the largest ACORN group comprising 3.64 million households. Controlling for household size surprisingly identifies group 11 'Asian Communities' as living the most

CO<sub>2</sub> intensive lifestyle even though the group comprises households with comparatively ‘moderate means’. Other high impact households tend to come from wealthier backgrounds and more rural areas living in bigger houses.

Once we control for the numbers of individuals per households the picture changes again as in rural households the number of individual tends to be higher. This also partially explains the high emissions per household in ACORN group 11, which has by far the largest household size with 3.27 members per household on average. Even though their per capita CO<sub>2</sub> impact still remains high, there are wealthier groups with higher impacts such as group 4 ‘Prosperous Professionals’ or group 5 ‘Educated Urbanites’. However, even with additional statistics on the socio-economic characteristics of the different groups, the understanding, which can be derived from such a descriptive analysis, is very limited as it remains unknown what their individual influence on aggregate CO<sub>2</sub> emissions are, i.e. the individual influences of the different actors cannot be disentangled. However, by putting the results from the input-output estimations together with a set of socio- economic statistics into a regression model, much light can be shed into this black box.

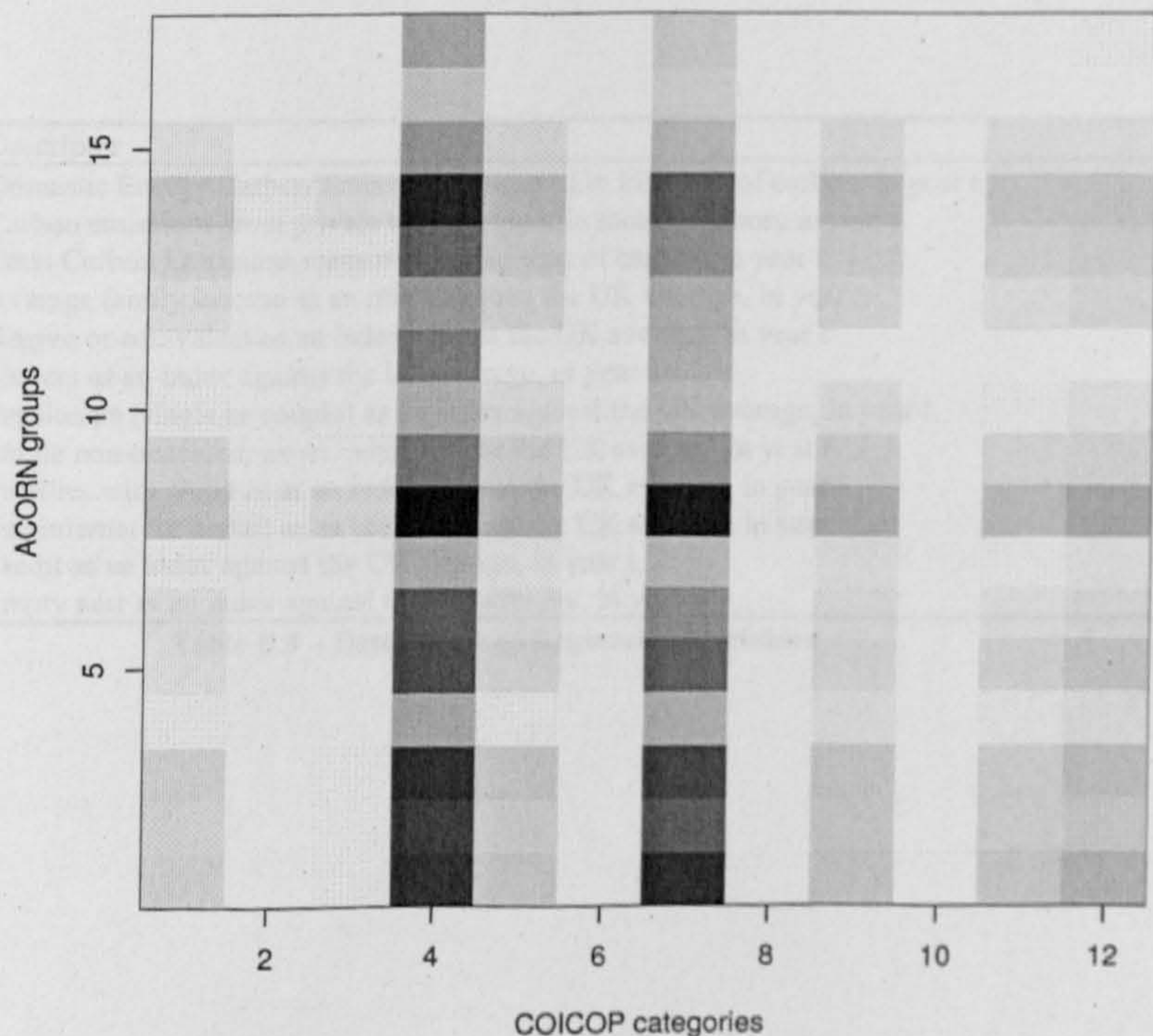


Figure B.2 – Matrix plot of CO<sub>2</sub> emissions by COICOP category and socio-economic group: the darker the colour, the higher the emissions)

## B.4 Impact of Socio-Economic Factors on Emissions

Having determined the emissions per ACORN group we can now estimate the impact of socio-economic variables on CO<sub>2</sub> emissions in the UK. We first present the data source for the determinants of emissions and then the regression methodology employed.

### B.4.1 Emission Determinants

Socio-economic variables that can potentially affect CO<sub>2</sub> emissions in the UK were obtained from the ACORN dataset. ACORN classifies, using detailed socio-economic information, the entire UK population into 5 categories, 17 groups and 56 types. ACORN groups were built using 400 variables, 30 per cent obtained from the 2001 Census, and the remainder from CACI's consumer lifestyle databases. The groups are presented in Table B.2. The variables used in this study, for group *i* and year *t* are shown in Table B.5.

Name	Descriptor
COE <sub>i,t</sub>	Domestic Energy Carbon Emissions measured in kilo tons of carbon, in year <i>t</i> .
COT <sub>i,t</sub>	Carbon emissions from private transport in kilo tons of carbon, in year <i>t</i> .
CO <sub>i,t</sub>	Total Carbon Emissions measured in kilo tons of carbon, in year <i>t</i> .
INC <sub>i,t</sub>	Average family income as an index against the UK average, in year <i>t</i> .
EDU <sub>i,t</sub>	Degree or equivalent as an index against the UK average, in year <i>t</i> .
SHARE <sub>i,t</sub>	Sharers as an index against the UK average, in year <i>t</i> .
PENS <sub>i,t</sub>	Pensioners (single or couple) as an index against the UK average, in year <i>t</i> .
SING <sub>i,t</sub>	Single non-pensioner as an index against the UK average, in year <i>t</i> .
FWC <sub>i,t</sub>	Families with children as an index against the UK average, in year <i>t</i> .
INTER <sub>i,t</sub>	Use internet for e-mail as an index against the UK average, in year <i>t</i> .
CRED <sub>i,t</sub>	Credit as an index against the UK average, in year <i>t</i> .
ENEST <sub>i,t</sub>	Empty nest as an index against the UK average, in year <i>t</i> .

Table B.5 – Description of Regression Variables

Variable	Mean	Std. Dev.	Minimum	Maximum	Cases
LCO	7.8385	0.2757	7.1827	8.5699	55
LCOE	7.2857	0.2988	6.7064	8.2997	55
LCOT	6.9661	0.2868	6.2121	7.4493	55
LINC	4.5631	0.3732	3.8501	5.2364	55
LBHO	4.5543	0.8854	2.7726	6.1115	55
LEDU	4.5023	0.6278	3.2958	5.7142	55
LSHARE	4.5912	0.6600	3.7612	6.4770	55
LPENS	4.4510	0.4690	3.3322	5.4161	55
LSING	4.5488	0.5344	3.6109	5.7683	55
LFWC	4.4592	0.5635	2.5649	5.4161	55
LINTER	4.5958	0.4088	3.4657	5.2933	55
LCRED	4.2073	0.9061	1.6094	5.7203	55
LENEST	4.4565	0.4272	3.1354	5.1360	55

Table B.6 – Descriptive Statistics

The final sample used consists of 55 observations for the year 2000, on each of 17 ACORN groups. The descriptive statistics of the data for the sample are reported in Table B.6. The natural log transformed variables are denoted with the corresponding name prefixed by the capital letter L.

	LINC	LBHO	LEDU	LSHARE	LPENS	LSING	LFWC	LINTER
LINC		.09840	<b>.89376</b>	.23225	-.30924	-.23822	<b>.35455</b>	<b>.94885</b>
LBHO			.16498	-.09174	.10425	-.06571	-.01445	.00278
LEDU				<b>.45135</b>	-.19432	.11906	-.02608	<b>.83056</b>
LSHARE					<b>-.53958</b>	<b>.45280</b>	-.11618	<b>.31815</b>
LPENS						-.00921	-.48707	-.45787
LSING							-.76021	-.21262
LFWC								<b>.42369</b>
LINTER								

Table B.7 – Correlation between determinants

A correlation matrix between determinants of emissions is presented in Table B.7. Pairwise correlation coefficient larger than 0.4 are highlighted in bold. There is a high correlation between income and education. Also access to internet services is highly correlated with education and income. Sharing and education are correlated. Sharers tend to be single students in cosmopolitan areas.

### B.4.2 Panel regression methodology and estimation

Panel methods can be applied to a cluster-sample such as this one where the clusters are the ACORN groups as defined in Table B.2. The ACORN dataset we use is a crosssectional dataset in which each observation belongs to a well-defined category, ACORN group and type. Each group is a cluster and it is obvious, as the names suggest, that unobserved group effects will be an important factor in explaining, say, income levels, within groups.

The specification used, using the variables defined in the previous Section, is

$$LCO_{it} = \alpha + \beta_1 LINC_{it} + \beta_2 LINC SQ_{it} + \beta \text{ other variables} + u_i + \varepsilon_{it} \quad (\text{B.5})$$

with  $i=1, \dots, N$  and  $t=1, \dots, T$  representing groups and types respectively.  $u_i$  are the unobserved group specific effects. The main concern in estimating this model is that income and the other variables included are correlated with the group effects. If so, a pooled OLS approach provides a biased estimator of the impact coefficients. Since outcomes within a group are likely to be correlated, allowing for an unobserved group effect is important.

We apply a within group transformation to the dependent,  $y$  and the independent,  $x$ , variables, i.e.,

$$\begin{aligned} \tilde{y}_{it} &= y_{it} - \bar{y}_i \\ \tilde{x}_{it} &= x_{it} - \bar{x}_i \end{aligned}$$

where  $\bar{y}_i = \frac{1}{T_i} \sum_t y_{it}$  and  $\bar{x}_i = \frac{1}{T_i} \sum_t x_{it}$  are the  $N$  within group-specific means.

$T_i$  represents the number of types per group. As the group sizes are not constant, a panel method for balanced data has to be applied.

By running an OLS on the transformed data we are estimating a panel fixed effect model and are able to control for individual heterogeneity. Table B.8 presents the panel data estimation for energy, transport, and both combined respectively. For each sector the pooled OLS, the fixed effect, and the random effect model results are presented. P-values for the null hypotheses that the coefficients are individually equal to zero against a two

sided alternative are reported in parenthesis below the estimated values. A degrees of freedom correction has been applied to the p-values to obtain the correct values.

### **B.4.3 Result discussion**

Table B.8 presents the results of the best panel data estimations for energy, transport, and both combined for a smaller subset of the variables obtain by means of a general to specific approach. All variables are significant at least at the 10 per cent level. The Hausman test presented in the last row of the table provides evidence of correlation between regressors and group effects. Thus only the FE coefficients will be interpreted.

Income variables (LINC and LINC SQ) are highly significant. We find evidence of a Kuznets curve. The estimated fixed effect turning points for all samples are all well above the sample mean incomes as well as above the income maxima of the sample. A high turning point for CO<sub>2</sub> is consistent with the literature on the EKC suggesting that EKC relationships are more likely to be found for certain types of environmental indicators, particularly those with a more short-term and local impact rather than those with a more global and long-term impacts (see, e.g., Arrow et al., 1995; Cole et al., 1997; Selden & Song, 1994). We note that OLS estimates of the turning points are much closer to the mean and within the sample range. This has a considerable interest to policy maker. Changes that might benefit the environment occur at much higher levels of income than those implied by standard OLS estimation. The income turning point of the transport sample is much higher than the energy regression.

Education (LEDU), keeping everything else constant, has one of the highest quantitative impact. Higher levels of education tend to reduce emissions. This result supports the green consumerism argument as in Pettit & Sheppard (1992). This result is particularly relevant for the policy maker as we control for the level of income with which education is correlated. We find that the use of internet (LINTER), controlling for everything else, reduces emissions. It would seem from our data that the use of information and communication technologies (ICT), in general, and the internet, in particular, allows households to significantly reduce their environmental impacts.

Sharing larger properties (LSHARE) has a large positive impact on emissions. It is highly significant both statistically and quantitatively. This result supports the idea that 'sharing' in terms of joint/communal ownership and access/use can lead to a mis- or overuse of resources as in Hardin (1968). People living alone (LSING), controlling for

everything else, have a lower impact on the environment. This together with the previous finding, highlights the importance of financial based incentives and could be of great value to the policy maker. As expected large homes (LBHO) have a negative impact on the environment.

	Energy			Transport			All		
	OLS	FE	RE	OLS	FE	RE	OLS	FE	RE
Constant	-7.083		-6.921	1.973		0.859	-3.276		-3.301
LINC	6.423	4.781	6.357	1.944	2.387	2.426	4.859	3.926	4.854
LINCSQ	-0.660	-0.450	-0.630	-0.170	-0.180	-0.197	-0.488	-0.350	-0.457
LBHO	0.086	0.067	0.0790	0.005	0.039	0.015	0.058	0.057	0.058
LEDU	-0.038	-0.220	-0.156	-0.098	-0.194	-0.173	-0.065	-0.224	-0.190
LSHARE	0.352	0.319	0.326	0.014	0.039	0.023	0.223	0.205	0.205
LSING	-0.380	-0.205	-0.281	-0.255	-0.154	-0.209	-0.338	-0.185	-0.234
LINTER	-0.263	-0.363	-0.322	0.258	0.060	0.154	-0.064	-0.193	-0.156
Hausman		12.62			14.20			14.48	
		(0.081916)			(0.047817)			(0.043245)	

Table B.8 – Panel regression results: best regression



## **B.5 CONCLUSION**

Motivated by the UK government's ambition to drastically reduce CO<sub>2</sub> emissions until 2050, this paper has explored the usefulness of input-output based lifestyle analysis models to inform energy conservation and CO<sub>2</sub> mitigation policies. It provides further evidence that 'housing' and 'travel' are the key policy areas to focus on. However, in understanding what makes the difference in emissions across socio-economic groups the input-output model shows to be very restricted. In fact, in-depth policy advice cannot be derived as the input-output model lacks any option to control for individual socioeconomic variables and their influence on CO<sub>2</sub> emissions. Therefore, by further analysing the detailed results from the input-output model, we are able to determine the impact of significant social factors and consumer behaviour on aggregate CO<sub>2</sub> emissions. This allows much more appropriately the assessment of different policy options in the UK's climate change challenge.

Using a panel regression approach we are able to control for many unobservable factors and estimate the impact of socio-economic factors on CO<sub>2</sub> emissions controlling for related and competing factors. For instance, in accordance with green consumerism arguments, we find that education (LEDU), keeping everything else constant, has one of the highest quantitative impact. Higher levels of education tend to reduce emissions. Also, among other things, we found evidence that the use of internet (LINTER), controlling for everything else, reduces emissions. This supports the argument that use of information and communication technologies (ICT), allows households to significantly reduce their environmental impacts.

Although we find evidence of an inverted U relationship between income and emissions, the estimated turning point is well above the maximum of our samples. This finding is consistent with a large strand of literature in environmental economics which asserts that an inverted U relationship between income and emissions is more for environmental indicators with a more short-term and local impact rather than those with a more global and long-term impact. This result is of considerable interest to the policy maker. Policy makers should not assume that economic growth will automatically solve the climate change problem as structural changes that might benefit the environment occur at an unattainably high level of income.

## B.6 REFERENCES

- Alakeson, V., Aldrich, T., Goodman, J., & Jorgensen, B., 2003, *Making the web work: Sustainable development in a digital society*, Xeris; London.
- Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., & Holling, C. S., 1995, Economic growth, carrying capacity, and the environment, *Ecological Economics* 15(2): 91–95.
- Brodersen, S., 1990, *Time and consumption*, chapter Reanalysis of the consumer surveys. Classification and method, Denmark Statistics: 273–290.
- Charkiewicz, E., Bennekou, S. v., & Young, A., 2001, *Transitions to Sustainable Production and Consumption. Concepts, Policies and Actions*. Maastricht: Shaker Publishing.
- Cohen, C., Lenzen, M., & Schaeffer, R., 2005, Energy requirements of households in Brazil, *Energy Policy* 33: 555–562.
- Cole, M., Rayner, A., & Bates, J., 1997, The environmental kuznets curve: An empirical analysis, *Environment and Development Economics* 2(4): 401–416.
- Duchin, F., 1998, *Structural Economics. Measuring Change in Technology, Lifestyle and the Environment*, Washington DC: Island Press.
- Gay, P. & Proops, J., 1993, Carbon-dioxide production by the UK economy: An input-output assessment, *Applied Energy* 44: 113–130.
- Gay, R., Davis, R., Phillips, D., & Sui, D., 2005, Modelling paradigm of the environmental impacts of the digital economy, *Journal of Organizational Computing and Electronic Commerce* 15(1): 61–82.
- Gershuny, J., 1987, Time use and the dynamics of the service sector, *Service Industry Journal* 7(4): 56–72.
- Government UK, 2005, *Securing the future - delivering UK sustainable development strategy*, Department for Environment, Food and Rural Affairs, London.
- Government UK, 2006, *Climate change - the UK government 2006 programme*. Technical report, Department for Environment, Food and Rural Affairs, London.
- Hardin, G., 1968, The tragedy of the commons, *Science* 162: 1243–1248.
- Hawken, P., Lovins, A., & Lovins, L., 1999, *Natural Capitalism - The next industrial revolution*, London: Earthscan.
- Hertwich, E. & Katzmayer, M., 2004, Examples of sustainable consumption - review, classification and analysis. Report 5, Norwegian University of Science and Technology Industrial Ecology Programme, Trondheim.
- Jalas, M., 2002, A time use perspective on the material intensity of consumption. *Ecological Economics* 41(1): 109–123.
- Jalas, M., 2005, The everyday context of increasing energy demands - time use survey data in a decomposition analysis, *Journal of Industrial Ecology* 9(1-2): 129–145.
- Kondo, Y., 2006, Environmental impacts of consumer's time use: Consumption "technologies" and the waste input-output model. Queen's College, Oxford. Conference of the International Society for Industrial Ecology.
- Lenzen, M., 1994, Energy and greenhouse gas cost of living for Australia during 1993/94, *Energy* 23(6): 497–516.
- Lenzen, M., Dey, C., & Foran, B., 2004, Energy requirements of Sydney households, *Ecological Economics* 49: 375–399.
- Lenzen, M., Pade, L., & Munksgaard, J., 2004, CO<sub>2</sub> multipliers in multi-region input-output models, *Economic Systems Research* 16(4): 391–412.
- Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., & Schaeffer, R., 2006, A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan, *Energy* 31: 181–207.
- Lintott, J., 1998, Beyond the economics of more. the place of consumption in ecological economics, *Ecological Economics* 25: 239–248.
- Mills, M., 1999, *The internet begins with coal: a preliminary exploration of the impact of the internet on electricity consumption*, Arlington: Greening Earth Society.
- Minx, J. & Baiocchi, G., 2006, *Handbook of Input-Output Methods for Industrial Ecology*, chapter Time Use and Sustainability. North Holland Publishing. forthcoming.

- Munksgaard, J., Minx, J., Christoffersen, L., & Pade, L.-L., 2006, *Handbook of Input-Output Methods for Industrial Ecology*, chapter Models for National CO2 Accounting. North Holland Publishing. forthcoming.
- Munksgaard, J. & Pedersen, K. A., 2001, Co2 accounts for open economies. producer or consumer responsibility? *Energy Policy* 29: 327–334.
- Munksgaard, J., Paade, L.-L., Minx, J., & Lenzen, M., 2006, Influence of trade on national co2 emissions, *International Journal of Global Energy Issues* 23(4).
- Office for National Statistics, 2005, *Family Spending*. A report of the 2004–05 expenditure and food survey. London: Office for National Statistics.
- Office for National Statistics, 1999, *Environmental Accounts 1999*, London: Office for National Statistics.
- Office for National Statistics, 2003, *United Kingdom Input-Output Analyses*. London: ONS. Download of Supply and Use Tables at: <http://www.statistics.gov.uk/input-output>.
- Office for National Statistics, 2005, *Environmental Accounts 2005*, London: Office for National Statistics.
- Pachauri, S. & Spreng, D., 2002, Direct and indirect energy requirements of households in India, *Energy Policy* 30: 511–523.
- Peters, G. & Hertwich, E. 2006, The importance of imports for household environmental impacts. *Journal for Industrial Ecology*. forthcoming.
- Pettit, D. & Sheppard, J., 1992, It's not easy being green: The limits of green consumerism in light of the logic of collective action, *Queens Quarterly* 99(3): 328–350.
- Princen, T., Maniates, M., & Conca, K., 2002, *Confronting Consumption*. London: MIT Press.
- Roundtable for Sustainable Consumption, 2006, *I will if you will*. Technical report, Sustainable Development Commission and National Consumer Council, London.
- Schaffer, A. & Stahmer, C., 2005, The part time society: a concept for more sustainable patterns of production and consumption, *GAIA* 14(3), 229–239.
- Schipper, L., Bartlett, S., Hawk, D., & Vine, E., 1989, Linking lifestyles and energy use. a matter of time? *Annual Review of Energy* 14: 273–320.
- Selden, T. M. & Song, D., 1994, Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions? *Journal of Environmental Economics and Management* 27(2): 147–162.
- Stahmer, C., 2004, Social accounting matrices and extended input-output tables. In OECD (Ed.), *Measuring sustainable development: Integrated economic, environmental and social frameworks*, Paris. OECD.
- Sui, D. & Rejeski, D., 2002, Environmental impacts of the emerging digital economy: The e-for-environment e-commerce? *Journal of Environmental Management* 29(2): 155–163.
- Vringer, K. & Blok, K., 1995, The direct and indirect energy requirements of households in Netherlands, *Energy Policy* 23(10): 893–910.
- Weber, C. & Perrels, A., 2000, Modelling lifestyle effects on energy demand and related emissions, *Energy Policy* 28: 549–566.
- Weizsäcker, E. U. v., Lovins, A. B., & Lovins, L. H., 1995, *Faktor Vier. Doppelter Wohlstand und Halbierter Ressourcenverbrauch*, München: Dörner Knauer Verlag.
- Wiedmann, T., Minx, J., Barrett, J., & Wackernagel, M., 2006, Allocating ecological footprints to final consumption categories with input-output analysis, *Ecological Economics* 56: 28–48.
- Wier, M., Lenzen, M., Munksgaard, J., & Smed, S., 2001, Effects of household consumption patterns on co2 requirements, *Economic Systems Research* 13(3), 259–274.
- Wilsdon, J., 2002, *Digital Futures: Living in a dot.com world*, London: Earthscan.

# C MODELS FOR NATIONAL CO<sub>2</sub> ACCOUNTING<sup>1</sup>

**Abstract:** Considering international negotiations on the reduction of greenhouse gases it is highly relevant to develop principles for a fair burden sharing between countries. Within this context it is also important to develop a uniform framework for accounting for national CO<sub>2</sub> emissions so that national targets are founded on a consistent basis. In this study we set up such a framework based on input-output modelling and the concept of producer or consumer responsibility as introduced in Munksgaard and Pedersen (2001). The aim of the paper is threefold: *First*, to categorise and outline different national CO<sub>2</sub> accounting models proposed in the input-output literature with a special focus on methodology and data requirements, *second*, to estimate and compare those models founded on a consistent multi-regional data set including input-output tables, energy flow matrices and emission factors for five countries, and *third*, to discuss the policy implications of the different models and investigate how they can be used for further policy analysis.

---

<sup>1</sup> Munksgaard, J., Minx, J.C., Christoffersen, L., and Pade, L.-L., 2007, Models for National CO<sub>2</sub> Accounting, in: Suh, S., Handbook of Input-Output Methods for Industrial Ecology, Springer, Dordrecht, forthcoming

## C.1 INTRODUCTION

In international climate change negotiations a country is commonly held responsible for all CO<sub>2</sub> emitted from its domestic territory. In the literature this commonly applied CO<sub>2</sub> accounting method is called “territorial” or “producer responsibility”. Driven by concerns about carbon leakage (Wyckhoff and Roop, 1994; Kondo, et al., 1998; Ahmad and Wyckhoff, 2003) and equity associated with the structure of trade relations between developing and developed countries (Schaeffer and De Sá, 1996; Machado et al., 2001) as well as import and export structures of small open economies (Munksgaard and Pedersen, 2001), “consumer responsibility” has been proposed as an alternative CO<sub>2</sub> accounting method.<sup>2</sup>

From an accounting perspective the difference between the two concepts lies in the treatment of trade related emissions. Besides its domestic emissions a country can either be held responsible for CO<sub>2</sub> embodied in exports or imports (or a combination of both). With world trade growing more than twice as fast as world GDP,<sup>3</sup> how to account for CO<sub>2</sub> emissions becomes increasingly relevant for countries in international climate change negotiations and for successful global mitigation efforts as the equity issue becomes more urgent and the threat of carbon leakage becomes more severe.

We do not want to answer the question: Who should be ultimately held responsible for emitting CO<sub>2</sub> to the atmosphere – the producer or the consumer? This has been extensively discussed in the literature before (e.g. Wyckhoff and Roop, 1994; Kondo et al., 1998; Munksgaard and Pedersen, 2001; Ferng, 2003; Bastianoni et al., 2004). However, little thought has been given to the different ways, in which we can set up or estimate national CO<sub>2</sub> accounts. This is largely a methodological question depending on data availability and research purpose. Therefore, in an input-output context we outline different models for assigning emission responsibilities at national and international level, what the differences in methodologies and data requirements are and in which policy context the models might be most appropriately applied.

---

<sup>2</sup> Some authors (Kondo et al., 1998; Ferng, 2003) have proposed mixtures of both principles though doubts need to be raised whether or not consensus could be reached in an international agreement with many actors. We will consider only the two “polar” cases of consumer and producer responsibility keeping in mind that there is theoretically an infinite number of ways to combine both in a “hybrid” responsibility concept.

<sup>3</sup> This figure refers to the growth in trade between the Kyoto reference year 1990 and 1999 (WTO, 2000).

The structure of the article is as follows. Section C.2 will develop a classification scheme for input-output models based on a discussion of different responsibility concepts used in input-output modelling. Based on this classification the literature will be reviewed in Section C.3. In Section C.4 the methodology of key models will be developed from a consistent multi-regional input-output framework. The data set will be introduced in Section C.5, before the results will be presented and discussed in Section C.6. Section C.7 turns to policy implications and potential model applications of both accounting methods and Section C.8 concludes.

## **C.2 RESPONSIBILITY AND IO MODELS**

The concept of Lifecycle Analysis (LCA) has shifted the borders of environmental responsibility for economic actors at the micro-level. It requires taking into account not only the environmental impacts on-site, but also the indirect ones upstream and downstream. Environmental input-output models – as introduced by authors like Daly (1968), Leontief (1970), Victor (1972) or Just (1974) among others – can take a similar lifecycle perspective at the macro-level and trace pollution all along the supply chain to final demand.<sup>4</sup> In particular, these kinds of models allow the assessment of physical flows from the natural environment into and out of the economic system (such as fuel inputs and CO<sub>2</sub> emissions) in terms of direct and indirect components, so as to assign the responsibility for these flows to different institutions or functional units on the production and consumption ends of an economy (De Haan, 2002).

More recently, input-output models have been used for shifting responsibilities for energy flows and associated CO<sub>2</sub> emissions in an additional, national accounting sense. The principle of *producer responsibility* assigns CO<sub>2</sub> emissions to the processes actually emitting carbon to the atmosphere. A country is therefore held responsible for all emissions associated with the provision of goods and services produced on its territory, wherever they are consumed.

---

<sup>4</sup> In fact, this has motivated a whole new branch of research called environmental input-output lifecycle assessment (EIO-LCA) (see for example: Hendrickson et al., 1998; Matthews, 1999; Joshi, 2000). However, it has been shown to be most fruitful to combine conventional process lifecycle analysis with EIO-LCA in hybrid LCA models as proposed by (Bullard et al., 1978) and later extended by Treloar (1997) and Lenzen (2001) among others. For a good introduction with key references see Nielsen and Weidema (2001).

This is shown in Figure C.1, where emissions associated with exports to the rest of the world (ROW) (quadrant 2) are added to country A's "domestic"<sup>5</sup> CO<sub>2</sub> account (quadrant 1). The *consumer responsibility* method books CO<sub>2</sub> emissions to the country of final use of goods and services. Hence, emissions associated with imports from ROW (quadrant 3) are added to domestic CO<sub>2</sub> (quadrant 1) in order to set up a consumer responsibility account. Subtracting quadrant 3 from 2 gives country A's CO<sub>2</sub> *trade balance* (Sánchez-Chóliz and Duarte, 2004; Munksgaard and Pedersen, 2001), essentially indicating whether this country is a net exporter or a net importer of carbon dioxide.

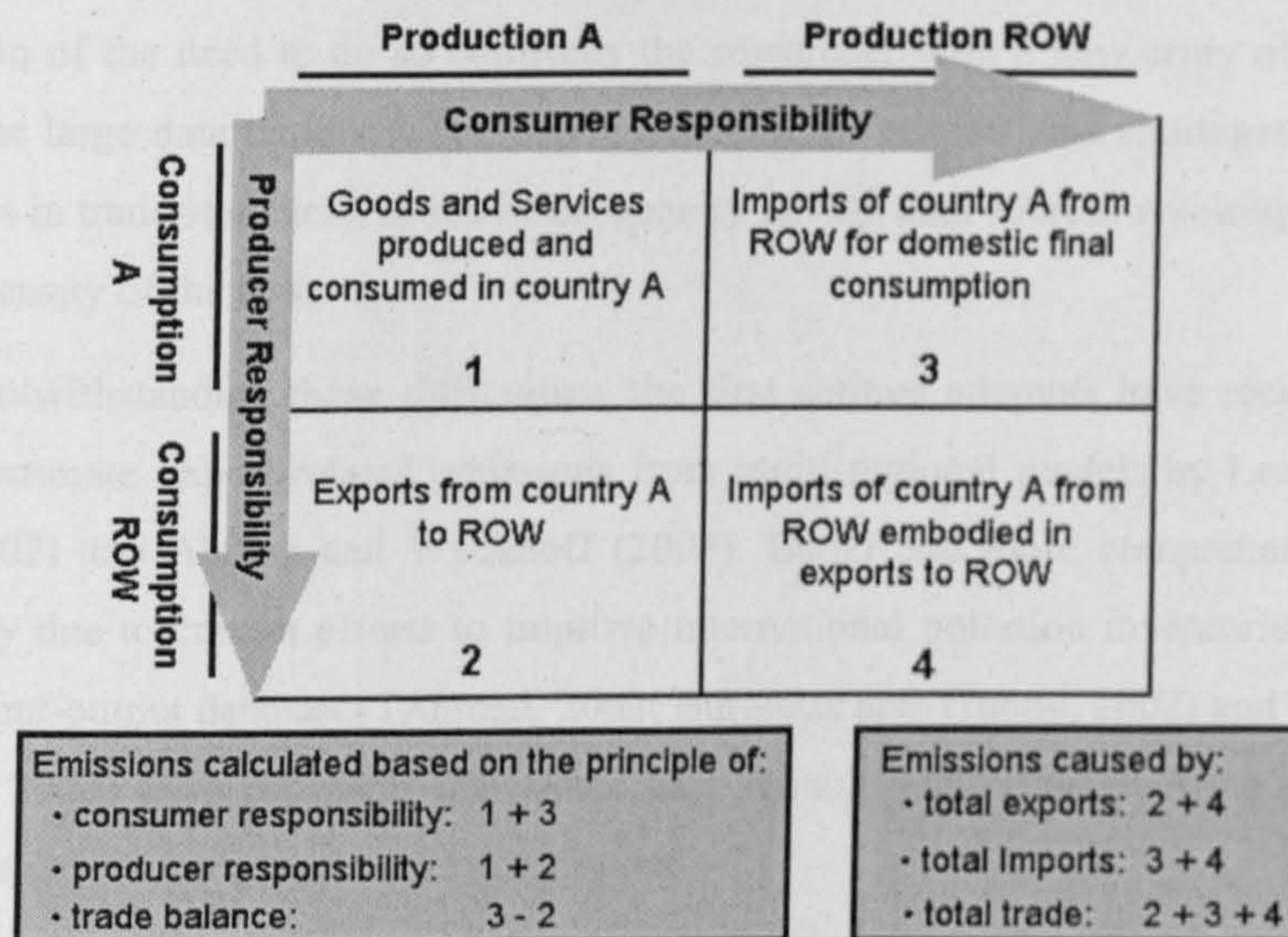


Figure C.1 - Producer versus Consumer Responsibility

For input-output modelling the distinction between producer and consumer responsibility raises further data-related questions that have not been addressed very well in the literature so far. Both accounting principles have usually been applied in single-region models to estimate a country's national CO<sub>2</sub> balance (e.g. Proops et al., 1993; Kondo et al. 1998; Lenzen, 1998; Munksgaard and Pedersen, 2001). Such a procedure is sound for producer responsibility accounts as the system boundaries of national data sources and accounting method coincide. Therefore, no methodological challenges are

<sup>5</sup> We refer to domestic here consistently in the sense of domestically produced and consumed goods and services. This means that "domestic" always excludes exports.

imposed by including trade in the form of export-related emissions into input-output models.

However, the single-region assumption needs to be challenged in models for setting up a consumer responsibility account, because the scope of the inquiry comprising the emissions associated with imports from all over the world exceeds the national boundaries of input-output tables. Therefore, doubt must be raised about the correctness and reliability of those accounts. A methodologically sound response to this challenge is to use a multi-regional input-output model ideally for setting up a consumer responsibility account covering all trading partners of the country accounted for. However, the recognition of the need to do so confronts the researcher with a new array of problems such as the large data requirements, country-specific or general data shortages (e.g. lack of services in trade statistics), or the heterogeneity among data sources resulting in a huge labour intensity of the task.

Notwithstanding those difficulties, the first serious attempts have recently been made to estimate import-related emissions from multi-regional models by Lenzen et al. (2004, 2002) and Ahmad and Wyckhoff (2003). Better and more comprehensive data availability due to current efforts to improve international pollution inventories (GTAP, 2003),<sup>6</sup> input-output databases (Ahmad, 2002; Burniaux and Truong, 2002) and trade data (Eurostat, 2003) raise prospects that even more reliable and comprehensive modelling approaches will be presented in the near future.

To make way for an intensified discussion, below we review and compare the different models that have been proposed in the literature so far. Thereby, completeness is intended in terms of modelling approaches rather than the studies included. Based on the above discussion a classification scheme can be based on three fundamental model characteristics:

- Accounting Principle: Producer versus consumer responsibility models;
- Estimation Method: Direct versus direct and indirect emission models;
- Data Framework: Single versus multi-regional. Multi-regional approaches will be further subdivided into uni-directional and multi-directional models,

---

<sup>6</sup> The Global Trade Analysis Project is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. The purpose of the project is to improve the quality of global economy-wide analysis through education and by developing analytical data bases, economic models, and innovative methodologies.



where only the latter takes inter-regional feedback effects into account, cf. van der Linden & Oosterhaven (1995).

These characteristics lead to seven major model categories as shown in Figure C.2, where an additional subdivision can be achieved by assigning the emissions to different institutions or functional units within the economy (industries versus commodity groups for different final demand entities at different levels of disaggregation):

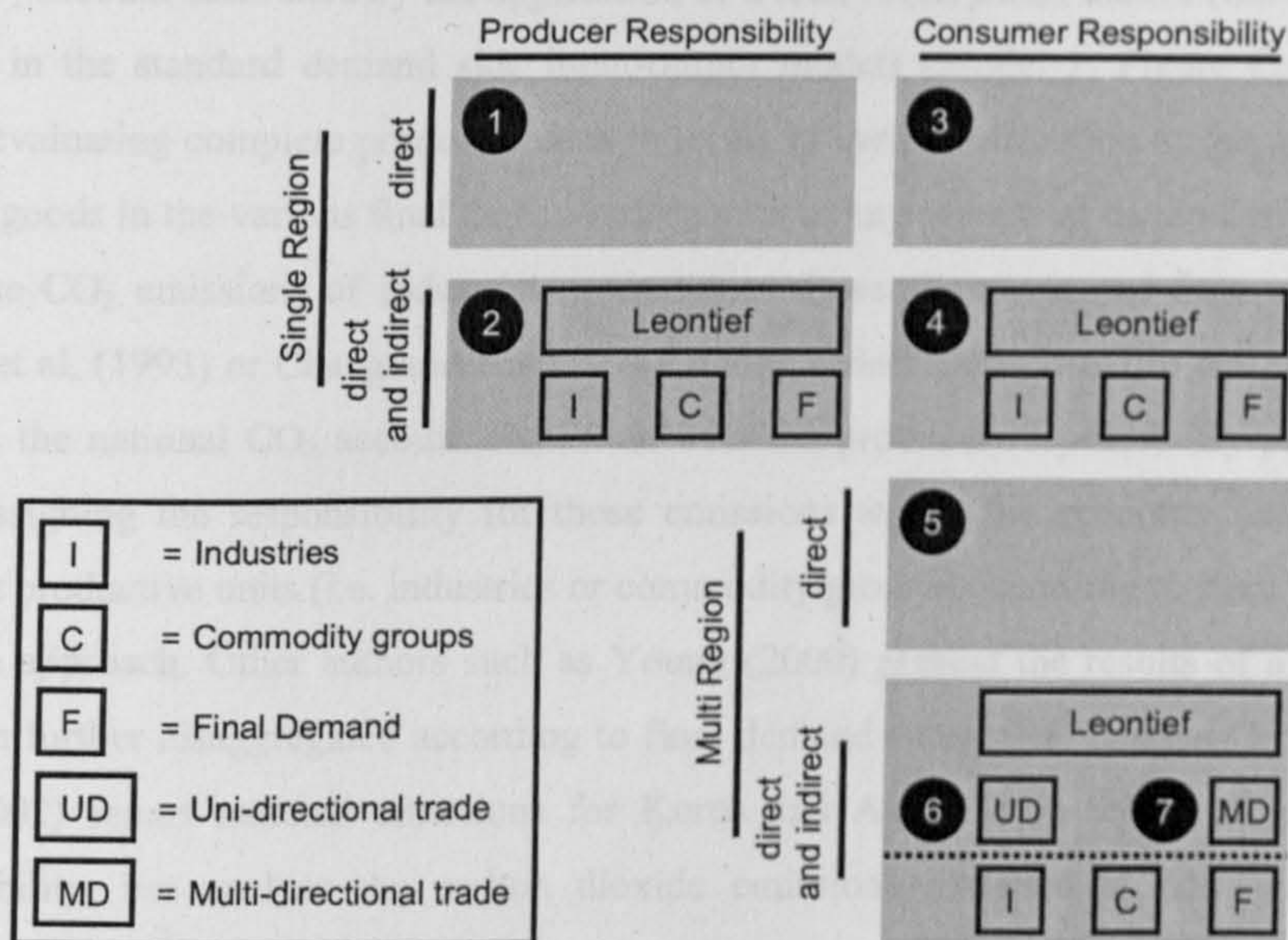


Figure C.2 – Classification of CO<sub>2</sub> Accounting Models

### C.3 LITERATURE REVIEW

#### C.3.1 Producer Responsibility Models

The least data intensive way to set up a producer responsibility CO<sub>2</sub> account is to use a direct emission model (Model 1, Figure C.2). Such models have mainly been applied in environmental accounting (Harris, 2001) and assign the emissions to those sectors actually emitting CO<sub>2</sub>. In particular, it is a summation of all on-site emissions across economic sectors and households in the economy.

The input-output literature has occasionally employed those models in a supplementary fashion (Gay and Proops, 1993; Gale, 1995; Munksgaard and Pedersen, 2001; Sánchez and Duarte, 2004). An exception is Yabe (2004), who uses a direct emission formulation in a competitive single-region model to assess changes in Japan's CO<sub>2</sub> account based on structural decomposition analysis.<sup>7</sup>

However, most input-output studies use direct and indirect emission models to set up a CO<sub>2</sub> account facilitated by the application of a total requirement matrix (the Leontief Inverse in the standard demand side input-output model) (Model 2, Figure C.2). This allows evaluating complete product chains in terms of their contribution to the provision of final goods in the various final demand categories as key objects of the analysis and to transpose CO<sub>2</sub> emissions of industrial processes to those. Common and Salma (1992), Proops et al. (1993) or Chang and Lin (1998) among others, therefore, use this model to estimate the national CO<sub>2</sub> account consistent with the producer responsibility principle, while assigning the responsibility for those emissions *within* the economy among the different productive units (i.e. industries or commodity groups) according to final use in a lifecycle approach. Other authors such as Young (2000) present the results of a similar approach further disaggregated according to final demand categories. Lenzen (1998) and Kim (2002) report national emissions for Korea and Australia in terms of producer responsibility, but analyse the carbon dioxide emissions assigned to domestic final demand entities at various levels of disaggregation in terms of consumer responsibility. This is facilitated by a competitive single-region model setup, where import-related emissions are deduced in the end for calculation of the national CO<sub>2</sub> account.

### C.3.2 Consumer Responsibility Models

Direct emission models have been rarely applied to estimate a nation's consumer responsibility CO<sub>2</sub> account. The only notable exception both in a single-region and multi-regional data framework (Models 3 and 5, Figure C.2) is Harris (2001). In this approach, on-site emissions of all products consumed in an economy are summed across sectors and households. Clearly this includes domestic and imported products.

---

<sup>7</sup> Interestingly, this allows him also to quantify the contribution of changes in Japan's trade structure to total emission change, and evaluate changes in the development of the trade balance indicator within a producer responsibility framework.

The majority of studies uses a direct and indirect emission formulation in single-region models (Model 4, Figure C.2). Therefore, many authors have followed the spirit of the consumer responsibility principle also on a subnational level and assigned CO<sub>2</sub> *within* the economy according to final use (e.g. Hetherington, 1996; Lenzen, 1998; Kondo et al. 1998). Munksgaard and Pedersen (2001) break the consumer responsibility account further down by consumption expenditure groups.

The first prominent approach to estimate consumer responsibility accounts from a multi-regional framework has been provided by Lenzen et al. (2002, 2004). They present a fully integrated multi-directional trade model for a small number of countries, trade in goods *and* services as well as a medium to high level of sectoral detail depending on the country under consideration. The paper shows significant differences in CO<sub>2</sub> emission estimates depending on the treatment of trade in single-region, uni-directional or multi-directional input-output models. Recently, Ahmad and Wyckhoff (2003) have published a study using a uni-directional trade model including many countries, only traded goods (no services) and a medium level of sectoral detail.

Despite this body of literature, many studies can be found, which have remained incomplete from a national CO<sub>2</sub> accounting perspective. There are mainly three types. First, there are studies which *only* estimate trade-related emissions being essentially concerned with the CO<sub>2</sub> trade balance of countries as defined in Figure C.1. Therefore, they have played an important role in the national CO<sub>2</sub> accounting literature as they have informed about the extent of differences in producer and consumer responsibility CO<sub>2</sub> accounts and “winners” and “losers” of current accounting practices (see Wyckhoff and Roop, 1995; Schaeffer and Sá, 1996; Machado, 2000; Machado et al., 2001; Sánchez and Duarte, 2004 among others). Second, there are some studies mainly interested in methodological issues related to the treatment of imports (Battjes et al., 1998; Blancas, 2000) or in particular, often bi-lateral trade relations (Hayami and Kiji, 1997; Hayami et al., 1999; Hayami and Nakamura, 2002). Third, there is a whole body of literature concentrating on emissions related to consumption activities of households. Often those studies calculate the total emissions motivated by households including imports in the assessment (Vringer and Blok, 1995; Weber and Perrels, 2000; Munksgaard et al., 2000; Pachauri and Spreng, 2002; Cohen et al., 2005) though the focus sometimes remains on the consumption of domestic goods (Bin and Dowlatabadi, 2005).

## C.4 MODEL DESCRIPTION

In this section the different national CO<sub>2</sub> accounting models will be outlined. For convenience of the reader two decisions have been made concerning their representation here: First, even though the estimations have been carried out in a more flexible make-use model, the maths of the standard Leontief model has been used in this model outline. However, in later sections all necessary information is given that allows the reader to understand the actual estimation process leading to our empirical results. Second, models are presented in an impact coefficient formulation even though estimations have been carried out in an augmented model (see, Miller and Blair, 1985, pp. 236). Matthews (1999) among others has shown that both models lead to identical results in a static setting (see also, Proops, 1977).

To set up national CO<sub>2</sub> accounts in *single-region* input-output models, data of the following type are required:

1) An input-output publication of monetary transactions within an economy containing:

- A [nx1] vector of domestic output  $x$  by industrial sector.
- A [nx1] vector of final demand  $y$  by industrial sector including exports to other countries.
- A [nxn] matrix of technical coefficients  $A$  indicating the input requirements of the  $j^{\text{th}}$  sector for intermediate goods from the  $i^{\text{th}}$  sector per monetary unit output of sector  $j$ .

2) An [mxn] energy use matrix  $E_{\text{ind}}$  indicating the fuel use of the  $k^{\text{th}}$  fuel type per unit output of the  $j^{\text{th}}$  industrial sector and an [mxn] energy use matrix  $E_{\text{hd}}$  giving the household's fuel use of the  $k^{\text{th}}$  fuel type per monetary unit of final demand for goods of the  $j^{\text{th}}$  industrial sector.

3) A [mx1] vector  $c$  of CO<sub>2</sub> emission per unit fuel used of the  $k^{\text{th}}$  type.

To set up national CO<sub>2</sub> accounts in *multi-region* input-output models additional data are required for the estimation process. These are:

4) National input-output tables, energy use intensity matrices and fuel coefficients as defined above for at least one additional country.

5) Bilateral import coefficient matrices  $A''$  (for  $i \neq j$ ), where the first superscript denotes the country of origin and the second superscript the country of destination of trade flows. Note that the domestic technology matrix  $A$  will be denoted  $A''$ .

### C.4.1 Producer responsibility models

In this section two models on producer responsibility are specified. The models are founded in the distinction between direct and indirect CO<sub>2</sub> emissions. Model 1 shows direct CO<sub>2</sub> emissions from on-site energy use, and model 2 shows direct and indirect CO<sub>2</sub> emissions including all upstream production activities as well. Thereby model 2 represents a life-cycle approach to responsibility, i.e. responsibility is not allocated based on an industry's direct energy use, but assigned according to energy requirements of all inputs needed to produce an industry's final product.

#### C.4.1.1 Direct emissions from production

One way to establish a CO<sub>2</sub> account based on the principle of producer responsibility denoted by  $\Omega_{\delta}^{PR}$  is to add up the emissions from industries  $\delta_{ind}^{PR}$  and from final demand<sup>8</sup>  $\delta_{fd}$  arising from the direct use of energy goods and services. We can obtain an estimate of  $\delta_{ind}^{PR}$  by premultiplying the total output vector  $x$  by the transposed emissions coefficient vector  $c$  and the industrial energy intensity matrix  $E_{ind}$ , that is

$$\delta_{ind}^{PR} = c' E_{ind} x \quad (C.1)$$

Note that  $x$  comprises all goods and services produced within a country, which are either consumed domestically or exported. In a similar way the direct emissions from final demand  $\delta_{fd}$  can be established by

$$\delta_{fd} = c' E_{fd} y \quad (C.2)$$

---

<sup>8</sup> Note that households are usually treated as the only emitting domestic final demand entity in national fuel use statistics.

where  $y$  is the final demand vector. Putting (C.1) and (C.2) together we can set up the desired producer responsibility CO<sub>2</sub> account, that is

$$\Omega_{\delta}^{PR} = \delta_{ind}^{PR} + \delta_{fd} = c' E_{ind} x + c' E_{fd} y \quad (C.3)$$

#### C.4.1.2 Direct and indirect emissions from production

In direct and indirect emission models a producer responsibility account  $\Omega_{\sigma}^{PR}$  can be estimated by adding up the direct and indirect emissions of industries  $\sigma_{ind}^{PR}$  and the direct emissions of final demand  $\delta_{fd}$  as calculated in (C.2).  $\sigma_{ind}^{PR}$  can be written as,

$$\sigma_{ind}^{PR} = c' E_{ind} (I - A)^{-1} y \quad (C.4)$$

where  $A$  is the [nxn] domestic direct requirement matrix and,  $I$  is an identity matrix of the same size and  $(I - A)^{-1}$  is the domestic Leontief inverse. Combining (C.4) with (C.2) gives the desired direct and indirect emission model for calculating national CO<sub>2</sub> accounts based on the concept of producer responsibility  $\Omega_{\sigma}^{PR}$ , that is

$$\begin{aligned} \Omega_{\sigma}^{PR} &= \delta_{fd} + \sigma_{ind}^{PR} = c' E_{fd} y + c' E_{ind} (I - A)^{-1} y \\ &= c' [E_{fd} + E_{ind} (I - A)^{-1}] y \end{aligned} \quad (C.5)$$

It should be clear that the *total* emission estimates  $\Omega_{\delta}^{PR}$  and  $\Omega_{\sigma}^{PR}$  are identical. However, they differ in their *sectoral* emission assignments as (C.1) accounts all emissions at the source sector and (C.4) re-allocates emissions according to the sector of final use using the Leontief inverse.

#### C.4.2 Consumer responsibility models

The consumer responsibility models developed in this section are also based on a distinction between direct and indirect CO<sub>2</sub> emissions. Besides, the models are specified as single-region or multi-region models.

### C.4.2.1 Single region approach

The single-region approach bears implications for the treatment of imports. Two assumptions are made. *First*, imported goods and services are produced with a production technology similar to the domestic technology. *Second*, environmental and energy technology is the same abroad as in the domestic economy, i.e. domestic energy and fuel coefficients can also be used for the calculation of CO<sub>2</sub> emissions from imported goods and services.

#### C.4.2.1.1 Direct emissions in a single region model

Direct emissions from industries in the single-region consumer responsibility model  $\delta_{ind}^{CR}$  can be estimated similar to (C.1). The only difference is that we exclude exports and include imports in our estimations, that is

$$\delta_{ind}^{CR} = \mathbf{c}'\mathbf{E}_{ind}(\mathbf{x}_{tot} - \mathbf{y}_{ex}) \quad (\text{C.6})$$

where  $\mathbf{x}_{tot} = \mathbf{x} + \mathbf{x}_{imp}$  is the total industrial output including total domestic production, exports and imports and  $\mathbf{y}_{ex}$  is the exports vector. Meanwhile the direct emissions estimate as provided in (C.2) remains unchanged, because all import-related emissions are accounted for in (C.6). Therefore, we can estimate our consumer responsibility account  $\Omega_{\sigma,SR}^{CR}$  using a direct emission formulation, that is

$$\Omega_{\sigma,SR}^{CR} = \delta_{ind}^{CR} + \delta_{fd} = \mathbf{c}'\mathbf{E}_{ind}(\mathbf{x}_{tot} - \mathbf{y}_{ex}) + \mathbf{c}'\mathbf{E}_{fd}\mathbf{y} \quad (\text{C.7})$$

#### C.4.2.1.2 Direct and indirect emissions in a single region model

A consumer responsibility CO<sub>2</sub> account  $\Omega_{\sigma,SR}^{CR}$  can be calculated as the sum of the direct and indirect emissions from industries  $\sigma_{SR,ind}^{CR}$  and the direct emissions from final demand  $\delta_{fd}$ .  $\sigma_{SR,ind}^{CR}$  consists of three components: *First*, emissions arising from domestic production for domestic final demand (excluding exports), *second*, the emissions arising from imports to intermediate demand, and *third*, emissions arising from

import of goods and services to final demand (excluding exports). Those components are represented in the equation below as the first, second and third term in the square brackets respectively,

$$\sigma_{SR,ind}^{CR} = \mathbf{c}' \mathbf{E}_{ind} \left[ (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}_{\neq exp} + \left( (\mathbf{I} - \mathbf{A}_{tot})^{-1} - (\mathbf{I} - \mathbf{A})^{-1} \right) \mathbf{y}_{\neq exp} + (\mathbf{I} - \mathbf{A}_{tot})^{-1} \mathbf{y}_{imp \neq exp} \right] \quad (\text{C.8})$$

where  $\mathbf{A}_{tot} = \mathbf{A} + \mathbf{A}_{imp}$ ,  $\mathbf{y}_{tot} = \mathbf{y} + \mathbf{y}_{imp}$  and  $\mathbf{y}_{\neq exp}$  are the domestic final demand vectors (excluding exports). By merging equations (C.8) and (C.2), we can set up  $\Omega_{\sigma,SR}^{CR}$ , that is

$$\begin{aligned} \Omega_{SR,\sigma}^{CR} &= \sigma_{SR,ind}^{CR} + \delta_{fd} \\ &= \mathbf{c}' \left[ \mathbf{E}_{ind} \left( (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}_{\neq exp} + \left( (\mathbf{I} - \mathbf{A}_{tot})^{-1} - (\mathbf{I} - \mathbf{A})^{-1} \right) \mathbf{y}_{\neq exp} + (\mathbf{I} - \mathbf{A}_{tot})^{-1} \mathbf{y}_{imp \neq exp} \right) + \mathbf{E}_{fd} \mathbf{y}_{hh} \right] \end{aligned} \quad (\text{C.9})$$

A first relaxation of the assumptions applied in single-region models is to add another set of emission coefficients for a more appropriate treatment of import-related emissions. Those coefficients should better reflect the environmental technologies used in the importing countries under assessment. The choice of coefficients depends on many factors such as trade structure, the level of economic development of the country under consideration and not least data availability. A second relaxation of the assumptions applied is to introduce different production technologies for imports. Lenzen et al. (2002; 2004), for example, model technologies for the rest of the world (ROW) based on an adjusted Australian input-output table. Battjes et al. (1998) show how a ROW technology can be estimated from a collection of input-output tables of a limited number of countries.



### C.4.2.2 Multi-region approach

#### C.4.2.2.1 Direct emissions in multi-regional models

The direct emissions from industries  $\delta_{MR,ind}^{CR}$  for country  $j$  can be estimated by using the information from the trade flow matrices as well as emission coefficient vectors and fuel use matrices from the exporting countries, that is

$$\delta_{MR,ind}^{CR} = \sum_{i=1}^I (\mathbf{c}^i)' \mathbf{E}^i \mathbf{x}^{ij} \quad (\text{C.10})$$

where  $\mathbf{c}^i$  and  $\mathbf{E}^i$  (for  $i \neq j$ ) represent environmental technology in the exporting countries,  $\mathbf{x}^{ij}$  the total imports of country  $j$  from country  $i$ , and  $(\mathbf{c}^j)' \mathbf{E}^j \mathbf{x}^{jj}$  (i.e.  $i = j$ ) the emissions from domestic production excluding exports. As the direct emissions from final demand remain unaffected, we can set up  $\Omega_{MR,\delta}^{CR}$  by

$$\Omega_{\delta}^{CR} = \delta_{MR,ind}^{CR} + \delta_{fd} = \sum_{i=1}^I (\mathbf{c}^i)' \mathbf{E}^i \mathbf{x}^{ij} + (\mathbf{c}^j)' \mathbf{E}^j \mathbf{y}^{jj} \quad (\text{C.11})$$

where the second term on the right-hand side corresponds to equation (C.2) when adding a country index.

#### C.4.2.2.2 Direct and indirect emissions in a uni-lateral model

Uni-directional trade models require detailed information for imports of the country under assessment. To give a better idea about the data arrangement, we use a hypothetical three country/region case and apply matrix algebra for the description of  $\sigma_{UD,ind}^{CR}$ . Afterwards  $\sigma_{UD,ind}^{CR}$  will be generalised for the  $n$ -country case, when we set up the consumer responsibility account  $\Omega_{UR,\sigma}^{CR}$  for uni-directional trade models. Within our three country setting,  $\sigma_{UD,ind}^{CR}$  can be calculated as follows,

$$\sigma_{UD,ind}^{CR} = \begin{pmatrix} \mathbf{c}^1 \mathbf{E}_{ind}^1 & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{c}^2 \mathbf{E}_{ind}^2 & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{c}^3 \mathbf{E}_{ind}^3 \end{pmatrix} \quad (\text{C.12})$$

$$\left[ \begin{pmatrix} \mathbf{I} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{11} & \mathbf{O} & \mathbf{O} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{O} \\ \mathbf{A}^{31} & \mathbf{O} & \mathbf{A}^{33} \end{pmatrix} \right]^{-1} \begin{pmatrix} \mathbf{y}_{exp}^{11} \\ \mathbf{y}^{21} \\ \mathbf{y}^{31} \end{pmatrix}$$

where  $\mathbf{A}^{ij}$  (for  $i \neq j$ ) are off-diagonal trade coefficient matrices,  $\mathbf{A}^{ii}$  (for  $i=1,2,3$ ) are the domestic technical coefficient matrices of all three countries,  $\mathbf{y}_{exp}^{11}$  is domestic final consumption and  $\mathbf{y}^{ii}$  (for  $i=2,3$ ) are the import final demand vectors from country 2 and 3 (ROW), respectively.

Equations (C.2) and a version of (C.12) generalised for the  $n$ -country case can be merged to set up a consumer responsibility account for country  $j$  in  $\Omega_{UD,\sigma}^{CR}$  the unidirectional model, that is

$$\begin{aligned} \Omega_{UD,\sigma}^{CR} &= \sigma_{UD,ind}^{CR} + \delta_{fd} = \\ &= \mathbf{c}^j \left[ \mathbf{E}_{fd}^j \mathbf{y}^{jj} + \mathbf{E}_{ind}^j (\mathbf{I} - \mathbf{A}^{jj})^{-1} \mathbf{y}^{jj} \right] \\ &\quad + \sum_{\substack{i=1 \\ i \neq j}}^j \mathbf{c}^i \mathbf{E}_{ind}^i \left[ (\mathbf{I} - \mathbf{A}^{ii})^{-1} \mathbf{y}^{ii} + (\mathbf{I} - \mathbf{A}^{ij})^{-1} \mathbf{y}^{ij} \right] \end{aligned} \quad (\text{C.13})$$

where the first term represents the emission from domestic production (i.e. excluding exports) and the second term represents imported emissions from the other countries.

#### C.4.2.2.3 Direct and Indirect emissions in a multi-directional trade model

Multi-directional trade models require a commodity trade-flow matrix on a bilateral basis for all the countries included in the model. In this way the structure of international trade is modelled as detailed as the industrial relationships in the well-known A-matrix. To set up a consumer responsibility account in a multi-regional model  $\Omega_{MD,\sigma}^{CR}$  we calculate the direct and indirect emissions of industries for country 1 in a multi-lateral setting  $\sigma_{MD,ind}^{CR}$  very similar to (C.13), that is

$$\sigma_{MD,ind}^{CR} = \begin{pmatrix} \mathbf{c}^1 \mathbf{E}_{ind}^1 & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{c}^2 \mathbf{E}_{ind}^2 & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{c}^3 \mathbf{E}_{ind}^3 \end{pmatrix} \quad (C.14)$$

$$\left[ \begin{pmatrix} \mathbf{I} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \mathbf{A}^{13} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{A}^{23} \\ \mathbf{A}^{31} & \mathbf{A}^{32} & \mathbf{A}^{33} \end{pmatrix} \right]^{-1} \begin{pmatrix} \mathbf{y}^{11} \\ \mathbf{y}^{21} \\ \mathbf{y}^{31} \end{pmatrix}$$

Note that no other final demand vectors are included as we are only interested in the emission account of country 1 here. If we wanted to set up the emission accounts for country 2 and 3 as well, we would need to add two additional columns to the final demand vector. Differences in results between (C.12) and (C.14) are due to the full interlinkage of the model, which gives rise to inter-country feedbacks as mentioned before.

To set up a country consumer responsibility CO<sub>2</sub> account in a multi-regional model  $\Omega_{MD,\sigma}^{CR}$  for country  $j$ , we can write in a generalised way for the  $n$ -country case,

$$\begin{aligned} \Omega_{MD,\sigma}^{CR} &= \sigma_{MD,ind}^{CR} + \delta_{fd} = \\ &= \mathbf{c}^j \left[ \mathbf{E}_{fd}^j \mathbf{y}^j + \mathbf{E}_{ind}^j (\mathbf{I} - \mathbf{A}^j)^{-1} \mathbf{y}^j \right] \\ &\quad + \sum_{\substack{i=1 \\ i \neq j}}^I \mathbf{c}^i \mathbf{E}_{ind}^i \left[ (\mathbf{I} - \mathbf{A}^i)^{-1} \mathbf{y}^i + (\mathbf{I} - \mathbf{A}^j)^{-1} \mathbf{y}^j + (\mathbf{I} - \mathbf{A}^j)^{-1} \mathbf{y}^j \right] \end{aligned} \quad (C.15)$$

## C.5 DATA DESCRIPTION

In Section C.6 each of the CO<sub>2</sub> account models will be estimated by using a dataset including input-output data for five countries: Denmark, Germany, Sweden, Norway and Australia representing the rest of the world (ROW). We use a generalised, multi-regional input-output model in a make and use formulation. From a methodological point of view the model is discussed in detail in (Lenzen et al. 2002, 2004). Here the most important estimation processes and assumptions are briefly reviewed.

Region	Input-output data			Energy and CO <sub>2</sub> data	
	$n_r$	$m_r$	Source	$f_r$	Source
Denmark	133	128	Statistics Denmark, 1999	40	Statistics Denmark, 1999
Germany	59	59	Statistisches Bundesamt, 2002b	37	Statistisches Bundesamt, 2002a www.umweltbundesamt.de
Sweden	39	39	Statistiska Centralbyran, 2002	23	Statistiska Centralbyran, 2002
Norway	118	229	Statistisk Sentralbyra, 2002	23	Statistisk Sentralbyra, 2002
ROW	106	134	Australian Bureau of Statistics, 2001	29	Australian Bureau of Agricultural and Resource Economics, 2000 Australian Greenhouse Office, 1999

Table C.1 – Data Sources and Features

Table C.1 summarises the input-output, energy and CO<sub>2</sub> data used for the model estimations in Section 6. Data are given by dimension and source, where  $m$  gives number of commodity groups and  $n$  the number of industrial sectors in the make and use tables, while  $f$  indicates the number of fuel types included by country. While Danish, German and Swedish input-output data were used unmodified, Australian data were augmented from 106 to 134 commodities (see Lenzen, 2001) and Norwegian data were compressed from 1309 to 229 commodities.

As indicated above, the rest of the world account was modelled on the basis of Australian input-output, energy and CO<sub>2</sub> statistics. This decision was mainly guided by data availability and quality, and is of course debatable. Nevertheless, this approximation is not unreasonable, since Australia features an economy that produces primary resources, manufactured goods and services. We assume that Australian energy and CO<sub>2</sub> inputs reflect world average production conditions, except for beef-cattle grazing and forestry, where CO<sub>2</sub> emissions from land use changes were excluded, and except for electricity generation, aluminium, basic iron and steel manufacturing, for which world average energy and CO<sub>2</sub> intensities were derived from previous studies (Lenzen and Dey, 2000; Michaelis et al., 1998; Wenzel et al., 1999; Worrell et al., 1997; World Bureau of Metal Statistics, 2001).

Bilateral trade flow matrices were estimated from OECD trade statistics (OECD, 2001) exclusively using non-survey techniques (Miller and Blair, 1985; Furukawa, 1986; Madsen and Jensen-Butler, 1999; Lenzen et al., 2004). For remaining commodities and (mainly) services not included in the OECD trade statistics, economy-wide constant trade coefficients were assumed. Imports from the ROW were calculated residually by subtracting imports from Denmark, Germany, Sweden and Norway from total imports as shown in the respective input-output tables. As national input-output tables do not show the same dimension we used transformation matrices obtained by scrutinizing handbooks

to link trade flow matrices to the national input-output classifications of the exporting (row) and importing (column) country. Valuation and classification issues were resolved by applying economy-wide basic price/f.o.b./c.i.f. ratios (see Ahmad and Wyckhoff, 2003) and using conversion matrices from Harmonised ITCS system into national trade statistics and vice versa (see Hayami et al., 1999). Currencies were treated in a mixed unit approach, in which the national production and final consumption data including exports are in national currencies, while trade flow matrices are in mixed units. As the trade data were recorded in US \$ currency conversion rates were applied to convert it into the exporting countries currency.

Emissions data were restricted to CO<sub>2</sub> which makes the main part of all greenhouse gases. Moreover, only the CO<sub>2</sub> emissions from energy use have been included. Whether bio-fuels/renewables are assigned a positive emission coefficient or an emission coefficient of zero is a matter of definition. Performing flow analyses on an annual basis it is most consistent to consider bio-fuels having a lifecycle of one year or less as CO<sub>2</sub> neutral.<sup>9</sup> Therefore those are assigned an emission coefficient of zero. On the other hand, renewable energy sources having a lifecycle longer than one year are assigned a positive emission coefficient. In order to be consistent with this principle some adjustments of the original emission coefficients are required.

Data were finally arranged in one compound matrix of size [1204x1204] as shown in Lenzen et al. (2004) and estimated based on an industry technology assumption.

## **C.6 RESULTS AND DISCUSSION**

Table C.2 shows the Danish production CO<sub>2</sub> account broken down into 11 commodity groups for the direct and indirect part of the account and five groups of direct energy use in households. CO<sub>2</sub> emissions from household energy use account for 11.6 million tons in 1997. Model 2 accounts for direct and indirect emissions in industries split up on domestic use (column 2) and exports (column 3). Of 65.9 million tons CO<sub>2</sub> produced in Denmark exports are accounting for 19.8 million tons (30%). Exports of food, “transport and communication” and electricity are the commodity groups having the biggest impact on Danish CO<sub>2</sub> emissions, whereas domestic end use is dominated by

“electricity, gas and fuels”, “other goods and services” and “transport and communication”. Production of “electricity, gas and fuels” accounts for 27% of all Danish CO<sub>2</sub> emissions.

Model Equation no.	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	
		Domestic use	Exports
	Model 1 Eq. (C.2)	Model 2 Eq. (C.4)	
<b>Commodity groups</b>			
Food	-	3.694	6.594
Beverages and tobacco	-	325	192
Clothing and footwear	-	85	245
Housing	-	2.026	57
Electricity, gas and fuels	-	13.536	4.238
Furnishing and househ. equipm.	-	1.361	2.430
Medical products, health serv.	-	1.003	582
Purchase of vehicles	-	22	12
Transport and communication	-	4.277	4.432
Recreation and culture	-	1.596	930
Other goods and services	-	6.584	61
<b>Energy use in households</b>			
Electricity	0	-	-
Gas	1.667	-	-
Liquid fuels	3.649	-	-
Hot water, steam etc.	533	-	-
Fuels and lubricants	5.771	-	-
<b>Total</b>	<b>11.620</b>	<b>34.509</b>	<b>19.773</b>
Model Equation no.		Model 2 Eq. (C.5)	
<b>Total responsibility</b>		<b>65.902</b>	

Table C.2 - Producer CO<sub>2</sub> responsibility account for Denmark, 1997, million tons

Table C.3-C.5 are the Danish consumer CO<sub>2</sub> accounts for each of the model approaches used in the treatment of imports: Single region model, uni-directional trade model and multi-directional trade model. The consumer CO<sub>2</sub> accounts are broken down into the same groups of commodities and energy types as used in the production account. Therefore, producer and consumer responsibility can be compared at the commodity level.

<sup>9</sup> Bio-fuels with a lifecycle of one year absorb the same amount of CO<sub>2</sub> as they liberate when broken down or combusted during one year

Model Equation no.	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
	Model 1 Eq. (C.2)	Model 4 Eq. (C.8)	
<b>Commodity groups</b>			
Food	-	8.466	1.082
Beverages and tobacco	-	437	202
Clothing and footwear	-	48	789
Housing	-	1.344	38
Electricity, gas and fuels	-	13.590	365
Furnishing and househ. equipm.	-	1.186	2.333
Medical products, health serv.	-	1.162	131
Purchase of vehicles	-	0	87
Transport and communication	-	6.604	325
Recreation and culture	-	1.765	1.421
Other goods and services	-	5.801	13
<b>Energy use in households</b>			
Electricity	0	-	-
Gas	1.667	-	-
Liquid fuels	3.649	-	-
Hot water, steam etc.	533	-	-
Fuels and lubricants	5.771	-	-
<b>Total</b>	<b>11.620</b>	<b>34.509</b>	<b>6.791</b>
Model		Model 4	
Equation no.		Eq. (C.9)	
<b>Total responsibility</b>		<b>58.812</b>	

**Table C.3 - Consumer CO<sub>2</sub> responsibility account for Denmark, 1997, million tons  
Single-region model**

Total responsibility of Danish consumers is shown in the bottom row of the tables. The single-region model estimate is 58.8 million tons CO<sub>2</sub>. This figure is raised to 69.2 million tons when the uni-directional trade model is applied and further to 70.2 million tons when the multi-directional model is used. In other words, leaving the single-region approach in favour of the multi-region approach is having a significant impact on national responsibility. In the case of Denmark the CO<sub>2</sub> trade balance turns from a surplus of 7.1 million tons into a deficit of 4.3 million tons when the multi-trade model is used.

Model Equation no.	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
	Model 1 Eq. (C.2)	Model 6 Eq. (C.12)	
<b>Commodity groups</b>			
Food	-	9.602	348
Beverages and tobacco	-	496	1.126
Clothing and footwear	-	65	1.058
Housing	-	1.654	125
Electricity, gas and fuels	-	13.895	1.056
Furnishing and househ. equipm.	-	1.600	2.965
Medical products, health serv.	-	1.459	1.646
Purchase of vehicles	-	0	2.126
Transport and communication	-	8.521	198
Recreation and culture	-	2.131	743
Other goods and services	-	6.668	62
<b>Energy use in households</b>			
Electricity	0	-	-
Gas	1.667	-	-
Liquid fuels	3.649	-	-
Hot water, steam etc.	533	-	-
Fuels and lubricants	5.771	-	-
<b>Total</b>	<b>11.620</b>	<b>46.091</b>	<b>11.453</b>
Model		Model 6	
Equation no.		Eq. (C.13)	
<b>Total responsibility</b>		<b>69.164</b>	

**Table C.4 Consumer CO<sub>2</sub> responsibility account for Denmark, 1997, million tons  
Uni-directional trade model**

It is interesting to make two kinds of comparisons at sector level: *First*, to detect the influence of the technology assumptions by using a single-region model as compared to a multi-region model and *second*, to see the influence of applying consumer responsibility as compared to producer responsibility.

CO<sub>2</sub> emissions from all commodity groups are affected by changing the technology assumptions, but not in the same way. When estimated by the multi-region approach the following commodity groups make a better performance, i.e. have lower CO<sub>2</sub> emissions: "Food", "transport and communication" and "recreation and culture". The remaining commodity groups make a poorer performance. What is surprising is the magnitude of difference for some commodity groups: "Beverages and tobacco", "Furnishing and household equipment", "Medical products and health services" and, not least, "Purchase of vehicles" are examples of differences in the range of 1-2 million tons CO<sub>2</sub> emissions. These comparisons on commodity level indicate that global CO<sub>2</sub> emissions could be reduced if international trade was based on environmental concerns.



This issue is addressed in a paper by Pade (2004). Inhomogeneity in the commodity groups compared cross-national might of course result in biased results. More precise information about differences in CO<sub>2</sub> embodiments will occur if a more detailed commodity level is applied in the analyses.

Model Equation no.	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
	Model 1 Eq. (C.2)	Model 7 Eq. (C.14)	
<b>Commodity groups</b>			
Food	-	9.715	349
Beverages and tobacco	-	502	1.185
Clothing and footwear	-	65	1.066
Housing	-	1.679	130
Electricity, gas and fuels	-	13.901	1.105
Furnishing and househ. equipm.	-	1.635	3.187
Medical products, health serv.	-	1.474	1.652
Purchase of vehicles	-	0	2.236
Transport and communication	-	8.677	220
Recreation and culture	-	2.165	802
Other goods and services	-	6.772	79
<b>Energy use in households</b>			
Electricity	0	-	-
Gas	1.667	-	-
Liquid fuels	3.649	-	-
Hot water, steam etc.	533	-	-
Fuels and lubricants	5.771	-	-
<b>Total</b>	<b>11.620</b>	<b>46.585</b>	<b>12.011</b>
Model Equation no.		Model 7 Eq. (C.15)	
<b>Total responsibility</b>		<b>70.216</b>	

Table C.5 - Consumer CO<sub>2</sub> responsibility account for Denmark, 1997, million tons  
Multi-directional trade model

Making the comparison between producer and consumer responsibility<sup>10</sup> at commodity level shows that “electricity, gas and other fuels” is still a case to point out. This commodity group comes out with the biggest difference in CO<sub>2</sub> emission when comparing the two accounting principles. As producer responsibility exceeds consumer responsibility by 2.7 million tons the problem of net CO<sub>2</sub> exports pointed out for 1990 still remains in the Danish 1997 accounts. However, this surplus is more than

<sup>10</sup> The comparison is made by adding “direct and indirect emissions” and “export” in the producer account, respectively “indirect emissions” and “import” in the consumer account.

counterbalanced by other commodity groups accounting for a trade deficit, e.g. “beverages and tobacco”, “furnishing and household equipment”, “medical products and health services” and “purchase of vehicles” – each having a net deficit of more than 1 million tons of CO<sub>2</sub>. Consequently, only making corrections for electricity trade without taking into account other commodities is making a significant error if the principle of consumer responsibility is generally applied.

## **C.7 MODEL APPLICATIONS FOR POLICY ANALYSIS**

Since the influence of greenhouse gas emissions on the global temperature has been detected there has been a need to account for the amount of CO<sub>2</sub> emitted to the atmosphere. Moreover, international agreements on the reduction of greenhouse gases presuppose the existence of an accounting framework implemented in each of the countries participating in the agreement. Further, this accounting framework has to meet some common characteristics agreed upon, e.g. about accounting principles to be used, data sources and consistency. Presently, national CO<sub>2</sub> emissions based on the principle of producer responsibility (Model 1) are reported to the Intergovernmental Panel on Climate Change (IPCC). According to this principle a country is held responsible for all emissions on its own territory.

A specific case on power market integration is illustrating the importance of developing international standards for the accounting of national CO<sub>2</sub> emissions, cf. Lenzen et al. (2004). In 1990 – the Kyoto Protocol basic year – Denmark imported a substantial amount of electricity from Norway thus reducing Danish CO<sub>2</sub> emissions to a figure much below average. As a result, electricity import had an indirect influence on the amount of Danish CO<sub>2</sub> emissions allowed according to the Kyoto Protocol. Facing this drawback the Danish energy administration decided to adjust Danish CO<sub>2</sub> emission figures for the influence of foreign electricity trade (Danish Energy Agency, 2003).

A major shortcoming of the Danish accounting principle is, however, that CO<sub>2</sub> emissions from electricity export are not accounted for by the importing country (i.e. primarily Norway), and consequently nobody is held responsible for the corresponding amount of CO<sub>2</sub>. Moreover, by only adjusting for one commodity (electricity) the Danish accounting principle is a hybrid between the producer and consumer principle. A full implementation of consumer responsibility means that adjustment should include all

commodities traded between countries. This lack of consistency demonstrates the need for elaborating international standards for CO<sub>2</sub> accounting.

This illustrative case of conflict between national CO<sub>2</sub> targets and power market integration highlights the general problem of trade between open economies, which face CO<sub>2</sub> targets. The results in Section 6 show that a significant amount of CO<sub>2</sub> is embodied in commodities traded between countries. Countries with net CO<sub>2</sub> exports might push the issue of considering the CO<sub>2</sub> trade balance in order to receive a CO<sub>2</sub> discount for emissions accounted for in the baseline scenario applied for the national CO<sub>2</sub> target. Taking such imbalances in foreign trade into account might reduce the reluctance of some open economies to accept a certain baseline for CO<sub>2</sub> emissions when negotiating future agreements on the allocation of national reduction targets.

The concept of a CO<sub>2</sub> trade balance making explicit the difference between embodied CO<sub>2</sub> in exports and imports (Munksgaard and Pedersen, 2001) could have implications for future negotiations on CO<sub>2</sub> reduction strategies, which might call for a reliable methodology for assessing greenhouse gases embodied in international trade. This need is also stressed by a recent study (Ahmad and Wyckoff, 2003) in which the principles of producer and consumer responsibility as well as the concept of a CO<sub>2</sub> trade balance have been adopted.

What kind of accounting model is the most appropriate to use? The choice of model can be discussed briefly in terms of the distinction between single-region and multi-region models as well as in terms of direct and direct and indirect models.

As long as the producer responsibility principle is applied, there is no reason to put a lot of effort into the highly labour-intensive task of building up a multi-regional model as both models deliver identical results. However, as soon as the consumer responsibility principle is adopted and import-related emissions enter the scope of the enquiry, multi-regional models seem superior to single-region models as they account for the differences in technology between exporting and importing countries. The bias associated with single-regional consumer responsibility models has been assessed by Lenzen et al. (2002; 2004). However, single-region models can certainly be the appropriate model choice when we move away from the sphere of emission accounting. Machado et al. (2001), for example, draw direct attention towards the assessment of a country “saves” or “displaces” of emissions, as a country does not produce all imported goods domestically. Such information cannot be provided by a multi-regional model.

At present Statistics Denmark applies a single-region approach to estimate the embodiments in Danish imports. The result is a CO<sub>2</sub> account showing so-called “global emissions” from Danish consumption (Statistics Denmark, 2004). Our calculations show, however, that even without taking into account the technologies actually used in developing countries it makes quite a difference for the estimation of consumer CO<sub>2</sub> responsibility if a multi-region or a single-region approach is used. We expect that developing countries will differ much more technologically from Danish technologies than the countries included in the case study. The assumption that the Danish technologies are representative of the production technologies in the import countries is therefore highly questionable, pointing to a need for developing a multi-region approach at the international level, which is able to estimate reliable national CO<sub>2</sub> accounts.

The choice between direct and “direct and indirect” models is mainly determined by the analyses to be made. If only the aggregate emission account needs to be set up, estimating direct emissions is certainly the easiest way to do so. Moreover, if a breakdown on sectors is needed in order to record pollution at the source, direct emission formulation is the appropriate choice as well. However, as soon as the aim is to assess CO<sub>2</sub> emissions according to the final purpose of consumption activities, the direct and indirect emission formulation is the one to go for.

What is the specific policy relevance of each of the models developed in Section C.4?

Model 1 on direct emissions from production is the one actually agreed upon for reporting national CO<sub>2</sub> emissions under the Kyoto agreement. The model serves the need to identify who is the actual emitter of CO<sub>2</sub> from combusting fuels. Thereby the model could be used to target a CO<sub>2</sub> reduction policy based on CO<sub>2</sub> taxes on energy use or CO<sub>2</sub> permissions. High direct CO<sub>2</sub> emissions will be an indicator for the tax burden to bear when a CO<sub>2</sub> tax regime is introduced.

Model 2 on direct and indirect emissions from production is a lifecycle approach to account for the emissions of CO<sub>2</sub> in production. The result of the model calculation is CO<sub>2</sub> emission multipliers. Comparing these at detailed sector or commodity level makes it possible to identify production activities having a high environmental impact. This kind of information is relevant for drawing up green accounts at industry level.

Model 3 to 7 are models within the consumer responsibility approach. Consequently, all models are accounting for the CO<sub>2</sub> embodiments of goods and services at end use level. Model 3 accounts for direct emissions in a single-region setting.

Compared to model 1 this model is not taking into account direct CO<sub>2</sub> emissions from exports, whereas direct emissions in imports to the country considered are accounted for. This model approach highlights the environmental impacts from trade on national CO<sub>2</sub> emissions. The direct CO<sub>2</sub> burden (or savings) from trade can be estimated by subtracting model 3 by model 1. Without taking into account indirect emission effects this figure shows whether trade is conflicting with a national CO<sub>2</sub> target.

Model 4 on direct and indirect emissions in a single-region model is the approach actually used by Statistics Denmark to account for the “global emissions” of consumption (final demand) in Denmark. As stressed in the previous sections this approach relies on the assumption that the technologies applied in importing countries are identical to Danish industry technologies. Obviously, this is not true. The model, however, is an appropriate means to account for savings in domestic CO<sub>2</sub> emissions from imports, but the model is only a rough indicator for the actual global impact from domestic consumption.

Model 5 estimates direct emissions based on a multi-region trade model.

Model 6 on direct and indirect emissions from uni-directional trade is founded in a multi-regional dataset including national input-output, energy and environmental statistics for some or all of the importing countries. Consequently, CO<sub>2</sub> emissions from imports are estimated by using country-specific data for the production technologies used in the industries actually producing the products consumed in the country considered. Being “uni-directional” implies, however, that this model approach is taking into account only first order trade effects.

Model 7 on direct and indirect emissions from multi-regional trade is the model to be recommended for making national consumer accounts as the model also considers indirect trade effects from domestic consumption. Thereby, this model is a comprehensive approach to a full lifecycle assessment of the global emissions from domestic consumption. This model is relevant for the discussion of the responsibility of nations for reducing global CO<sub>2</sub> emissions. The model is also suitable for analysing the CO<sub>2</sub> impacts from international trade.

Of course the choice of model to be used within the consumer approach is also a question of data access. Not many countries supply the kind of detailed data needed for such a kind of modelling. Even if this was so, then it is not a straightforward task to build up a consistent multi-regional dataset. This points to a need for elaborating multinational models like GTAP (Global Trade Analysis Project, cf. Hertel, 1997) to be used for

national CO<sub>2</sub> accounts. Such models, however, have to be agreed upon by the countries participating in international agreements. As conflicting interests might occur between actual CO<sub>2</sub> exporting and importing countries, this is of course not an easy task.

## **C.8 CONCLUSION**

The survey made in this study shows that the concept of national CO<sub>2</sub> responsibility has gained increasing interest in the literature. Inspired by lifecycle assessment at microeconomic level a macroeconomic approach to consumer responsibility has been taken in a range of studies in which input-output models are used to estimate national CO<sub>2</sub> emissions. Consumer responsibility says that final demand (consumption) is responsible for all upstream CO<sub>2</sub> emissions from domestic as well as foreign production activities.

In the growing field of interest for national CO<sub>2</sub> responsibility there is a need for a formal treatment of the different accounting principles applied. In this paper we have developed alternative models to account for national CO<sub>2</sub> emissions. Besides the fundamental distinction between producer and consumer responsibility the models also distinguish between direct and indirect emissions. The full accounting of all indirect emissions upstream in production is one of the benefits from using input-output modelling. The treatment of imports is essential when consumer responsibility is considered and requires international trade statistics, and national input-output tables, energy and CO<sub>2</sub> accounts. If data are restricted to national sources a first step approach is to use a single-region model assuming imports to be produced with production technologies similar to the domestic technologies. If input-output tables, energy and environmental data are accessible for countries of imports a multi-regional model approach is recommended. Most in line with traditional input-output modelling is to use a multi-directional trade model taking into account induced trade effects ad infinitum. Thereby international trade relationships are treated similar to industry relationships in the traditional single-region model applying the Leontief inverse matrix.

The developed accounting models have been used to estimate Danish 1997 CO<sub>2</sub> emission accounts by using a five country dataset. Results show that Danish consumers are responsible for more CO<sub>2</sub> emissions than Danish producers. A difference of 4.3 million tons CO<sub>2</sub> between the two accounts points to an equivalent deficit on the Danish

CO<sub>2</sub> trade balance. Results also indicate that the proper treatment of imports is a key issue if an international framework for consumer responsibility is to be implemented. Danish CO<sub>2</sub> consumer responsibility is increased by more than 10 million tons when substituting the single-region by the multi-region trade approach. The difference between the two alternative multi-trade approaches, however, only amounts to 1 million tons CO<sub>2</sub>.

Results for Denmark are based on a dataset including the technologies of some main trading partners. Ideally, all trading partners should be considered. However, this calls for a huge amount of data including countries not even having the kind of data needed. Besides data accessibility the challenge to integrate different data sources within a uniform framework exists. This is a huge task for national statistical bureaus and points to a need for establishing an international model approach like the GTAP model developed for analysing international trade issues.

To conclude, we highly recommend the development of national CO<sub>2</sub> accounting models based on different approaches to responsibility and equity. Such models are of relevance for future climate negotiations facing different positions on the interpretation of equity and fairness. Many open economies like Denmark will have the position that in order to achieve equitable reduction targets, international trade has to be taken into account when assessing nations' responsibility for abating climate change.

## C.9 REFERENCES

- Ahmad, N., 2002, The OECD Input-Output Database, Paper presented at the 14<sup>th</sup> International Conference on Input-Output Techniques, 10-15 October, Montreal.
- Ahmad, N. and Wyckhoff, A., 2003, Carbon Dioxide Emissions Embodied in International Trade of Goods, *STI Working Paper Series DST/DOC (2003) 15*, OECD, Paris, <http://www.oecd.org/sti/working-papers>.
- Australian Greenhouse Office, 1999, *Australia's National Greenhouse Gas Inventory*, Internet site (Australian Greenhouse Office).
- Bastianoni, S., Pulselli, F.M. and Tiezzi, E., 2004, The Problem of Assigning Responsibility for Greenhouse Gas Emissions, *Ecological Economics* 49: 253-257.
- Battjes, J.J., Noorman, K.J., and Biesiot, W., 1998, Assessing the energy intensities of imports, *Energy Economics* 20: 67-83.
- Bin, S. and Dowlatabadi, H., 2005, Consumer Lifestyle Approach to US Energy Use and the Related CO<sub>2</sub> Emissions, *Energy Policy* 33(2): 197-208.
- Blancas, A., 2000,, A Dynamic Input-Output Model of NAFTA's Effects on Pollution, Paper presented at International Conference on Input-Output Techniques, 21-25 August, Macerata, Italy.
- Bullard, C., Penner, P. and Pilati, P., 1978, Net Energy Analysis: A Handbook for Combining Process and Input-Output Analysis, *Resources and Energy* 1(3): 267-313.
- Burniaux, J.M. and Truong, T.P., 2002, GTAP-E – An Energy-Environmental Version of the GTAP Model, *GTAP Technical Papers* 16. <http://www.gtap.agecon.purdue.edu/resources/download/1203.pdf>
- Chang, Y.F. and Lin, S.J., 1998, Structural Decomposition of Industrial CO<sub>2</sub> Emissions in Taiwan. An Input-Output Approach, *Energy Policy* 26(1): 5-12.
- Cohen, C., Lenzen, M. and Schaeffer, R., 2005, Energy Requirements of Households in Brazil, *Energy Policy* 33(4): 555-562.
- Common, M.S. and Salma, U., 1992, Accounting for Changes in Australian Carbon Dioxide Emissions, *Energy Economics* 14(3): 217-225.
- Danish Energy Agency, 2003, *Energy Statistics 2002*, Section of Statistics, (Danish Energy Agency, Copenhagen).
- Daly, H., 1968, On Economics as a Life Science, *Journal of Political Economy* 76(3): 392-406.
- De Haan, M., 2002, Disclosing International Trade Dependencies in Environmental Pressure Indicators. The Domestic Consumption Perspective, Paper presented at the International Input-Output Conference, 10-15 October, Montreal.
- Eurostat, 2003, *International Trade in Services 1992-2001. Compilation Guide*, European Commission, Office for Official Publication of the European Communities, Luxembourg
- Ferng, J.J., 2003, Allocating the Responsibility of CO<sub>2</sub> Over-Emission from the Perspectives of Benefit Principle and Ecological Deficit, *Ecological Economics* 46: 121-141.
- Furukawa, S., 1986, *International Input-Output Analysis. Compilation and Case Studies of Interaction Between ASEAN, Korea, Japan and the United States, 1975*, *IDE Occasional Paper Series* 21, Institute of Developing Economics, Tokyo.
- Gale, L.R., 1995, Trade Liberalisation and Pollution. An Input-Output Study of Carbon Dioxide Emissions in Mexico, *Economic Systems Research* 7(3): 309-320.
- Gay, P.W. and Proops, J.L.R., 1993, Carbon-Dioxide Production by the UK Economy. An Input-Output Assessment, *Applied Energy* 44(2): 113-130.
- GTAP, 2003, *Towards an Integrated Data Base for Assessing the Potential for Greenhouse Gas Mitigation*. [http://www.gtap.agecon.purdue.edu/databases/projects/Land\\_Use\\_GHG/default.asp](http://www.gtap.agecon.purdue.edu/databases/projects/Land_Use_GHG/default.asp)
- Harris, R., 2001, Methods for Estimating Air Emissions from the Production of Goods Imported into the UK, *Eurostat Working Paper* 2/2001/B/5, <http://europa.eu.int/eurostat.html>
- Hayami, H. and Kiji, T., 1997, An Input-Output Analysis on Japan-China Environmental Problem, *Journal of Applied Input-Output Analysis* 4: 23-47.



- Hayami, H., Nakamura, M., Asakura, K. and Yoshioka, K., 1999, The Emissions of Global Warming Gases. Trade Between Canada and Japan, in: Canadian Economics Association Annual Meeting, University of Toronto, Canada.
- Hayami, H. and Nakamura, M., 2002, CO<sub>2</sub> Emission of Alternative Technology and Bilateral Trade between Japan and Canada, *KEIO Economic Observatory Discussion Paper No. 75*, Keio University, Japan
- Hendrickson, C. Horvath, A., Joshi, S. and Lave, L.B., 1998, Economic Models for Input-Output Lifecycle Analysis, *Environmental Science and Technology* 29(9): 184A-191A.
- Hertel, T.W., 1997, Global trade analysis: modeling and applications, Cambridge University Press.
- Hetherington, R., 1996, An Input-Output Analysis of Carbon Dioxide Emissions for the UK, *Energy Conversion Management* 37(6-8): 979-984.
- Joshi, S., 2000, Product Environmental Life Cycle Assessment Using Input-Output Techniques, *Journal of Industrial Ecology* 3(2-3): 95-120.
- Just, J., 1974, Impacts of New Energy Technology Using Generalized Input-Output Analysis, in: Macrakis, M. (ed.), *Energy*, MIT Press, Cambridge.
- Kim, J.H., 2002, Changes in Consumption Patterns and Environmental Degradation in Korea, *Structural Change and Economic Dynamics* 13: 1-48.
- Kondo, Y., Moriguchi, Y. and Shimizu, H., 1998, CO<sub>2</sub> Emissions in Japan. Influences of Imports and Exports, *Applied Energy* 59(2-3): 163-174.
- Lenzen, M., 1998, Primary Energy and Greenhouse Gases Embodied in Australian Final Consumption. An Input-Output Analysis, *Energy Policy* 26(6): 495-506.
- Lenzen, M., 2001, A Generalised Input-Output Multiplier Calculus for Australia, *Economic Systems Research* 13(1): 65-92.
- Lenzen M, L-L Pade and J Munksgaard, 2002, CO<sub>2</sub> multipliers in multi-region input-output models. Fourteenth International Conference on Input-Output Techniques, Montreal, October 10-15, 2002.
- Lenzen M, Pade, L-L and Munksgaard J, 2004, CO<sub>2</sub> multipliers in multi-region input-output models. *Economic Systems Research* 16(4), December 2004.
- Lenzen. M. and Dey, C.J., 2000, Truncation Error in Embodied Energy Analysis of Basic Iron and Steel Products, *Energy* 25: 577-585.
- Leontief, W., 1970, Environmental Repercussions and the Economic Structure. An Input-Output Approach, *The Review of Economics and Statistics* 52(3): 262-271.
- Machado, G.V., 2000, Energy Use, CO<sub>2</sub> Emission and Foreign Trade. An IO Approach Applied to the Brazilian Case, Paper presented at the International Conference on Input-Output Techniques, 21-25 Aug., Macerata, Italy.
- Machado, G.V., Schaeffer, R. and Worrel, E., 2001, Energy and Carbon Embodied in the International Trade of Brazil: An Input-Output Approach, *Ecological Economics* 39: 409-424.
- Madsen, B. and Jensen-Butler, C., 1999, Make and Use Approaches to Interregional Accounts and Models, *Economic Systems Research* 11(3): 277-299.
- Matthews, S., 1999, The External Cost of Air Pollution and the Environmental Impact of the Consumer in the US Economy, PhD Thesis, Graduate School of Industrial Administration, Carnegie Mellon University, Pittsburgh.
- Michaelis, P., Jackson, T. and Clift, R., 1998, Exergy Analysis of the Lifecycle of Steel, *Energy* 23(3): 213-220.
- Miller, R.E. and Blair, P.D., 1985, Input-Output Analysis. Foundations and Extensions, Prentice Hall, Englewood Cliffs, NJ, USA.
- Munksgaard, J. and Pedersen, K., 2001, CO<sub>2</sub> Accounts for Open Economics. Producer or Consumer Responsibility?, *Energy Policy* 29: 327-334.
- Munksgaard, J., Pedersen, K.A. and Wier, M., 2000, Impact of Household Consumption on CO<sub>2</sub> Emissions, *Energy Economics* 22: 423-440.
- Nielsen, A.M. and Weidema, B.P. (eds.), 2001, Input-Output Analysis. Shortcuts to Lifecycle Data? Danish Environment Protection Agency, Environment Project No. 581, Papers presented at a Workshop in Copenhagen on 29<sup>th</sup> September.
- OECD, 2001, ITCS International Trade by Commodity Statistics, Harmonised System 88, 1990-2000, 4 CD Rom, OECD.
- Pachauri, S. and Spreng, D., 2002, Direct and Indirect Energy Requirements of Households in India, *Energy Policy* 30: 511-523.

- Pade, LL., 2004, Restructuring international trade regarding CO<sub>2</sub> reductions – Is there anything to learn from best practice? Conference paper presented at IAEE annual conference in Teheran May 2004.
- Proops, J.L.R., 1977, Input-Output Analysis and Energy Intensities. A Comparison of Some Methodologies, *Applied Mathematical Modelling* 1(4): 181-188.
- Proops, J.L.R., Faber, M. and Wagenhals, G., 1993, Reducing CO<sub>2</sub> Emissions. A Comparative Input-Output Study for Germany and the UK, Springer Verlag, Berlin.
- Sánchez-Chóliz, J. and Duarte, R., 2004, CO<sub>2</sub> Emissions in International Trade. Evidence for Spain, *Energy Policy* 32(18): 1999-2005.
- Schaeffer, R. and De Sá, A.L., 1996, The Embodiment of Carbon Associated with Brazilian Imports and Exports, *Energy Conversation Management* 37(6-8): 955-960.
- Statistics Denmark, 1999, *Input-output tables* (in Danish: Input-output tabeller), Electronic file (unpublished), Danmarks Statistik.
- Statistics Denmark, 2004, Danish Input-Output Tables and Analysis 2002 – Imports, Employment and Environment. Statistics Denmark, Copenhagen.
- Statistisches Bundesamt, 2002a, *Umweltökonomische Gesamtrechnung: Material- und Energieflussrechnung 2001*, Fachserie 19, Reihe 5 (Metzler-Poeschel, Stuttgart, Germany).
- Statistisches Bundesamt, 2002b, *Volkswirtschaftliche Gesamtrechnung: Input-Output-Rechnung 1997*, Fachserie 18, Reihe 2 (Metzler-Poeschel, Stuttgart, Germany).
- Statistisk Sentralbyrå, 2002, *Input-output tables and energy statistics*, Electronic files (unpublished) (Statistics Norway).
- Statistiska Centralbyrån, 2002, *Input-output tables and energy statistics*, Electronic files (unpublished) (Statistics Sweden).
- Treloar, G., 1997, Extracting Embodied Energy Paths from Input-Output Tables. Towards an Input-Output Based Hybrid Energy Analysis Method, *Economic Systems Research* 9: 375-391.
- van der Linden, J.A. and Oosterhaven, J., 1995, European Community intercountry input-output analysis: construction method and main results for 1965-85, *Economic Systems Research*, 7(3): 249-269.
- Victor, P.A., 1972, Pollution. Economy and Environment, George Allen and Unwin Ltd, London.
- Vringer, K. and Blok, K., 1995, The Direct and Indirect Energy Requirements of Households in the Netherlands, *Energy Policy* 23(10): 893-910.
- Weber, C. and Perrels, A., 2000, Modelling Lifestyle Effects on Energy Demand and Related Emissions, *Energy Policy* 28: 549-566.
- Wenzel, P., Wenzel, B. and Wagner, H.J., 1999,, Laenderspezifische Strombereitstellungs- und CO<sub>2</sub> Emissionsfaktoren, *Energiewirtschaftliche Tagesfragen* 49(7): 432-437.
- World Bureau of Metal Statistics, 2001, Metal Statistics 1990-2000, World Bureau of Metal Statistics, Ware, UK.
- World Trade Organisation, 2000, International Trade Statistics 2000, WTO Publications, Geneva.
- Worrel, E., K. Price, N. Martin, J. Farla and R. Schaeffer, 1997, Energy Intensity in the Iron and Steel Industry. A Comparison of Physical and Economic Indicators, *Energy Policy* 25(7-9): 727-744.
- Wyckhoff, A.W. and Roop, J.M., 1994, The Embodiment of Carbon in Imports of Manufactured Products. Implications for International Agreements on Greenhouse Gas Emissions, *Energy Policy* 22(3): 187-184.
- Yabe, N., 2004, An Analysis of CO<sub>2</sub> Emissions of Japanese Industries during the Period between 1985 and 1995, *Energy Policy* 32: 595-610.
- Young, C.E.F, 2000, International Trade and Industrial Emissions in Brazil. An Input-Output Approach, Paper presented at the International Conference on Input-Output Techniques, 21-15 August, Macerata, Italy.

# **D INFLUENCE OF TRADE ON NATIONAL CO<sub>2</sub> EMISSIONS<sup>1</sup>**

**Abstract:** International trade has an impact on national CO<sub>2</sub> emissions and consequently on the ability to fulfil national CO<sub>2</sub> reduction targets. Through goods and services traded in a globally interdependent world, the consumption in each country is linked to greenhouse gas emissions in other countries. It has been argued that in order to achieve equitable reduction targets, international trade has to be taken into account when assessing nations' responsibility for abating climate change. Especially for open economies such as Denmark, greenhouse gases embodied in internationally traded commodities can have a considerable influence on the national 'greenhouse gas responsibility'. By using input-output modelling we analyse the influence from international trade on national CO<sub>2</sub> emissions. The aim is to show that trade is the key to define CO<sub>2</sub> responsibility on a macroeconomic level and that imports should be founded in a multi-region model approach. Finally, the paper concludes on the need to consider the impact from foreign trade when negotiating reduction targets and base line scenarios.

---

<sup>1</sup> Munskgaard, J., Paade, L.-L., Minx, J. and Lenzen, M., 2005, Influence of Trade on National CO<sub>2</sub> Emissions, *International Journal of Global Energy Issues* 23(4): 324-336.

## **D.1 INTRODUCTION**

In international climate change negotiations a country is commonly held responsible for all CO<sub>2</sub> emitted from its domestic territory. In the literature this commonly applied CO<sub>2</sub> accounting method is called *territorial* or *producer responsibility*. However, this is not the only way to allocate emissions to countries. In the Montreal Protocol (UNEP, 2000) or in environmental footprinting (Wackernagel and Rees, 1996), for example, countries are held responsible for what they consume. An analogous method to account for CO<sub>2</sub> emissions has been introduced to the global warming debate under the notion of *consumer responsibility* (e.g., Munksgaard and Pedersen, 2001).

These accounting principles differ only in the treatment of CO<sub>2</sub> emissions related to imports and exports. This gives a crucial role to international trade in two respects: First, methodologically, the treatment of trade-related emissions in the model becomes a key issue. Second, politically, the way by which to account for CO<sub>2</sub> emissions becomes increasingly relevant as many countries are facing CO<sub>2</sub> reduction targets to be fulfilled.

Founded in national accounts including energy use and environmental effects input-output analysis is a good approach to the kind of modelling needed. By using such an approach this paper aims to compare different models of CO<sub>2</sub> accounting and to demonstrate how these models can be used to estimate measures of relevance to the discussion about a fair burden sharing of global CO<sub>2</sub> reductions (see Rose *et al.*, 1998; Ferng, 2003).

The structure of the paper is as follows: Section D.2 is a brief literature survey on CO<sub>2</sub> accounting and responsibility with an exemplary policy case study for energy trade in Denmark. In Section D.3 different model approaches to imports within an input-output framework are compared. Examples of using single-region models are shown in Section D.4. In Section D.5 we present examples of using multi-region models to analyse the CO<sub>2</sub> impact of trade. In Section D.6 we make a model comparison on results founded in a common data set for five regions including Denmark. Finally, Section D.7 concludes.

## D.2 CO<sub>2</sub> ACCOUNTING AND RESPONSIBILITY

The concept of Life Cycle Analysis (LCA) has shifted the borders of environmental responsibility for economic actors on the micro level. It requires not only to take onsite, but also upstream and down-stream environmental impacts into account. Therefore, complete product chains are evaluated in terms of their product outputs as key objects of analysis and environmental requirements of processes need to be transposed to those (De Haan, 2002). This has commonly been referred to as 'taking direct and indirect environmental impacts into account'.<sup>2</sup>

Environmental input-output models as introduced by authors like Daly (1968), Leontief (1970), Victor (1972) and Just (1974), among others, can take a similar lifecycle perspective on the macro level and trace pollution all along the supply chain to final demand – from the cradle to the grave.<sup>3</sup> In particular, they allow the assessment of physical inflows like fuel inputs and outflows like CO<sub>2</sub> emissions in terms of direct or indirect components and the assignment of responsibility for emissions to different institutions (or functional units) on the production and consumption end of an economy.

More recently with increasing economic interdependence of countries and interest in trade issues on the policy level and in research, input-output models have been used for shifting responsibilities for energy flows and associated CO<sub>2</sub> emissions in an additional – a national accounting – sense. Triggered by concerns about carbon leakage (Wyckhoff and Roop, 1994; Kondo and Moriguchi, 1998) and equity associated with the structure of trade relations between developing and developed countries (Schaeffer and De Sa, 1996; Machado *et al.*, 2001; Ahmad and Wyckhoff, 2003) as well as import and export structure of small open economies (Munksgaard and Pedersen, 2001), national CO<sub>2</sub> accounts have been set up by either adding CO<sub>2</sub> emissions associated with exports or imports to emissions from domestic final demand. These are two consistent, distinct ways of national CO<sub>2</sub> accounting.

---

<sup>2</sup> Direct emissions are defined here as emissions arising directly from the use of energy goods. In contrast, indirect emission arises from the use of non-energy goods and services.

<sup>3</sup> In fact, this has motivated a whole new branch of research called Environmental Input-Output Life Cycle Assessment (EIO-LCA) (see for example: Hendrickson *et al.*, 1998; Matthews, 1999; Joshi, 2001). However, it has shown to be most fruitful to combine conventional process life cycle analysis with EIO-LCA as proposed by (Bullard *et al.*, 1978) and later extended by Treloar (1997) and Lenzen (2001a) among others. For a good introduction with key references see Weidema and Nielsen (2001).

Commonly, national CO<sub>2</sub> emissions have been calculated based on the principle of *territorial* or *producer responsibility* as agreed in international climate change negotiations (IEA, 2001). In this line of thinking a country is held responsible for all emissions on its own territory. CO<sub>2</sub> is assigned to the processes actually emitting carbon to the atmosphere, *i.e.*, industrial processes, energy production and the use of fuels in households. Those processes also comprise emissions associated with exports to other countries. However, doubts have been raised in the Brazilian Proposal whether responsibility principles applied in the Kyoto Protocol are satisfactory for the majority of countries involved (Brazilian Proposal, 1997; Ahmad and Wyckhoff, 2003; Rosa *et al.*, forthcoming). From a national CO<sub>2</sub> accounting perspective an alternative is the concept of *consumer responsibility* as introduced to the literature by Munksgaard and Pedersen (2001) though other authors have discussed similar concepts under different names before as Proops *et al.* (1993) or Kondo and Moriguchi (1998) among others. Here, CO<sub>2</sub> emissions are booked to the country of final use of goods and services. Therefore, also the emissions imported directly or embodied in goods and services from foreign countries are added to a country's CO<sub>2</sub> account, whilst exports are not accounted for.

This importance of international trade with regard to CO<sub>2</sub> emissions can be illustrated by the case of electricity traded between Denmark and Norway. Whereas electricity produced in Norway has a low CO<sub>2</sub> impact due to the use of hydropower, Danish electricity production has a high CO<sub>2</sub> impact due to inputs of fossil fuels, *e.g.*, coal. Consequently, producing electricity in Denmark for exports will increase emissions of CO<sub>2</sub> from Danish territory whereas electricity exports from Norway will have no impact on emissions of CO<sub>2</sub>. This raises the question of whether the Norwegian electricity consumer or the Danish producer should be held responsible for CO<sub>2</sub> embodied in electricity exports from Denmark to Norway.

In 1990 – the Kyoto base year – Denmark imported a huge amount of electricity from Norway which reduced Danish CO<sub>2</sub> emissions in 1990 to a figure much below normal. In this way electricity import had an indirect influence on the amount of Danish CO<sub>2</sub> emissions allowed according to the Kyoto Protocol. Facing this drawback of electricity-market integration the Danish energy administration decided to adjust Danish

CO<sub>2</sub> emissions for the influence of foreign electricity trade, cf. the Danish Energy Agency (2004).<sup>4</sup>

A major drawback of the Danish accounting principle is, however, that CO<sub>2</sub> emissions from electricity export are not accounted for by the importing country (*i.e.*, primarily Norway). Thereby nobody is held responsible for the amount of CO<sub>2</sub> emitted to the atmosphere from international electricity trade. Moreover, by only adjusting for one commodity (electricity) the Danish accounting principle is a hybrid between the producer and consumer principle as proposed in the literature by Kondo and Moriguchi (1998) and Ferng (2003). A full implementation of consumer responsibility means that adjustment should include all commodities traded between countries. This lack of consistency demonstrates the need for elaborating international standards for CO<sub>2</sub> accounting and therefore also draws attention to the methodological treatment of trade in the models used to account for national emissions of CO<sub>2</sub>.

### **D.3 MODEL APPROACHES**

For input-output modelling the distinction between producer and consumer responsibility raises important data-related questions that have not been addressed very well in the literature so far. Both accounting principles have usually been applied in single-region models to estimate a country's national CO<sub>2</sub> balance (Common and Salma, 1992; Proops *et al.*, 1993; Kondo and Moriguchi, 1998; Lenzen, 1998; Munksgaard and Pedersen, 2001; Ferng, 2003; Sánchez-Chóliz and Duarte 2004). Single-region models are founded only in national data therefore assuming that imports are produced using domestic technology. While a single-region model is sound for producer responsibility accounts, only taking into account production activities inside the border of one country, national CO<sub>2</sub> inventories calculated according to the consumer responsibility principle require a multi-country model – ideally covering the whole world.<sup>5</sup> The neglect of such

---

<sup>4</sup> Adjusting for foreign electricity trade implies that actual fuel input for power production is adjusted for variations in net export of electricity, *i.e.*, actual emissions are reduced in years in which Danish net export of electricity is positive and vice versa. Besides, Danish CO<sub>2</sub> emissions are adjusted for variations in average annual temperature so that in cold years the actual emission level is reduced whereas the level is increased in warm years.

<sup>5</sup> However, it needs to be stressed that for analytical rather than accounting purposes the choice of a single region model to calculate the emissions associated with imports can certainly be an appropriate one.

methodological requirements introduces considerable error into analysis as shown by Lenzen *et al.* (2003).

However, due to data restrictions and the high workload involved in setting up multi-regional models, most studies have used single-region models and determined factor embodiments in imported commodities by applying the domestic production technology and energy-use structure. Thereby, imports are either treated exogenously to the input-output model (see Ferng, 2003; Schaeffer and de Sá 1996; Wyckhoff and Roop 1994) or endogenously (that is as an intrinsic element of the model, see Yabe, 2004; Sánchez-Chóliz and Duarte, 2003; Lenzen, 1998; Kondo and Moriguchi, 1998; Pedersen, 1996; Denton, 1975).

However, just recently, the first serious attempts have been made to estimate trade-related emissions from multi-regional models as done by Ahmad and Wyckhoff (2003) and Wyckhoff and Roop (1994) for uni-directional trade and Lenzen *et al.* (2002; 2003) for multi-directional trade.

Hence, as illustrated in Figure D.1 for five countries C1, C2, C3, C4, and C5, we find three different input-output trade models in the literature:

- *Single or autonomous regions.* In this model imported commodities are treated as if produced by domestic technologies. This means assuming that foreign industries exhibit factor multipliers that are identical to those of the domestic industries. Direct and indirect effects of production are included and no feedback trade loops are considered. This model is analysed by a single-region model as done in *e.g.*, Sánchez-Chóliz and Duarte (2004), Munksgaard and Pedersen (2001), Lenzen (1998), Pedersen (1996), Schaeffer and de Sá (1996).
- *Unidirectional trade.* In this model imported commodities are treated as produced in the countries of origin. This means considering national differences with regard to production inputs and efficiency, energy use and CO<sub>2</sub> emission coefficients. This model implies the application of a multi-region input-output model as done in *e.g.*, Ahmad and Wyckhoff (2003), Wyckhoff and Roop (1994). However, no feedback trade loops are taken into account.
- *Multi-directional trade.* This model also implies the application of a multi-region input-output model as shown in model II in Figure D.1. However,



feedback trade loops, e.g., import from country 2 to country 4 induced by export from country 4 to country 1. This model needs to be analysed by the use of a compound multi-region input-output model as is shown in Lenzen *et al.* (2002).<sup>6</sup> Note that many multi-region models do not cover explicitly the entire world and that usually the remainder is modelled as the ‘rest of the world’ region (C3 in Figure D.1).

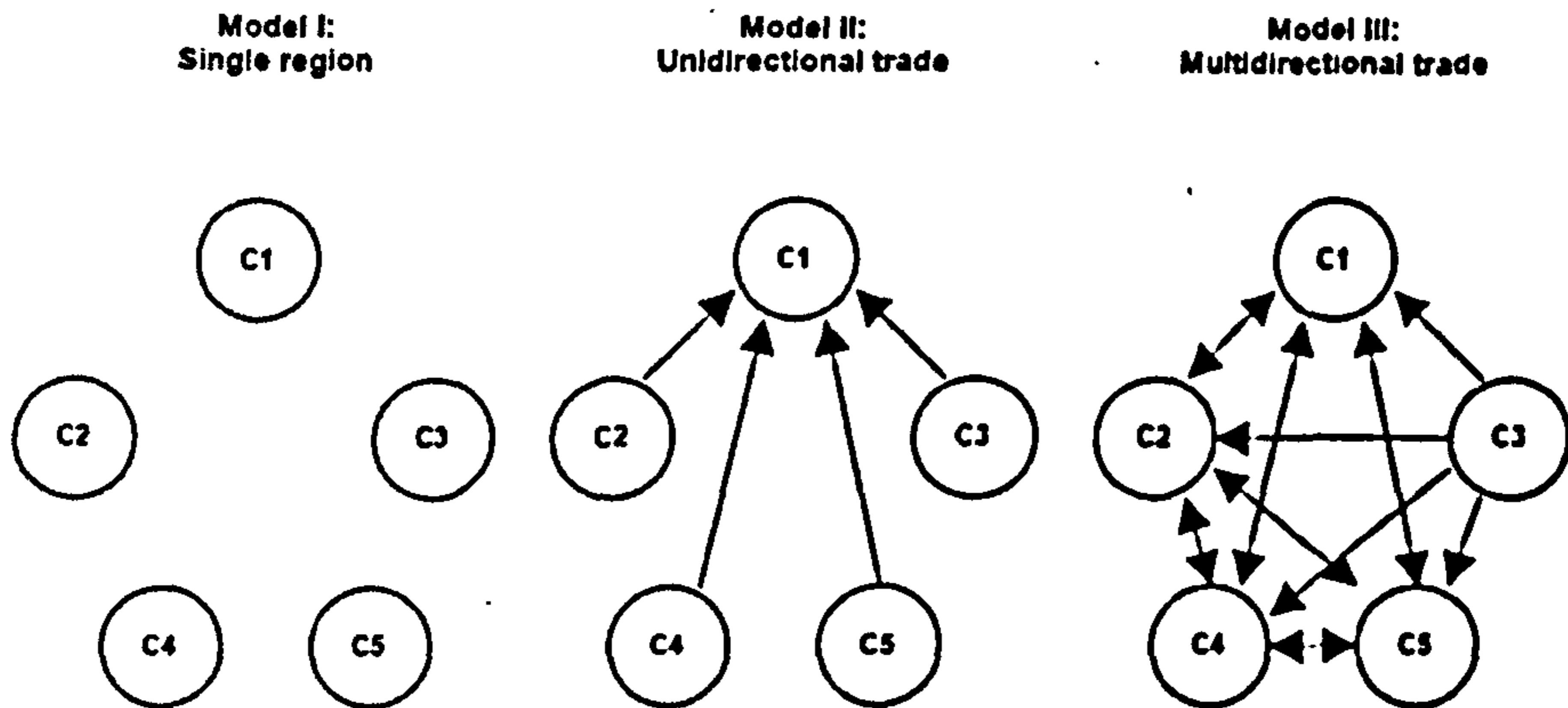


Figure D.1 - Schematic overview of three trade scenarios

Better and more comprehensive data availability due to current efforts to improve international pollution inventories (GTAP, 2003), input-output databases (Ahmad, 2002; Burniaux and Truong, 2002) and trade data (Eurostat, 2003) raise prospects that even more comprehensive modelling approaches will be presented in the near future.

#### D.4 EXAMPLES OF USING SINGLE REGION MODELS

Munksgaard and Pedersen (2001) use a noncompetitive single-region model to estimate both producer (emissions assigned to industries and direct household energy use) and consumer responsibility accounts (emissions assigned to final demand entities at various levels of disaggregation). Interestingly, they find a continuously declining trade

---

<sup>6</sup> Compound means, that the input-output matrices of all countries are combined with all environmental data in one multi-region input-output matrix, which is then inverted to calculate multipliers.

balance indicator between 1966 and 1992 with Denmark turning from a net importer to a net exporter of emission during the 1980s, cf. Figure D.2.

From 1966 to 1984 the Danish CO<sub>2</sub> trade balance showed a permanent surplus of up to 7.4 million tonnes per year. From 1989 to 1994 the CO<sub>2</sub> trade balance has changed dramatically turning into a deficit of 6.9 million tonnes in 1994 from a surplus of 0.4 million tonnes in 1987. Consequently, it has become more difficult to reach the national CO<sub>2</sub> reduction target as an increasing part of emissions from Danish territory is caused by foreign demand.

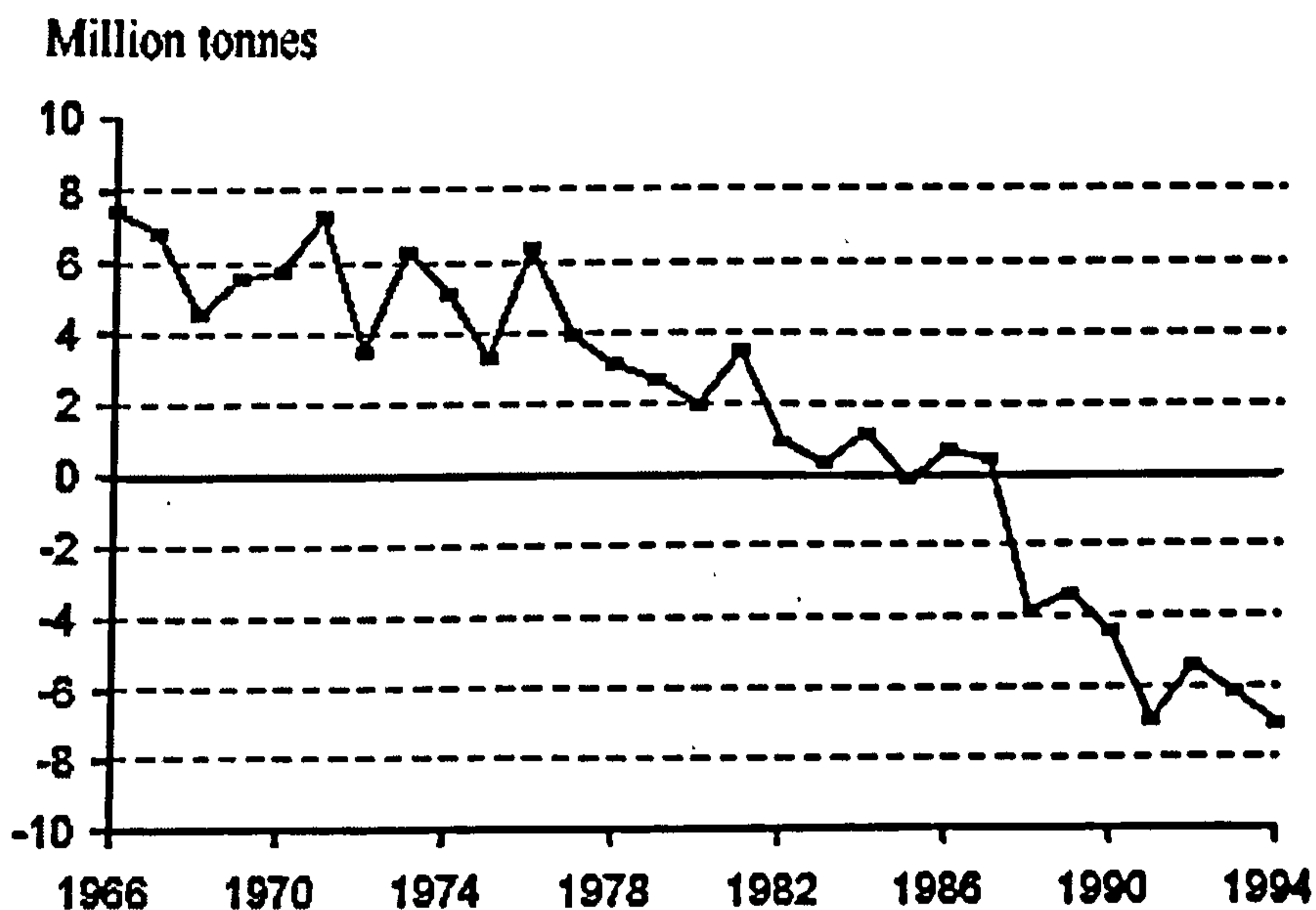


Figure D.2 – Danish CO<sub>2</sub> Trade Balance (net import of CO<sub>2</sub> from 1966-1994)

The deterioration of the CO<sub>2</sub> trade balance is connected with the increased surplus on the Danish trade balance, *i.e.*, that exports have increased more than imports during the period. Another reason is that the reduction of CO<sub>2</sub> intensity in imports has been bigger than the reduction of CO<sub>2</sub> intensity in exports, cf. Munksgaard and Larsen (1999). However, this is due to a change in the composition of imports towards less CO<sub>2</sub>-intensive commodities as foreign production technologies are assumed being identical to Danish technologies.

Therefore, they find evidence that small and open economies might be disadvantaged by current accounting practices. Using a competitive single-region model

formulation and assigning emissions to industrial sectors, Kondo and Moriguchi (1998) find that the opposite is true for Japan, which as a net importer of emissions consumes more emissions than it is held responsible for by current accounting practices. Interestingly, they propose the concept of 'attributed emissions', which is a weighted mixture differentiated by industry of producer and consumer responsibility accounting practice. Lenzen (1998) in his competitive, single-region, hybrid energy model finds that Australia is a net exporter of emissions, but warns of jumping to a conclusion highlighting the fact that it still ranks among the highest per capita CO<sub>2</sub> emitters. Differing to Kondo and Moriguchi he assigns emissions to different final demand entities as done by Munksgaard as well.

## **D.5 EXAMPLES OF USING MULTI-REGION MODELS**

Wyckhoff and Roop (1994) estimate CO<sub>2</sub> emissions embodied in trade of 21 different groups of manufactured goods. They present one of the few multi-region approaches for the assessment of carbon emissions associated with trade. In a uni-directional trade model they use input-output tables for six countries: Canada, France, Germany, Japan, UK and USA, accounting for almost half of the import flows to OECD countries, and bilateral trade flow matrices for 21 categories of manufactured goods. An extension of this study has recently been presented by OECD (Ahmad and Wyckhoff 2003). Ahmad and Wyckhoff 2003 also apply a uni-directional trade model to estimate CO<sub>2</sub> trade balances for 24 OECD countries for the year 1995. The estimates suggest that emissions associated with the domestic consumption of products are higher than the domestic production of emissions for the OECD as whole and significantly so for some countries. For many countries, the difference between the two accounting principles is often more than +/-10%.

However, a uni-directional approach does not allow accounting for interregional feedback effects as discussed in Sonis and Hewings (2001) leading to some error in CO<sub>2</sub> estimates. As a methodological improvement Lenzen *et al.* (2003) use a multi-directional trade model to analyse the influence from trade on national CO<sub>2</sub> emissions when using the consumer responsibility approach. The model includes five regions: Denmark, Sweden, Norway, Germany and ROW (rest of the world). The model has been used to estimate CO<sub>2</sub> multipliers for different industries on a country level, cf. Table D.1.

By showing direct and indirect emissions of CO<sub>2</sub> per unit of consumption the CO<sub>2</sub> multipliers contain important information about the environmental effects of consumption. Adding the dimensions of industries and countries give the possibility to detect what kind of industries is most CO<sub>2</sub> detrimental, and further to compare these industries across countries to get an indication of where production should be located in order to minimise global CO<sub>2</sub> emissions. Of course this comparison only serves as a very rough estimate as capacity constraints in the short-run will limit the benefits from restructuring trade.

Industry	Total CO <sub>2</sub> intensity (kg/US\$)				
	DK	D	SV	NO	RW
Financial services	0.08	0.34	0.08	0.22	0.15
Communication	0.17	0.14	0.16	0.18	0.38
Computers	0.34	0.40	0.36	0.40	0.85
Construction	0.37	0.45	0.39	0.41	0.76
Vehicles	0.57	0.57	0.43	0.83	0.97
Basic non-ferrous metals	0.82	2.46	1.43	0.25	2.29
Basic iron and stell.	1.59			2.90	3.56
Basic chemicals	1.04	1.49	0.56	2.72	3.00
Commercial fishing	1.38	0.62	1.79	1.47	1.14
Electricity, gas and district heat	5.88	5.20	2.01	0.15	9.31

Table D.1 – CO<sub>2</sub> Multipliers in five regions

Results indicate that Denmark is setting the benchmark when 'Electronic equipment and computers' and 'Construction' are considered, whereas Sweden shows best performance with regard to 'Vehicle manufacturing' and 'Basic chemicals'. Representing the ROW technology Australia has lowest CO<sub>2</sub> intensities with regard to 'Commercial fishing' and Norway has lowest intensities with regard to production of energy, which is not very surprising considering the fact that almost all electricity is based on hydropower production. Differences between the countries considered seem to be of minor importance when production of 'Communication' and 'Financial services' is considered.

It is obvious that the level of aggregation has some influence on the results obtained in Table D.1, *i.e.* that the industries shown in the table are very inhomogeneous. A rough estimate for the benefits of restructuring international trade so as to locate production where CO<sub>2</sub> emissions are lowest indicate that Danish CO<sub>2</sub> emissions could be reduced by about 55–70 %.

## D.6 MODEL COMPARISON

Using a single-region input-output model assuming factor uses of foreign industries to be identical to those of domestic industries can introduce an error into the CO<sub>2</sub> embodiments in internationally traded commodities and hence into national CO<sub>2</sub> accounts founded in consumer responsibility. In order to obtain an estimate of the magnitude of this error we have investigated all three trade scenarios shown in Figure D.1 by using input-output data for Denmark, Germany, Sweden, Norway and Australia (assuming Australian production technologies to represent the rest of the world). The model results in Table D.2 provide Danish consumer responsibility accounts for CO<sub>2</sub> embodiments of CO<sub>2</sub> in exports and imports and the Danish CO<sub>2</sub> trade balance.<sup>7</sup>

Scenario	I: Autonomous regions	II: Unidirectional trade	III: Multidirectional trade
CO <sub>2</sub> consumer responsibility	47.1	56.0	56.9
Exports	30.1	37.6	38.4
Imports	18.0	34.4	36.0
CO <sub>2</sub> trade balance	-12.0	-3.2	-2.3

Table D.2 – Comparison of 1997 Danish CO<sub>2</sub> trade balances obtained from input-output models with varying degree of interaction (in mega tonnes (Mt))

These results demonstrate that considering explicitly the production technologies, energy use structure and CO<sub>2</sub> emissions of all trading partners has a significant influence on estimates for CO<sub>2</sub> embodied in trade, and hence for the national contribution to emissions, based on consumer responsibility. Results from the multi-region CO<sub>2</sub> analysis are explained in more detail in Lenzen *et al.* (2003).

To indicate the difference in CO<sub>2</sub> multipliers between industries as well as the variations between the model results a comparison of the Danish CO<sub>2</sub> multipliers is shown in Figure D.3. Figure D.3 also highlights that Danish industries have much different CO<sub>2</sub> intensities. Lowest intensities are in the service industries and highest intensities (besides energy production) are in the steel and iron industries and in fishery. As also appears in Figure D.3, direct intensities are relatively bigger in primary industries (*e.g.*, fishery) as compared to industries of higher production layer (*e.g.*, services). Finally, it appears that CO<sub>2</sub> intensities for some industries are very sensitive to the model approach used for analysis, *e.g.*, whether a single-region or a multi-region approach has been used. This indicates that production

technologies for some industries are varying more between countries than for other industries and that also import ratios are varying between the Danish industries considered.

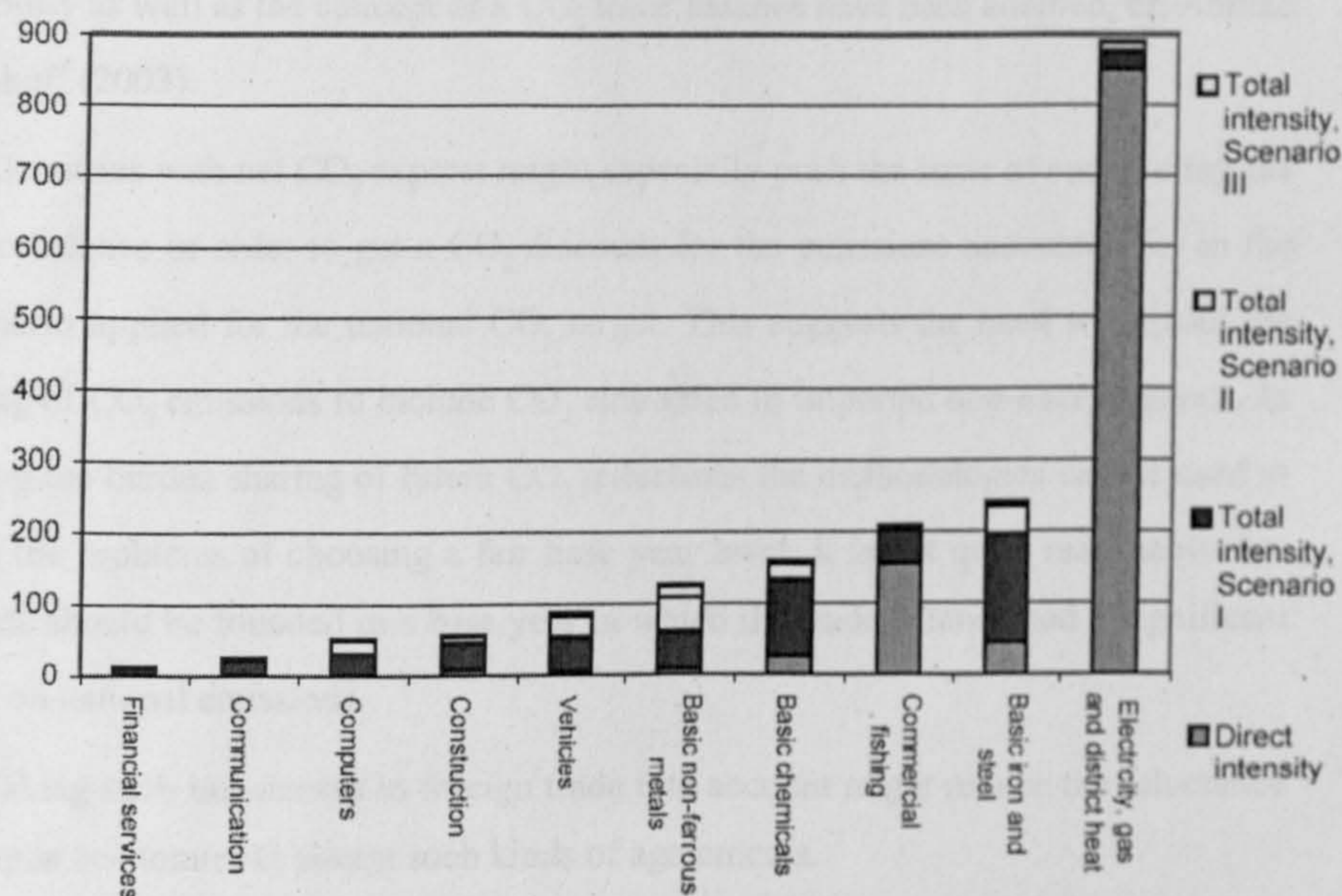


Figure D.3 – CO<sub>2</sub> intensities for 10 Danish industries (g/DKK)

## D.7 CONCLUSION

The embodiment of CO<sub>2</sub> in commodities traded internationally points to the question: Who is responsible for emitting CO<sub>2</sub> to the atmosphere – the consumer or the producer? Based on the distinction between consumer and producer responsibility as introduced in Munksgaard and Pedersen (2001) we in this paper compare different models for the treatment of imports within the field of input-output modelling. Further, we survey the literature to show examples of different model applications.

The case of Denmark illustrates that a significant amount of CO<sub>2</sub> is embodied in foreign trade. It also illustrates that there is an inherent conflict between a national CO<sub>2</sub> target for domestic CO<sub>2</sub> emissions and the aim of improving the foreign trade balance.

<sup>7</sup> The concept of a CO<sub>2</sub> trade balance is introduced in Munksgaard and Pedersen 2001.

The concept of a CO<sub>2</sub> trade balance could have implications for future negotiations on CO<sub>2</sub> reduction strategies, which might call for a reliable methodology for assessing greenhouse gases embodied in international trade. This need is also stressed by a recent study made by OECD in which the principles of producer and consumer responsibility as well as the concept of a CO<sub>2</sub> trade balance have been adopted, cf. Ahmad and Wyckoff (2003).

Countries with net CO<sub>2</sub> exports might especially push the issue of considering the CO<sub>2</sub> trade balance in order to get a CO<sub>2</sub> discount for the emissions accounted for in the base scenario applied for the national CO<sub>2</sub> target. This suggests the need to expand the accounting of CO<sub>2</sub> emissions to include CO<sub>2</sub> embodied in imported non-energy goods. In negotiating the burden sharing of future CO<sub>2</sub> reductions the methodologies can be used to eliminate the problems of choosing a fair base year level. It is not quite reasonable that CO<sub>2</sub> targets should be founded in a base year in which the trade balance had a significant influence on national emissions.

Taking such imbalances in foreign trade into account might reduce the reluctance of some open economies to accept such kinds of agreements.

## D.8 REFERENCES

- Ahmad, N.; 2002; The OECD input-output database, Paper Presented at the 14th International Conference on Input-Output Techniques, Montreal, October 10–15.
- Ahmad, N. and Wyckhoff, A., 2003, Carbon dioxide emissions embodied in international trade of goods, STI Working Paper Series, DSTI/DOC(2003)15, OECD, Paris, <http://www.oecd.org/sti/working-papers>
- Brazilian Proposal, 1997, Proposed elements of a protocol to the United Nations framework convention on climate change, Presented by Brazil in Response to the Berlin Mandate, Document FCCC/AGBM/1997/MISC1/ADD.3.
- Bullard, C.W. et al., 1978, Net energy analysis. A handbook for combining process and input-output analysis, *Ressources and Energy* 1: 267–313.
- Burniaux, J.M. and Truong, T.P., 2002, GTAP-E – An energy-environmental version of the GTAP model, GTAP Technical Papers, No. 16, <http://www.gtap.agecon.purdue.edu/resources/download/1203.pdf>
- Common, M.S. and Salma, U., 1992, Accounting for changes in Australian carbon dioxide emissions, *Energy Economics* 14(3): 217–225.
- Daly, H., 1968, On economics as a life science, *Journal of Political Economy* 76(3): 392–406.
- Danish Energy Agency, 2003, Energy statistics 2002 (in Danish), Section of Statistics, Copenhagen: Danish Energy Agency.
- Denton, R.V., 1975, The energy cost of goods and services in the Federal Republic of Germany, *Energy Policy* 3(4): 179–184. #
- Eurostat, 2003, International trade in services 1992–2001, Compilation Guide, European Commission, Office for Official Publication of the European Communities, Luxembourg.
- Ferng, J.J., 2003, Allocating the responsibility of CO<sub>2</sub> over-emission from the perspectives of benefit principle and ecological deficit, *Ecological Economics* 46: 121–141.
- GTAP, 2003, Towards an Integrated Data Base for Assessing the Potential for Greenhouse Gas Mitigation, [http://www.gtap.agecon.purdue.edu/databases/projects/Land\\_Use\\_GHG/default.asp](http://www.gtap.agecon.purdue.edu/databases/projects/Land_Use_GHG/default.asp)
- Haan, M. de, 2002, Disclosing international trade dependencies in environmental pressure indicators. The domestic consumption perspective, Paper Presented at the International Input Output Conference, Montreal, October 10–15.
- Hendrickson, C. et al., 1998, Economic models for input-output lifecycle analysis, *Environmental Science and Technology*.
- International Energy Agency (IEA) (2001) CO<sub>2</sub> Emissions from Fuel Combustion, Paris: OECD.
- Joshi, S., 200, Product environmental life-cycle assessment using input-output techniques, *Journal of Industrial Ecology* 3 (2–3): 95–120.
- Just, J., 1974, Impacts of new energy technology using generalized input-output analysis, in M. Macrakis (Ed.) *Energy*, Cambridge: MIT Press.
- Kondo, Y. and Moriguchi, Y., 1998, CO<sub>2</sub> emissions in Japan: influences of imports and exports, *Applied Energy* 59 (2–3): 163–174.
- Lenzen, M., 1998, Primary energy and greenhouse gases embodied in Australian final consumption: an input-output analysis, *Energy Policy* 26(6): 495–506.
- Lenzen, M., 2001a, A generalised input-output multiplier calculus for Australia, *Economic Systems Research* 13(1): 65–92.
- Lenzen, M., Pade Hansen, L-L. and Munksgaard, J., 2002, CO<sub>2</sub> multipliers in multi-region input-output models, Conference on Input-Output Techniques, Montreal, October 10–15.
- Lenzen, M., Pade Hansen, L-L. and Munksgaard, J., 2003, CO<sub>2</sub> multipliers in multi-region input-output models, Paper submitted to *Economic Systems Research*.
- Leontief, W., 1970, Environmental repercussions and the economic structure. An input-output approach, *The Review of Economics and Statistics* 52(3): 262–271. #
- Machado, G.V. et al., 2001, Energy and carbon embodied in the international trade of Brazil: an input-output approach, *Ecological Economics* 39: 409–424.



- Matthews, S., 1999, The external cost of air pollution and the environmental impact of the consumer in the US economy, *PhD Thesis*, Graduate School of Industrial Administration, Carnegie Mellon University Pittsburgh.
- Munksgaard, J. and Larsen, A., 1999, *A Sustainable Energy Policy (in Danish)*, AKF Forlaget.
- Munksgaard, J. and Pedersen, K.A., 2001, CO<sub>2</sub> accounts for open economies: producer or consumer responsibility?, *Energy Policy* 29(4): 327–335.
- Pedersen, O.G., 1996, Input-output analysis and emissions of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>. Linking physical and monetary data', in C. Madsen *et al.* (Eds) *Modelling the Economy and the Environment*, Berlin: Springer Verlag.
- Proops, J.L.R. *et al.*, 1993, *Reducing CO<sub>2</sub> Emissions. A Comparative Input-Output Study for Germany and the UK*, Berlin: Springer Verlag.
- Rosa, L.P., Ribeiro, S.K., Muylaert, M.S. and de Campos, C.P., 2004, Comments on the Brazilian proposal and contributions to global temperature increase with different climate responses – CO<sub>2</sub> emissions due to fossil fuels, CO<sub>2</sub> emissions due to land use change, *Energy Policy* 32(13): 1499–1510.
- Rose, A. *et al.*, 1998, International equity and differentiation in global warming policy, *Environmental and Resource Economics* 12: 25–51.
- Sánchez-Chóliz, J. and Duarte, R., 2004, CO<sub>2</sub> emissions in international trade. Evidence for Spain, *Energy Policy*, 32(18): 1999–2005.
- Schaeffer, R. and De Sá, A.L., 1996, The embodiment of carbon associated with Brazilian imports and exports, *Energy Conversation Management* 37(6–8): 955–960.
- Sonis, M. and Hewings, G.J.D., 2001, Feedbacks in input-output systems. Impacts, loops, and hierarchies, in M.L. Lahr and E. Dietzenbacher (Eds.) *Input-Output Analysis. Frontiers and Extensions*, Palgrave, Chippenham.
- Treloar, G., 1997, Extracting embodied energy paths from input-output tables. Towards an input-output based hybrid energy analysis method, *Economic Systems Research* 9: 375–391.
- UNEP, 2000, The Montreal protocol of substances that deplete the ozone layer, *Secretariat for the Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol of Substances that Deplete the Ozone Layer*, Nairobi, Kenia, <http://www.unep.org/ozone/pdf/Montreal-Protocol2000.pdf>
- Victor, P.A., 1972, *Pollution. Economy and environment*, London: George Allen and Unwin Ltd.
- Wackernagel, M. and Rees, W.E., 1996, Our ecological footprint. Reducing human impact on the Earth, *New Society*, Gabriola Island, BC.
- Weidema, B.P. and Nielsen, A.M. (Eds.), 2001, *Input/Output Analysis – Shortcuts to Life Cycle Data? Environmental Project No. 581*, Miljøstyrelsen, Ministry for Environment and Energy, Copenhagen, Denmark.
- Wyckhoff, A.W. and Roop, J.M., 1994, The embodiment of carbon in imports of manufactured products. Implications for international agreements on greenhouse gas emissions, *Energy Policy* 22(3): 184–187.
- Yabe, N., 2004, An analysis of CO<sub>2</sub> emissions of Japanese industries during the period between 1985 and 1995, *Energy Policy* 32: 595–610.