Sangwon Suh
Editor

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Handbook of Input-Output Economics in Industrial Ecology

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Preface

From the early 2000s, the members of the Society for Environmental Toxicology and Chemistry (SETAC)-Europe noticed that they were hearing more often during their annual meetings about something called input-output economics. The SETAC-Europe had been the cradle of Life Cycle Assessment (LCA) methodology, and its members were mainly engineers and natural scientists. For many of them, input-output economics was an area that was greatly interesting and equally foreign. About the same time, the members of the International Input-Output Association (IIOA) could not miss that a substantial number of the presentations of their biannual meetings were themed around the environment and sustainability. This was the time when new sessions on LCA and Industrial Ecology started to be organized during IIOA meetings. It was also the time that the International Society for Industrial Ecology (ISIE) took off, providing a home for many who were working between the interfaces of traditional disciplines.

In the course of these meetings, it became clear that LCA researchers, input-output economists, and industrial ecologists had a lot to learn and benefit from each other. At the same time, it was also clear that there were disciplinary barriers hampering effective communication among these groups. A common language and platform for communication was in need among these groups to materialize the benefits.

Recognizing these needs, the LCA steering committee of SETAC-Europe, then chaired by Angeline de Beaufort, approved a new SETAC-Europe Working Group (WG) on Input-Output Analysis (IOA) in 2003, for which I served as a chair for 3 years. The first meeting of the WG and its first workshop was held on May 1, 2003 in Hamburg, Germany involving around a dozen SETAC-Europe members. It became evident during the first meeting that the WG should reach out to other societies to embrace broader expertise in and around input-output economics. The ISIE and its executive director, John Ehrenfeld, recognized the WG and approved the second workshop to be held in conjunction with its biannual conference on July 2, 2003 in Ann Arbor, MI, USA, where over 70 participants were gathered. The WG continued to meet in Prague, Czech Republic and in Stockholm, Sweden, which served as an important international platform for exchanging knowledge and experience among researchers from various backgrounds.

This handbook is a result of the multiple years of efforts rooted from these numerous workshops and meetings. It contains contributions from around 70 authors from 19 countries embracing the state-of-the-art theory and principles as well as practical applications of input-output economics for answering the questions in industrial ecology. The group of authors within this handbook represents a wide spectrum of expertise from academia, national laboratories, statistical offices, and research institutes, and contributors include the scholars holding editorial responsibilities of key journals of the field, such as the *Journal of Industrial Ecology*, *Economic System Research*, and *International Journal of Life Cycle Assessment*, as well as the past and the current leaders of various professional societies.

The handbook covers an array of topics including the history of industrial ecology and input-output economics, material flow analysis, LCA, sustainable consumption, policy applications, energy and climate change, waste management, national accounts and statistics, and new developments in modeling and theory. Particularly, this handbook is designed to offer a comprehensive coverage on three major issues: (1) theory and method of key analytical tools and models; (2) fundamental accounting principles and compilation of basic data; and (3) practical applications of the tools and models at various scales. First, various analytical tools and modeling techniques that are of particular importance to industrial ecology applications are comprehensively treated in this handbook, which includes hybrid models for LCA, Material Flow Analysis (MFA) and energy analysis; physical and hybrid-unit IO models; Waste IO model; multi-regional IO models; dynamic IO model; thermodynamic analysis; linear programming and optimization techniques; graph theory and network analysis; use of scenarios; and Structural Decomposition Analysis (SDA). Second, basic accounting frameworks and compilation of required data for these analytical tools and models are shown, which covers e.g., the supply-use framework, resources accounts, time-use survey, Social Accounting Matrices (SAMs), compilation of environmental IO databases of Japan (3EID) and the U.S. (CEDA). Third, use of these data, tools and models for micro-, meso-, as well as macro-scale applications are presented throughout the chapters. Readers will also notice the difference in mode of writing in some chapters: for instance, some are written more as a practical and instructive guide (e.g., the step-by-step approaches for net energy analysis of Chapter 24) and some are done more as a theoretical contribution (e.g., the multistage process-based make-use system of Chapter 35).

Each of the 38 chapters of this handbook is self-contained, while some chapters provide boxes to explain some of the basics, which can be referenced across the chapters. The boxes like "General accounting structure of a Physical Input-Output Table" (Chapter 4) and "Taxes in Input-Output Tables" (Chapter 18) are good examples. Balancing geographical and disciplinary coverage with the depth of the contributions was an important consideration in designing the handbook as well, so that it can serve a wide range of audiences with different knowledge levels, disciplinary backgrounds and geographical locations. As a consequence, some chapters may serve the needs of a particular group of audiences better than others.

This handbook could not have been produced without the help and support of many. I thank Angeline de Beaufort, John Ehrenfeld, and Faye Duchin for their generous supports to this initiative. I thank the members of the SETAC-Europe LCA steering committee, and the councils of the ISIE and IIOA for their support in organizing some of the early meetings. I thank Helias Udo de Haes, Gjalt Huppes and my colleagues at the Institute of Environmental Sciences (CML) for their encouragement and support during the early stage of the initiative. I thank Scott Matthews, Chris Hendrickson and other colleagues at the Department of Civil and Environmental Engineering at Carnegie Mellon University (CMU) for their support while I was working at CMU. I thank Shri Ramaswamy at the Department of Bioproducts and Biosystems Engineering of the University of Minnesota (UMN) for his support to this work. In the course of its evolution, this handbook has been in the hands of four publisher-editors: Henny A.M.P Hoogervorst, Esther Verdries, Fabio de Castro, and Fritz Schmuhl. I thank all of them for their patience and excellence. I am grateful to the series editor, Arnold Tukker for his valuable advices. The assistants from the members of the Industrial Ecology Lab at the University of Minnesota were invaluable. I thank Junghan Bae, Ryan Barker, Yiwen Chiu, Amber Illies, Jinseon Park, Brian Ramackel, Kyo Suh, Brian Walseth, and Yang Yi for their help. Last, but not least, I thank all the authors for their valuable contributions, patience and faith. For some chapters, there were area leaders who greatly helped structure this handbook and facilitate peer-reviews. I thank area leaders Susanne Kytzia (PART II), Annemarth Idenburg (PART V), Manfred Lenzen (PART VI), Shinichiro Nakamura (PART VII), and Reid Bailey (PART IX) for their leadership.

Having gone through a long journey, this volume came not without regrets. Keeping track of a large number of manuscripts, peer-reviews, and revisions was not an easy task, and given the large number of authors involved, human factors should have been better incorporated in planning and scheduling each step. At the beginning, it was the intention to assign each alphabet to note a particular matrix in input-output economics, like **V** for supply matrix, for instance, and use it consistently throughout the handbook. After spending quite some time juggling around the letters over several chapters, I realized that there are only 26 letters in the alphabet, while innovativeness of the authors knows no limit. While this handbook was being shaped, my career had to span over three institutes across the Atlantic, and at times other duties and commitments interrupted the editing process, sometimes for an extended period. I would like to offer my sincere apologies for those who have been awaiting this handbook for a long time.

I wish that this handbook serves as a one-stop reference book for both industrial ecologists and input-output economists who are exploring the other discipline. I believe that this handbook is a useful guidance also for those who study LCA, energy and climate change policy, environmental product policy and sustainable consumption. I wish that the readers find this handbook a valuable companion in their journey across disciplines.

October 2008, Twin cities *S. Suh*

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Part I
Introduction

Chapter 1
Industrial Ecology in the Age of Input-Output Analysis

Reid Lifset

To some, industrial ecology is the field that seeks to understand and replicate the dense network of by-product exchanges found in the famous industrial district of Kalundborg, Denmark. To others, it is the attempt to look to natural systems for models for industrial design and practice. To still others, it is nearly any effort to mesh environmental concerns with production and consumption.

A handbook on input-output analysis needs more clarity than this, both to provide context for the individual chapters and to provide an introduction to those less familiar with industrial ecology. This opening chapter will provide such an introduction by first reviewing the goals, history, elements and state of development of the field. It will then examine six dimensions of industrial ecology in terms of their potential relationship to input-output analysis.

Definition and Goals

The very name *industrial ecology* conveys some of the content of the field. Industrial ecology is *industrial* in that it typically focuses on product design and manufacturing processes. It views firms as agents for environmental improvement because they possess the technological expertise that is critical to the successful execution of environmentally-informed design of products and processes. Industry, as the portion

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of society that produces most goods and services, is a focus[1] because it is an important but not exclusive, source of environmental damage.[2]

Industrial ecology is *ecological* in at least two senses. As argued in the seminal publication by Frosch and Gallopoulos (1989) that did much to coalesce this field, industrial ecology looks to non-human 'natural' ecosystems as models for industrial activity. This is what some researchers have dubbed the 'biological analogy' (Allenby and Cooper 1994; Wernick and Ausubel 1997). Many biological ecosystems are especially effective at recycling resources and thus are held out as exemplars for efficient cycling of materials and energy in industry. The most conspicuous example of industrial re-use and recycling is the now-widely discussed industrial district in Kalundborg, Denmark (Ehrenfield and Gertler 1997). The district contains a cluster of industrial facilities including an oil refinery, a power plant, a pharmaceutical fermentation plant, and a wallboard factory. These facilities exchange by-products and what would otherwise be called wastes. The network of exchanges has been dubbed 'industrial symbiosis' as an explicit analogy to the mutually beneficial relationships found in nature and labeled as symbiotic by biologists.

Second, industrial ecology places human technological activity – industry in the widest sense – in the context of the larger ecosystems that support it, examining the sources of resources used in society and the sinks that may act to absorb or detoxify wastes. This latter sense of 'ecological' links industrial ecology to questions of carrying capacity, ecological resilience and to biogeochemistry (especially the grand nutrient cycles), asking whether, how and to what degree technological society is perturbing or undermining the ecosystems that provide critical services to humanity. Put more simply in the words of two pioneers in the field, economic systems are viewed not in isolation from their surrounding systems, but in concert with them (Graedel and Allenby 1995).

Robert White, as president of the US National Academy of Engineering, summarized these elements by defining industrial ecology as "the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities (White 1994)."

History

Specifying when a field began is an exasperating, even quixotic task. Both in terms of intellectual content and in terms of institutional activity, there are always

[1] The primary emphasis on industry is changing, however, as industrial ecology increasing attends to questions of consumption. See (Hertwich 2005) and the special issue of the *Journal of Industrial Ecology* on consumption and industrial ecology (volume 9, number 1–2) as well as the discussion later in this chapter.

[2] This chapter builds on, extends and updates a similar introduction in the *Handbook of Industrial Ecology* (Lifset and Graedel 2002).

ideas and activities that are precedent. The organized, self-conscious emergence of this field, however, can be usefully tied to the publication of "Strategies for Manufacturing" in a special issue, "Managing Planet Earth" of *Scientific American* in 1989 (Frosch and Gallopoulos 1989). In that article, the authors proposed many of the ideas that now make up the core of the field: the biological analogy (by discussing "industrial ecosystems"), the need for a systems perspective in environmental analysis, management and policy, and the opportunities for closing materials loops. The *Scientific American* article sparked interest among key groups in the U.S. For example, the U.S. National Academy of Engineering had recently begun a program on technology and the environment that, through symposia and publications (Jelinski et al. 1992), advanced related ideas. The imprimatur of the National Academy helped give the ideas legitimacy. AT&T, the large telecommunications firm, through the interest of some key executives, began to sponsor symposia and provide fellowships to university faculty (Laudise et al. 1998). This, of course, engendered interest in academe. A report published by a prominent management consulting firm and reprinted in the *Whole Earth Review* brought the ideas to the attention of the business community (Tibbs 1992).

Despite these identifiable publications and activities, the antecedents for industrial ecology are numerous – the ideas that now make up industrial ecology did not spring from whole cloth. Robert Ayres played an especially important role in developing many of the concepts. An article by Ayres and his colleagues in the *American Economic Review* and a subsequent book on the application of the materials balance approach to environmental economics (Ayres and Kneese 1969; Kneese et al. 1970) were seminal in this regard. Even here, the precedents are numerous and important. Belgian researchers explicitly developed a notion of industrial ecology in the early 1980s, and the Japanese had an Industrial-Ecology Working Group as early as 1970 (Erkman 1997).

In northern Europe, concepts such as no-waste and low-waste technology had been discussed since the early 1970s and gradually evolved into the fields of cleaner technology and cleaner production (CP). CP began with a focus on engineering changes to production processes as a means of reducing the generation of waste and emissions and of avoiding the use of toxic substances, but broadened to include life-cycle-based analyses of production and consumption. As a result, as the emerging field of industrial ecology crossed the Atlantic from North America, it discovered an extensive body of expertise and literature that bolstered its depth and breadth.

Given the combination of the systems focus of industrial ecology and its emphasis on the closing of materials loops, it is not surprising that industrial ecology embraced life-cycle assessment (LCA) and the related concepts of life-cycle management (LCM), integrated product policy (IPP), design for environment (DfE) and extended producer responsibility (EPR). It was especially in these areas (and in materials flow analysis) that the growing community of researchers and policy analysts in Europe and Japan made major contributions to the field.

The allied study of materials flows per se grew partly in parallel and partly in conscious combination with the other elements of industrial ecology (Tukker et al. 1997). Materials flow analysis emerged from several sources. When MFA took the form of substance flow analysis (SFA, the tracking of individual substances through society and the environment at various scales), it built on efforts emerging from toxic substances policy to traces the sources and destinations of problematic materials through the economy to their fate in the environment (Hansen and Lassen 2002; Tukker et al. 1997; van der Voet et al. 2000). Substance flow analysis also grew out of research in the earth sciences and ecology in the grand nutrient cycles.[3] When MFA examined all of the flows in the economy in aggregate, it built on efforts to extend national income accounting to incorporate resource use and environmental releases (see the chapter in this Handbook by de Haan) and on long, if sometimes underattended, traditions in the social sciences (Fischer-Kowalski 1998; Fischer-Kowalski 1998). These different threads in the MFA research community came together when ConAccount, a research network (a "concerted action") initially funded by the European Union,[4] was founded in 1996.

In 1996, the Norwegian University of Science and Technology (NTNU) launched the first university degree program in industrial ecology (Marstrander et al. 1999). In 1997, the Yale University School of Forestry & Environmental Studies hired Thomas Graedel as the first professor of industrial ecology and launched the *Journal of Industrial Ecology* as a peer-reviewed quarterly to serve the international industrial ecology community.[5] The initial institutional development of the field was completed when an international professional and scientific society was launched in 2001 and held its first global conference in Leiden in the Netherlands in 2001.

Elements of Industrial Ecology

The hallmarks of industrial ecology are a cluster of tools and concepts including LCA, MFA DfE and eco-industrial parks and the biological analogy. This list, however, does not exhaust the full scope of the field. For example, the study of eco-efficiency, of the components of life-cycle management or integrated product policy (e.g., extended producer responsibility, eco-labeling, environmental supply chain management/reverse logistics, and green procurement) and of corporate environmental management are thought by many, but not all, to be part of industrial ecology. For the purpose of this handbook, the precise boundaries of the field are not crucial.[6]

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[3] See the chapters in the section, "The Grand Cycles: Disruption and Repair" in the book by Socolow, Andrews, Berkhout and Thomas (Socolow et al. 1994).

[4] The formal title of the EU project was entitled "Coordination of Regional and National Material Flow Accounting for Environmental Sustainability".

[5] See http://mitpress.mit.edu/JIE

[6] For a discussion of the scope of the field and some frameworks that explicate the relationship among the elements, see (Lifset and Graedel 2002). The description of the various tools and concepts as the elements of industrial ecology is not meant to be canonical nor to imply that those elements are uniquely subsumed under the rubric of industrial ecology. Other authors have inevitably formulated the hierarchy of concepts differently.

Instead, six cross-cutting themes in industrial ecology are examined as a means of explicating the relationship to input-output analysis:

- The biological analogy
- The use of systems perspectives
- The role of technological change
- The role of companies
- Dematerialization and eco-efficiency, and
- Forward-looking research and practice.

The Biological Analogy

The biological analogy has been applied at a variety of levels, including products, facilities, districts and regions, primarily using notions borrowed from ecosystem ecology regarding the flow and especially the cycling of materials, nutrients and energy in ecosystems as a potential model. The archetypal example is the industrial symbiosis in Kalundborg, but the search for other such arrangements and even more conspicuously the effort to establish such symbiotic networks is emblematic of industrial ecology – so much so that many with only passing familiarity of the field have mistakenly thought that industrial ecology focused only on efforts to establish eco-industrial parks.

This analogy has been posited more generically as well, not merely with respect to geographically-adjacent facilities (Lifset 2004). Graedel and Allenby have offered a typology of ecosystems varying according to the degree to which they rely on external inputs (energy and materials) and on release of wastes to an external environment. Expressed another way, the ecosystems vary according to the linearity of their resource flows (Graedel and Allenby 2003). The efficient cycling of resources in a biological system is held out as an ideal for industrial systems at many scales. This framework thus connects the biological analogy to strong emphasis in industrial ecology on the importance of closing materials cycles or 'loop closing'.

The connection between the biological analogy and input-output analysis is twofold. First, both the ecosystem ecology and input-output analysis trace the flow of resources within defined systems and between a system and its external environment. Second and more specifically, ecology and input-output analysis have borrowed from each other with the former adopting portions of the mathematical framework developed in the latter.[7] More recently, Bailey and colleagues have taken the adaptation of ecological input-output analysis and re-applied it to industrial systems (Bailey et al. 2004a, 2004b). Suh (2005) argues that input-output analysis as used in ecology and economics have much in common in their model formulation, but that they look systems from opposite directions: ecologists start from the input side (nutrient and energy inputs) and economists start from the output side (final demand).

[7] See, for example, the work of H.T. Odum, Hannon, Finn and Patten as described by in overviews by (Bailey et al. 2004a) and (Suh 2005).

Systems Perspective

Industrial ecology emphasizes the critical need for a systems perspective in environmental analysis and decision making. The goal is to avoid narrow, partial analyses that can overlook important variables and, more importantly, lead to unintended consequences. The systems orientation is manifested in several different forms:

- Use of a life cycle perspective
- Use of materials and energy flow analysis
- Use of systems modeling, and
- Sympathy for multi-disciplinary and interdisciplinary research and analysis

The pursuit of a systems perspective is perhaps the most direct and important connection between industrial ecology and input-output analysis. If, what it means to view something through a system perspective is to emphasize the structure that includes the significantly interacting components of a phenomenon,[8] then it is not surprising that what constitutes a system for the purposes of industrial ecology varies – by preference of the researcher and by the problem at hand.[9] Typically, the phenomena studied entail more than a single firm or process although individual organizations or technologies are often studied with reference to the system of which they are a part. An obvious example of the latter case would be the study of an individual firm as part of a supply chain.

LCA and Input-Output Analysis

The effort to use a life cycle perspective, that is, to examine the environmental impacts of products, processes, facilities or services from resource extraction through manufacture to consumption and finally to waste management is reflected both in the use of formal methods such as life-cycle assessment (Guinée 2002) and in attention to approaches that imply this cradle-to grave perspective and apply it in managerial and policy settings as well as in research contexts. This latter group includes product chain analysis (Wrisberg and Clift 1999), integrated product policy (IPP, also known as product-oriented environmental policy) (Jackson 1999), greening of the supply chain (Guide and van Wassenhove 2004), and extended producer responsibility (EPR) (Lifset 1993; Organisation for Economic Cooperation and Development 1996).[10]

The connection between LCA and input-output analysis is overt and one of the motivations for this handbook. Efforts to couple input-output analysis to

[8] I owe this formulation to Stephen Levine of Tufts University.

[9] Not only do problems shape system boundaries and researchers vary in how they think system boundaries should be drawn, but disciplines frame system definitions differently. For a good description of how engineers and social scientists define systems, see the discussion by (Clift et al. 1995).

[10] Give definitions.

life-cycle assessment were pursued by Japanese researchers in the early 1990s (Moriguchi et al. 1993). Input-output analysis gained visibility in the industrial ecology literature when researchers at Carnegie Mellon University and elsewhere developed approaches to LCA that used IO analysis (Lave et al. 1995; Matthews and Small 2000). The CMU group put their tool, dubbed environmental input-output life-cycle analysis (EIO-LCA), on the internet, allowing use at no charge and attracting the attention of researchers and analysts around the world.[11]

IO LCA addresses the problem of system boundaries and indirect effects in conventional, process-based LCA (Suh et al. 2004). Conventional LCA captures only those emissions that occur within the semi-arbitrarily-drawn system boundary. For an assessment of the life-cycle of a car, for example, LCA obviously encompasses the emissions arising from the assembly of the car, from manufacture of steel used in the car – including the emissions from the energy used to power the factory making the steel – but does not necessarily include the energy used to mine the coal used in the power plant at the steel factory. While a variety of rules of thumb and analytically more elaborate methods (Raynolds et al. 2000) are used in an attempt to draw the system boundary in a manner that captures all of the important impacts, the possibility of missing important releases and therefore important environmental impacts remains. It is not the just releases from individual processes that may be overlooked, but also the aggregate of the all of the releases from the processes outside modeled system that may change the results of the LCA. Further, the potentially idiosyncratic character of the definition of the system boundary poses problems of commensurability of results from competing LCAs.

IO LCA resolves this problem by using the input-output tables commonly maintained by most countries (as well as a large number of other governmental jurisdictions) to trace the flow of products and services through the economy. In IO LCA, data on resource use and environmental releases are coupled with the monetary input-output tables. The result is a model that encompasses the complete supply chain of the economy activity involved in producing a given good or service and the attendant materials and energy flows. The power of IO LCA to avoid truncation errors (i.e., the omission of resource inputs or emissions related to processes outside the system boundary) has been described by Lenzen,[12] who argues that conventional LCA can suffer from errors of as much as 50% (Lenzen 2000).

Input-output LCA is also often used as a screening tool, allowing researchers to estimate the relative importance of indirect resource use or emissions. This can provide guidance in a "traditional" LCA about the need for additional or better quality data in a specific sector or of the significance of the choice of where to draw the system boundary.

Input-output LCA has its own limitations – beyond those which it shares with conventional LCA. These include price inhomegeneity (varying prices for the same product), data age, assumptions regarding imports and the correspondence of IO

[11] The site <www.eiolca.net> attracts about 15,000 active users per month.

[12] To be precise, Lenzen argues for the use of hybrid LCA which combines conventional, process-based LCA with input-output analysis.

tables to the product system under study. Process LCAs can use a variety of data sources, both public and private, whereas IO LCA relies on government-generated IO tables which are typically several years old.[13] IO LCA's strength – that is, the capturing of production activities throughout the economy – is also a source of one of its weaknesses. Environmental data on pollutant releases are typically not available across the entire economy commensurate with the scope of the IO tables, nor in consistent levels of detail across sectors. In basic IO models using single-region domestic input-output tables, imported commodities are assumed to be produced using the same technology and structure as the domestic industries (Suh et al. 2004). There is also often a mismatch between the sectors represented in the IO tables and the particular system being studied in the LCA.[14] (Joshi 1999) provides a method for resolving the latter problem.[15]

Energy and Material Flow and IO Analysis

Analysis of industrial or societal metabolism, that is, the tracking of materials and energy flows at a variety of scales is also motivated by a system orientation. Here reliance of research in industrial ecology on mass balances – making sure that inputs and outputs of processes add up in conformance with the first law of thermodynamics – reflects an effort at comprehensiveness. Because of the use of mass balances at these different scales, industrial ecology often involves the mathematics of budgets and cycles, stocks and flows (Graedel and Allenby 2003). By tracking chemical usage in a facility (Reiskin et al. 1999), nutrient flows in a city (Björklund et al. 1999), flows of heavy metals in river basins (New York Academy of Sciences 2002; Stigliani et al. 1993), or materials viewed in aggregate in national economies (Adriaanse et al. 1997; Bringezu et al. 2003; Daniels and Moore 2001), industrial ecology seeks to avoid overlooking important uses of resources and/or their release to the environment. The tracking of materials and energy is sometimes embedded in the consideration of natural, especially biogeochemical, cycles and of how anthropogenic activities have perturbed those flows. For example, the study of anthropogenic perturbations of the nitrogen cycle is an important contribution of industrial ecology (Ayres et al. 1994; Socolow 1999).

Here the connection between industrial ecology and input-output analysis is so close that the challenge is to keep the differences clear. Materials flow analysis literally tracks inputs and outputs (and net changes to stock) of materials. Input-

[13] Process LCAs which rely on government environmental or economic data also fall prey to the problem of data age.

[14] (Lenzen 2000) argues that there are six sources of error in IO analysis: (1) source data uncertainty, (2) imports assumption uncertainty, (3) estimation uncertainty for capital flow, (4) proportionality assumption uncertainty, (5) aggregation uncertainty and (6) allocation uncertainty.

[15] Analyses that combine IO LCA and process LCA have been developed specifically because the combination of these two approaches can remedy many of the challenges outlined in this chapter. The rapidly advancing work on hybrid approaches is described by (Suh et al. 2004) and (Suh and Huppes 2005), but is beyond the scope of this chapter.

output analysis derived from the approaches developed by Leontief using monetary accounts and augmented by physical data on inputs and releases (Leontief 1970b) overlaps strongly with MFA. In MFA, as it developed in industrial ecology, the starting points are the physical data. In contrast, input-output analysis built on economics starts with monetary data and adds physical data (or converts the monetary data to physical data). IO analysis has the capacity, however, to express both dimensions as companion quantity input-output and price input-output models (Duchin 1994b).

The MFA and input-output analysis overlap most conspicuously in physical input-output tables (PIOT) which provide information on material flows at the level of economic sectors, in particular on inter-industry relations, separating material inputs used for production processes from those directly delivered to final demand (see the chapter by Giljum and Hubacek in this Handbook). In contrast, substance flow analysis, while in principal not incompatible with input-output analysis, has not made use of IO analysis as extensively. For two examples, however, see the study by (Konijn et al. 1997) on iron steel and zinc and the study of aluminum by Bailey (Bailey et al. 2004b) who also provides a useful and more detailed account of the intersections between MFA and input-output analysis.

Systems Modeling and Input-Output Analysis

This same effort to examine human–environment interaction from a holistic perspective is manifested in formal systems modeling including dynamic modeling (Ruth and Harrington 1997), use of process models (Diwekar and Small 1998), and integrated energy, materials and emissions models such as MARKAL MATTER (2000) and integrated models of industrial systems and ecosystems or the biosphere (Alcamo et al. 1994; Sheehan et al. 2003). Such systems modeling not only increases the comprehensiveness of environmental analysis; it can also capture some of the interactions among the factors that drive the behavior of the system being studied (Boon et al. 2003). Conceptual discussions of the nature of industrial ecology and sustainable development have highlighted the importance of nonlinear behavior in human and environmental systems and argued that chaos theory and related approaches hold out potential for the field (Allenby 1999; Kay 2002; Ruth 1996), but little quantitative work in this vein has been done to date.

Here the industrial ecology modeling and the typical – i.e., static, open modeling – approaches to input-output analysis remain somewhat separate, because dynamic modeling endogenizes change and takes time lags into account. The assumptions of linearity in input-output analysis make this more difficult, though not impossible. (See, for example, the chapter by Levine, Gloria and Romanoff in this Handbook for an approach to incorporating time lags and thus the stock and flow effects so important to much of industrial ecology.) Duchin (1992, 2004) argues more generally that input-output analysis as used by industrial ecologists – primarily in the form of input-output LCA – has been limited to static, open models, but that IOA can and has been extended to account for stocks as well as flows, endogenize change, and incorporate nonlinearities.

Traditional input-output analysis quantified exchanges of goods and money between various parts of the industrial economy – approximately what in life-cycle assessment would be called cradle-to-gate.[16] But industrial ecology seeks to examine the entire life cycle including use and end-of-life management of products and IO analysis thus ignores key stages in the life cycle. This gap in IO analysis, however, is being filled as new work incorporates product use and waste management (Joshi 1999; Nakamura and Kondo 2002; see also the chapter by Nakamura in this volume).

Multidisciplinary and Input-Output Analysis

Finally, the imperative for systems approaches is also reflected in a sympathy for the use of techniques and insights from multiple disciplines (Graedel 2000; Lifset 1998). There have been some notable successes (Carnahan and Thurston 1998; van der Voet et al. 2000), but multi-disciplinary analysis – where several disciplines participate but not necessarily in an integrative fashion – is difficult – and interdisciplinary analysis – where the participating disciplines interact and shape each other's approaches and results – is even more so. Interdisciplinarity remains an important challenge for not only industrial ecology, but all fields.

In concrete terms, input-output analysis is an economic sub-discipline. Its use in industrial ecology melds economics with engineering and to a lesser extent, environmental science. Further, IO analysis is especially conducive to the integration of technical information, because of the explicit way in which physical relationships are captured in the IO tables. At the same time, as with any interdisciplinary effort, the combination of IOA and industrial ecology requires competence in both fields.

Technological Change

Technological change is another key theme in industrial ecology. It is a conspicuous path for pursuing the achievement of environmental goals as well as an object of study (Ausubel and Langford 1997; Chertow 2000; Grübler 1998; Norberg-Bohm 2000). In simple terms, many in the field look to technological innovation as central means of solving environmental problems. It should be noted, however, that while that impulse is shared widely within the field, agreement as to the degree to which this kind of innovation will be sufficient to solve technological problems remains a lively matter of debate (Ausubel 1996; Graedel 2000; Huesemann 2003).

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[16] Cradle-to-gate is typically taken to refer to the process stages from resource extraction to delivery to one of the stages of manufacturing or distribution (varying according to the product or material being studied). IO analysis encompasses economic activities up to and including the production of the final product. As a result, cradle-to-gate only imprecisely corresponds to IO analysis.

Ecodesign (or design for environment – DFE) is a conspicuous element of industrial ecology. By incorporating environmental considerations into product and process design *ex ante*, industrial ecologists seek to avoid environmental impacts and/or minimize the cost of doing so. This is technological innovation at the micro-level, reflecting technological optimism and the strong involvement of academic and professional engineers. Ecodesign frequently has a product orientation, focusing on the reduction in the use of hazardous substances, minimization of energy consumption, or facilitation of end-of-life management through recycling and reuse (White 2003). Implicitly, ecodesign relies on the life cycle perspective described earlier by taking a cradle to grave approach.

Eco-design is complemented by research that examines when and how technological innovation for environmental purposes is most successful in the market (Preston 1997). The focus on technological change in this field also has a macro version, examining whether technological change is good for the environment or how much change (of a beneficial sort) must be accomplished in order to maintain environmental quality. Here the IPAT equation (Impact $=$ Population $\times$ Affluence $\times$ Technology) has provided an analytical basis for parsing the relative contributions of population, economic growth (or, viewed in another way, consumption), and technology on environmental quality (Chertow 2000; Wernick et al. 1997; York et al. 2005). The equation provides a substantive basis for discussion of questions of carrying capacity implicit in the definition of industrial ecology offered earlier.

Input-output analysis bears a complicated relationship to the aspects of technological changes embraced by industrial ecology. For many purposes, IO analysis is conducive to the investigation of these issues. Input-output tables embody technology descriptions insofar as they specify the inputs to a process and the resulting outputs, including, in the case of environmental IO analysis, emissions and wastes. Thus, IO analysis is especially well suited to scenario analysis where a particular technological configuration is specified through the quantification of the relevant inputs and outputs. This means that a technological innovation or, more broadly, a future defined by the diffusion of that innovation and the economic and environmental consequences can be quantified (as defined by the IO model). This sort of what-if analysis can be applied at a variety of scales. For one example of this sort of environmental assessment of technology adoption, see the study of economic and environmental implications of adoption of nano-composites in automobiles by (Lloyd 2003). Duchin and Lange use input-output analysis at a broader scale to argue that improvements arising from technological change will be not be sufficient to offset other environmental pressures (Duchin 1994a).

Input-output analysis is also amenable to quantification of technological change through structural decomposition analysis (SDA). Changes in economic output can be disaggregated into those that arise from technological or efficiency improvements, those that are due to overall growth (or decline) in the overall level of economic activity and those that are attributable to shifts within the economy (from one sector to another). Thus if input-output analysis is augmented with physical data as described in this handbook, then the shifts in mass or energy flows caused by technological change can be isolated through SDA (Farla and Blok 2000; Hoffren et al. 2000).

Role of Firms and Industries

Business plays a special role in industrial ecology in several respects. Because of the potential for environmental improvement that is seen to lie largely with technological innovation, businesses as a locus of technological expertise are an important agent for accomplishing environmental goals. Further, some in the industrial ecology community view command-and-control regulation as importantly inefficient and, at times, as counter-productive. Perhaps more significantly, and in keeping with the systems focus of the field, industrial ecology is seen by many as means to escape from the reductionist basis of historic command-and-control schemes (Ehrenfeld 2000). Regardless of the premise, a heightened role for business is an active topic of investigation in industrial ecology and a necessary component of a shift to a less antagonistic, more cooperative and, what is hoped, a more effective approach to environmental policy (Schmidheiny 1992; Socolow 1994).

Examinations of the role of business are not confined to individual firms or supply chains. They are also manifested in research and attention to industry sectors. LCA, MFA and systems modeling have been used to assess the environmental impact of, for example, the pulp and paper industry ("Roundtable on the Industrial Ecology of Pulp and Paper", 1997) (Ruth and Harrington 1997) or the auto industry (Graedel and Allenby 1998; Keoleian et al. 1997; Wells and Orsato 2005). Industry sectors have also been the unit of analysis in studies of industry voluntary codes of conduct and standards (Nash and Ehrenfeld 1997; Rosen et al. 2000, 2002).

Intermediate between the firm level and sector level analysis are investigations of supply chains. In one sense, supply chains are a subset of the product life cycle – encompassing the upstream portion of the life cycle. Environmental management of the supply chain, however, emphasizes the business relationship between firms in the chain (Guile and Cohon 1997) as well as the opportunities to revise logistical practices and networks for environmental purposes (see the work of the European research network, RevLog, <www.fbk.eur.nl/OZ/REVLOG/>) Because IO analysis inherently examines inter-industry flows along supply chains, it is well suited for the assessment of changes. For an example, see the study of the environmental and cost tradeoffs of centralized warehousing and increased cargo transport by (Matthews and Hendrickson 2002).

IO analysis, of course, is equally well suited to sector level assessments. In contrast, IOA has not been widely used for the study of individual firms. (Lin and Polenske 1998), however, point out that the Chinese have done extensive work on enterprise level IO analysis and propose an application of input-output analysis for use in business planning.

Dematerialization and Eco-Efficiency

Moving from a linear to a more cyclical flow of materials entails not only closing loops, but using fewer resources to accomplish tasks at all levels of society. Reducing resource consumption and environmental releases thus translates into a cluster of related concepts: dematerialization, materials intensity of use, decarbonization and eco-efficiency. Dematerialization refers to the reduction in the quantity of materials used to accomplish a task; it offers the possibility of de-coupling resource use and environmental impact from economic growth. Dematerialization is usually measured in terms of mass of materials per unit of economic activity or per capita and typically assessed at the level of industrial sectors, regional, national or global economies (Adriaanse et al. 1997; Wernick et al. 1997). Decarbonization asks the analogous question about the carbon content of fuels (Nakicenovic 1997). Inquiry in this arena ranges from analysis of whether such reductions are occurring (Cleveland and Ruth 1998), whether dematerialization per se (i.e., reduction in mass alone) is sufficient to achieve environmental goals (Reijnders 1998; van der Voet et al. 2005) and what strategies would be most effective in bringing about such outcomes (von Weizsäcker et al. 1997).

The intersection between investigation of dematerialization on the one hand, and other elements of industrial ecology such as industrial metabolism with its reliance on the analysis of the flows of materials on the other is clear because both involve quantitative characterization of material flows. There is also overlap with industrial ecology's focus on technological innovation. This is because investigations of dematerialization often lead to questions about whether, at the macro or sectoral level, market activity and technological change autonomously bring about dematerialization (Cleveland and Ruth 1998)[17] and whether dematerialization or other variants of eco-efficiency, expressed in terms of the IPAT equation, is sufficient to meet environmental goals (York et al. 2005).

At the firm level, an analogous question is increasingly posed as a matter of eco-efficiency, asking how companies might produce a given level of output with reduced use of environmental resources (DeSimone et al. 1997; Fussler and James 1996; OECD 1998). Here, too, the central concern is expressed in the form of a ratio: desired output divided by environmental resources consumed (or environmental impact). The connection between this question and industrial ecology's focus on the role of the firm and the opportunities provided through technological innovation is conspicuous as well. As with the discussion of the role of business in industrial ecology, here too IO analysis is readily applicable to macro level assessments of changes in resource consumption and environmental releases. And it is less suited to firm level investigations as well for the reasons described above.

Forward-Looking Analysis

Much of research and practice in industrial ecology is intentionally prospective in its orientation.[18] It asks how things might be done differently to avoid the creation

[17] See also the special issues of the *Journal of Industrial Ecology* on E-commerce, the Internet and the Environment <http://mitpress.mit.edu/jie/e-commerce> and on Biobased Products <http://mitpress.mit.edu/jie/bio-based> for collections of articles exploring whether and how technological change might bring about non-incremental environmental improvement.

[18] This does not mean that history is ignored. Industrial metabolism, for example, pays attention to historical stocks of materials and pollutants and the role that they can play in generating

of environmental problems in the first place, avoiding irreversible harms and damages that are expensive to remedy. Eco-design thus plays a key role in its emphasis on anticipating and designing out environmental harms. More subtly, the field is optimistic about the potential of such anticipatory analysis through increased attention to system-level effects, the opportunities arising from technological innovation and from mindfulness of need to plan and analyze in and of itself. IO analysis is quite conducive to scenario analysis, making it an obvious tool for environmental assessment of technology adoption or of life style change (Duchin 1998). At the same time, in its basic form, IO analysis is static and reliant on data that are typically a few years out of date. Thus, unless the more sophisticated (and complicated) versions of IO analysis are used, longer term projections that do not address the need to account for the changes in the underlying input-output ratios must be avoided.

Conclusion

Members of the industrial ecology fraternity envision the field in different ways. Some see the potential of the biological analogy and non-equilibrium thermodynamics (Ehrenfeld 2004). Others call for greater integration with ecological science – literally, not merely metaphorically (Bohe 2003). Others emphasize more interaction of the now largely technical community with policymakers and corporate managers. Many point to the need for greater attention to the role of agency, that is, in the words of Andrews (2000) to go beyond merely describing "what" and to add accounts of "how".

Greater use of IO analysis will surely improve the investigations of "what", making the field better at assessment and scenario analysis. Duchin argues that dynamic IO[19] is well suited to the investigation of "how" because it permits the specification of the technical characteristics of particular methods of reducing pollution or, more generally, of pursuing sustainable development (Duchin 1992). If she is correct, then the successful use of IO analysis by industrial ecologists will need to extend beyond the open, static IO models currently used in LCA. (It is less clear, however, if dynamic IOA addresses the questions of agency raised by Andrews to the extent that he is really asking not only "how" but "who".) The greater comprehensiveness achievable through dynamic IO analysis will make industrial ecology more robust

fluxes in the environment (Ayres and Rod 1986). However, industrial ecology does not emphasize remediation as a central topic in the manner of much of conventional environmental engineering.

[19] Dynamic modeling can mean many things to many people – from any analysis that incorporates time whatsoever to those which endogenize change in the parameters or the form of the relevant equations. Dynamic input-output analysis is usually taken to refer to the model developed by (Leontief 1970a) that incorporates demand for capital goods. Here, however, I refer to later extensions of that model (Duchin and Szald 1985) that resolve certain limitations in the original formulation.

in responding to the questions of real world policymakers, analysts and managers while at the same time it will make the methods of industrial ecology one step more arcane to those practitioners.

Thus, as industrial ecology moves beyond its initial formulations and foci, IO analysis, as the publication of this handbook attests, is poised to become a major tool in its toolkit. As this very brief overview suggests, IO analysis can both improve and extend the work of industrial ecology. This is particularly true with respect to industrial ecology's aspirations to apply a systems perspective on environmental problems and proposed remedies. For other aspects of the field – the biological analogy, for example – the gains are likely to be less dramatic but could still be useful.

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Chapter 2
Input-Output Economics and Material Flows

Faye Duchin

Two fields of scientific inquiry can be interconnected effectively only through a clear conceptual overlap. Moreover, the overlapping (that is, the common) concepts must have proven their internal operational effectiveness separately in each one of the adjoining disciplines (Leontief 1959, 1985).

Introduction

The theory of international trade based on comparative advantage is the most ambitious of economic theories as it explains the operation of the entire world economy in terms of consumption, production, and factors of production in each individual region. Factors of production are those inputs that are required for production but cannot themselves be produced in business establishments (at least not in a single production period) and are, furthermore, of limited mobility. For this reason, the available quantities, or endowments, of these factors in a region constrain its production capacity. Thus the relatively lowest-cost producer of some product can increase production only until the available amount of some factor is exhausted; then a higher-cost producer must take over. The potentially limiting factors are taken to be labor, capital, and land, where "land" implicitly includes not only the soil but also everything on or under the surface such as fresh water, energy resources, metals, and other mineral ores.

Despite the importance for economists of the theory of international trade, its empirical implementation in models of the world economy has been relatively limited until now, for reasons to which I return in the last section of this chapter. Someplace between the abstract theory of international trade and the large body of empirical

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work analyzing individual economies, the crucial economic roles of land, water, and mineral resources[1] have become obscured. Physical measures of factor endowments and factor requirements for production are absent from economic databases, and land is no longer treated as a factor of production distinct from capital assets. The place of physical measures of the factor inputs to production has been largely taken over by the monetized concept of "value-added," defined for an individual production establishment and, by extension, for an entire sector, as the residual when the payments for inputs produced in other sectors are subtracted from the sector's total revenues. Value-added is sometimes disaggregated into employee compensation, profits, and a residual.

Input-output economics accords a place of privilege to physical quantities measured in physical units. However, this potential has not been fully exploited because input-output models, like other economic models, are typically implemented using databases in money values only. Today, there is significant and growing interest in input-output economics coming from quarters outside of economics. In particular, industrial ecologists, often with a background in engineering, are using input-output models to analyze the flows of materials and energy through an economy in order to quantify the environmental impacts associated with particular products and processes. Industrial ecologists are attracted to the basic input-output model because it can absorb their data about physical flows at a moderate level of detail and capture the fundamental interdependence of all parts of an economy while also revealing physical relationships. These colleagues bring to collaboration with input-output economists not only new areas of expertise but also new questions and concerns, namely about the environment, that can stimulate new thinking on both sides. A deeper collaboration between industrial ecologists and input-output economists requires dispelling three main misconceptions. I attempt to do that in this chapter by exhibiting relevant work from the literature in input-output economics and indicating specific areas where new thinking is required. These misconceptions follow:

Misconception 1 The general form of the basic input-output model is $(I - A)\, x = y$, where all variables are measured in money values.

Fact: The basic input-output model includes both a quantity model and a price model. The quantity model tracks flows of products (goods and services) throughout the economy, and the price model determines their unit prices. This fact is widely ignored because the quantity model is typically implemented in money units, a special case of quantity unit, and the special case is unfortunately mistaken for the general case. The product flows represented in the basic model include mineral commodities but not mineral resources, land, or water. However, the latter can, and should, be represented in the basic input-output model, but they are generally not visible because of the second misconception.

[1] I distinguish three types of mineral resources: fuels, metals (primarily used as materials), and non-metals in their natural settings. The *mineral commodities* are obtained from *mineral resources* by processes that include extraction and preliminary cleaning or concentration. For brevity, I sometimes use the word resources to include all mineral resources as well as land and water.

Misconception 2 Value-added, the difference between a sector's revenues and its outlays for the products produced by other sectors, is a money value without a direct physical counterpart.

Fact: There is a direct physical counterpart to value-added, and this is the appropriate representation for the quantity model. Value-added is the sum of payments to all factors of production, generally defined to include labor and capital. However, mineral resources, land, and water are also factors of production, and the time has come to explicitly include them as such in both quantity and price models. Conceptually, resource flows of factor inputs should not be confounded with inter-industry flows of products in a quantity model. The theoretical significance of their role as sources of value-added in the price model should be simultaneously represented.

Misconception 3 The basic input-output model has two shortcomings that limit its usefulness for industrial ecologists. First, input-output models deal only with flows, but industrial ecologists need to analyze stocks also. Second, input-output models assume a linear relationship between final deliveries and outputs, but non-linear models are needed to adequately represent and analyze many phenomena, namely stock-flow relationships.

Fact: The dynamic input-output model represents stock-flow relationships and has long been recognized as an important extension of the basic input-output model for both theory building and empirical analysis. Other extensions of the basic input-output model are equally important for industrial ecologists, notably the input-output model of the world economy, which captures the sectoral interdependencies across all trading partners. These models do not assume a linear relationship between output and final deliveries (or between product prices and factor prices). Additional model extensions will no doubt be developed in the course of the collaboration of input-output economists and industrial ecologists, and they should likewise not be limited by the assumptions, or the simple mathematical form, of the basic input-output model.

The objective of this chapter, then, is to describe three fundamental properties of input-output economics. The first property is the relation between the quantity input-output model and the price input-output model, a distinction not made frequently enough even by input-output economists. Sectoral outputs and factors are measured in appropriate units, such as tons, kilowatt-hours, or dollars' worth, in the quantity model, while the unit prices of individual factors and products figure in the price model. Just as the quantity model follows the "supply chain," for an individual product or an entire bill of goods, the price model makes it possible to track the "value chain" for the same final deliveries.

Second, value-added is disaggregated into the payments of wages, profits, and rents for specific categories of resources measured in appropriate units. While this step is easily achieved in practice, it is conceptually fundamental and provides the vital and explicit link to collaboration of input-output economists with industrial ecologists by way of energy use, material flows, and increasingly the use of land and water. As Leontief said almost a half century ago in the quote that opens this chapter, each partner's separate interest in the area of overlap is necessary to assure effective collaboration across disciplines. The congruence of value-added and factors of production with material flows is precisely such an area of overlap.

Third, input-output economics is a conceptual framework for analyzing applied problems rather than a particular mathematical formula or a specific body of data. While most applications to date use only the basic linear model, this constitutes only the simplest representation of input-output relationships. Three different types of models are described and contrasted in order to demonstrate how the input-output framework provides conceptual guidance for developing new models to analyze new problems. These start with the simplest example, which like the basic input-output model is still based on a matrix inverse, and progresses to representations of other kinds of relationships.

The rest of the paper is divided into five sections. Section 2 is devoted to a discussion of scenarios about sustainable economic development. The chapter begins with this topic because there is no point in developing new models and techniques until it is clear what questions they are intended to address. Section 3 replaces the most common implementation of a basic input-output model with all variables measured in money units by an equally simple framework that distinguishes a quantity model from a price model and includes an income equation that makes explicit the links between them. Section 4 shows how value-added in the monetized model is replaced by factor quantities including physical measures of all inputs in the quantity model and the corresponding unit prices for resources as well as products in the price model and provides a numerical example for a hypothetical economy to demonstrate the concepts.

The concepts of input-output economics can also be applied to more complex relationships than the models of Sections 3 and 2.4, and the fifth section provides brief descriptions of three important examples. The first example extends the basic model by adding row-and-column pairs describing incomes and outlays of households to the coefficient matrix and then inverting it. The next example is the dynamic input-output model, where profits (row) and investment (column) for each sector are related to the planned increase in production capacity for that sector as represented by a difference equation. The final example is an input-output model of the world economy, represented by a linear program where each region's output is constrained by physical measures of factor availability.

Scenarios About Sustainable Development

While growth is a common criterion for gauging economic progress, it is only one of several considerations for sustainable development, which takes multiple economic, environmental and social considerations equally into account. Defining scenarios for sustainable development is a substantial challenge, and it is discussed briefly in this section. It is an equally demanding but distinct challenge to analyze their plausibility and their implications. Analyzing scenarios about sustainable development requires a model that does not build in assumptions about growth and that can handle the representation of resources and environmental pollution. An input-output framework is ideally suited to analyzing scenarios about prospects for sustainable development.

The purpose of a scenario analysis is to evaluate a scenario by identifying bottlenecks, recognizing unexpected opportunities, and quantifying a variety of implications. Scenarios are both economic and physical: economic in that they reflect assumptions about how people make their livelihoods and use their incomes and physical because they involve assumptions about technological choices, resource use, and environmental degradation. Contrary to the assumptions built in too many kinds of economic models, a scenario may assume the adoption of technologies that are more expensive but environmentally more desirable than the ones they replace, or of lifestyles that involve less rather than more consumption of material goods. Input-output models are well suited to analyzing these kinds of scenarios because the models do not incorporate the maximization assumptions about profits and consumption that are common to virtually all other kinds of economic models. Ultimately a model can be used to analyze a scenario only if the scenario assumptions are well defined and quantifiable in terms of the variables and parameters figuring in the model. The level of detail of an input-output model and the nature of most of its parameters (inputs per unit of output) are well-suited to the representation of scenarios about sustainable development.

I offer one scenario as an example. In this scenario consumers in rich countries shift from high-calorie meat-based diets to a lower overall intake and a mix of foods that is mainly plant-based. This switch is important from an environmental point of view because a plant-based diet is generally less resource-intensive than one based on meat. A change in the diet would be represented by changes in the composition of consumption, requiring different patterns of production. The analysis needs to assess changes in domestic production, in imports and exports, and in the relative prices of different foods. All of these will have an impact on the use of land and water, mineral resources and chemical products, and so on.

At the same time that consumers in the rich countries might be motivated to make such changes in their eating habits, the growing populations of the developing countries will surely aim at adding animal products to their diets. In particular, China can be expected to import increasing quantities of feed grain for livestock, other agricultural and food products, and possibly fresh water. With an input-output model of the world economy, one could evaluate the extent to which less resource-intensive diets in the rich countries could offset future improvements in diets in developing economies and assess the land and water requirements of the scenario, the implication for different sectors in different geographic regions, and the impact on relative prices of agricultural products. For further discussion of this scenario, see (Duchin 2005a). This scenario can also be analyzed in the context of a one-region model, but then changes in the region's imports and exports need to depend on exogenous assumptions.

The Quantity Model and its Price Dual

The Quantity and Price Models

The equation $(I - A)\,x = y$ and the so-called Leontief inverse matrix $(I - A)^{-1}$ are often treated as comprising the entire analytic core of input-output economics. This matrix equation is only the simplest relationship that describes the interdependence of the inputs and outputs of different parts of an economy. Yet this equation alone, coupled with the assumption that all variables are measured in money units, is used in the vast majority of empirical input-output studies, and it is the one into which, increasingly over the past several years, industrial ecologists have incorporated their data on product life cycles and material flows. There is a certain irony in this choice of input-output model for an analysis that accords importance to physical quantities of energy use and material flows, as will become apparent below. The objective of this section is to provide a better alternative.

The familiar equation is only an abbreviated form of the basic input-output model. The full model for an economy described in terms of n sectors requires three equations:

$$(I - A)\,x = y \tag{2.1}$$

$$(I - A')\,p = v \tag{2.2}$$

$$p'y = v'x. \tag{2.3}$$

where A is the $n \times n$ input-output matrix, and x, y, p, and v are $n \times 1$ vectors: x is the vector of output levels, y is final deliveries, p is unit prices, and v is value-added per unit of output. Each sector's output is quantified in a unit appropriate for measuring the characteristic product of that sector. Thus steel and plastics would be measured in tons,[2] electricity in kWh, and computers and automobiles in numbers of standard units (i.e., number of computers of average capability). Even some service sector output may be measured in a physical unit, such as number of insurance policies. However, some sectors have output mixes that are so heterogeneous as to be more usefully measured in the money value of output, say dollars' worth of business services. An input-output model places no restriction on the choice of units for measuring output, whether physical or monetary units, nor does it require that all quantities be measured in the same unit. The resulting table, and the coefficient matrix derived from it, can be constructed with no conceptual difficulty in a mix of units and. In the coefficient matrix A derived from a mixed-unit flow table, the ijth element is equal to the ijth element of the flow table divided by the jth row total (since it makes no sense to calculate the jth column total in a mixed-unit table). The A matrix may instead be constructed directly as a coefficient matrix using engineering information, such as that developed for the use phase of life-cycle studies.

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[2] These would be tons of a standard product, such as a certain quality of steel.

Equation (2.1) is called a quantity input-output model. If variables are measured in physical quantities such as tons or computers, the corresponding technical coefficients are ratios of physical units such as tons of plastic per computer. If y is given, the solution vector x represents the quantities of sectoral outputs.

Equation (2.2) is the input-output price model, and the components of the vector of unit prices are price per ton of plastic, price per computer, etc. For a sector whose output is measured in dollars in Equation (2.1), for example business services, the corresponding unit price is simply 1.0. With this equation one can compute the impact on unit prices of changes in technical coefficients (A) or in value-added per unit of output (v). Finally, Equation (2.3), called the income equation, is derived from the first two: this identity assures that the value of final deliveries is equal to total value-added, not only in the actual base-year situation for which the data have been collected but also under scenarios where values of parameters and exogenous variables are changed.

It generally escapes notice that Equation (2.1) has the attributes of a *quantity* model when, as is most frequently the case, the outputs of all sectors are all measured in money units. One component of the output vector, in money terms, would be the value of the output of plastic or steel, each figure being the implicit product of a quantity and a unit price, but with inadequate information to distinguish the quantity from the price. Under these circumstances, there is no perceived benefit from a separate price model: all elements of the price vector in Equation (2.2) would be 1.0, and the price model is therefore deemed to be trivial. This is a faulty conclusion, however, since even in this extreme case (i.e., where are quantities are measured in a money unit), the price model provides additional information: it yields the percentage *changes* in unit prices associated with changes in A or v. When, as this chapter recommends, some of the variables of the quantity model are measured in nonmonetary physical units, the solution prices are in money values per physical unit.

For industrial ecologists no characteristic of an economic model can be more important than the systematic distinction of quantities from prices and the use of compatible quantity and price relationships. Once the data have been collected for a quantity model, very little additional information is needed to also implement the price model (only the unit prices of factors). Some input-output economists have long made use of mixed-unit quantity with and without corresponding price models; examples are (Duchin 1990; Duchin and Lange 1998; Leontief et al. 1977).

Tracking the Value Chain

The quantity input-output model can track inputs and outputs along the full supply chain by identifying and quantifying both direct and indirect inputs to the final products under analysis. Links in the chain are revealed in the power expansion to the solution for the output vector in the quantity model:

$$x = y + Ay + A^2y + A^3y + \ldots, \tag{2.4}$$

where y is the vector of products delivered and each succeeding term on the right-hand side represents the direct outputs required to deliver the preceding round of inputs. This equation follows from the easily verified fact that $I = (I - A)(I + A + A^2 + A^3 + \ldots)$, or $(I - A)^{-1} = (I + A + A^2 + A^3 + \ldots)$, and from Equation (2.1), $x = (I - A)^{-1}y$. The contribution of each succeeding term is smaller than the one before, so a good approximation to total production, x, is achieved if the righthand side is truncated after several rounds.

While this power expansion is well known, it is less appreciated that the price model can also be written in this form:

$$p = v + A'v + A'^{2}v + A'^{3}v + \ldots \tag{2.5}$$

This equation shows that the price of a product is equal to the value-added paid out in the sector producing the product plus the value-added for all direct inputs and all rounds of indirect inputs. Using the price equation one could disaggregate the price of, say, food into value-added received at the farm, the food-processing sectors, and the supermarket. These conceptual linkages are even more useful when value-added is disaggregated, as below, according to its main factor components.

Factor Inputs: The Conceptual Link Between Economic Value-Added and Resource Flows

Value-Added as Payments to Factors of Production

The case was previously made that an input-output table, or matrix, in only money values obscures the underlying physical flows because it fails to distinguish the quantity from the unit price of a product, for example the number of cars from the price per car or the amount of steel from the price per ton. Nowhere is this shortcoming more strikingly problematic, however, than in the case of value-added.

Also called net output, value added in the input-output tables prepared by statistical offices is essentially the amount paid for the use of labor and capital.[3] But quantities of labor and capital can in principle be measured, and the objective of this section is to replace the monetized notion of value-added by its quantity and price components: quantities of factor inputs for the quantity model and unit prices of factors for the price model. Land, mineral resources, and water are included as factor inputs. Since many sources of water are not priced, it is not surprising that they are left out of monetized accounts. But obviously water has as much claim for inclusion in the analysis of scenarios for sustainable development as land and minerals, resources that are converted to price commodities before being absorbed into the production process.

[3] This ignores the relatively small residual consisting of subsidies and certain taxes.

Mineral resources are generally not included as factors of production because they are considered "free gifts of nature." In input-output tables the mining sectors purchase goods and services from other sectors as well as the labor and capital for transforming the purchased inputs into resource commodities, such as a ton of processed coal or iron pellets or alumina. The sector's commodity output is duly recorded as product, but the resource input of raw coal or iron ore or bauxite is simply not represented! The challenge of this section is to make these resources visible.

For classical economists, rent, the income earned by the owners of land and other resources, was kept conceptually distinct from profits and wages. However, rents on land are not explicitly represented in input-output tables as a component of value-added because they are relatively small for most sectors except agriculture and mining, especially in the industrialized economies, and because economists today treat land as a capital asset that earns profits just like built capital.

Three steps are needed for a proper representation of factors of production: to interpret value-added as payments to factors of production; to add land, water and mineral resources to capital and labor as distinct factors of production with unit prices (wages for labor, profits on capital, and rents or royalties on resources), and to represent the quantities of factors of production in the quantity model and their unit prices in the price model. In this way resource inputs can be represented in the input-output model using the same concepts and units employed by industrial ecologists.

Model with Factor Inputs and Factor Prices

The proposed representation provides direct links from mineral resources and their extraction to the processing and use of mineral commodities in other sectors of the economy. Following these links one can calculate the resource content for any final bill of goods and quantify the use of those resources at all points along the supply chain. In the price model, the rents earned by the owner of the resource, usually the sovereign state where the resource is located, can be distinguished from profits earned in the extracting sector, usually by foreign concessionaires, and at subsequent stages of processing and fabrication. The price model can trace, for a given product, not only the total value-added but also the incomes earned by individual factors in every sector that has contributed to its production. The sum of all these factor incomes, those paid out directly in the producing sector and indirectly in those sectors whose outputs it purchases, is the unit price of the product.

The basic input-output model with explicitly identified factor inputs and factor prices is shown in Equations (2.6–2.9) where value-added, v, is disaggregated into k components, each described by a quantity and a price. Thus $v = F'\pi$, where F is the $k \times n$ matrix of factor inputs per unit of output, and π is the k-vector of factor prices. Defining f as the k-vector of total factor use in physical units, the equations are as follows:

$$(I - A)x = y \tag{2.6}$$

and

$$Fx = f \tag{2.7}$$

$$(I - A')p = F'\pi \tag{2.8}$$

$$p'y = \pi'Fx. \tag{2.9}$$

Numerical Example

This section provides a numerical description of a hypothetical economy using a basic input-output quantity model, price model, and income equation with the explicit representation of resources measured in physical units as factors of production (Equations (2.6–2.9)). The example provides a concrete illustration of the concepts described earlier; in particular it demonstrates the relationships between products and factors and between the quantity model and the price model.

The hypothetical economy in question produces wheat, coal, iron pellets, machinery and electricity using labor, capital, land, raw coal, and iron ore as factors of production. Outputs of the first three sectors are measured in tons; machinery is measured in number of units, and electricity in kWh. Land is measured in hectares, raw coal in tons, iron ore in tons of metal content, labor in person-years, and capital in the money unit, dollars. The coal mining sector extracts and cleans the raw coal and sells a coal commodity while the iron mining sector extracts iron ore and concentrates it to pellets. The factor prices are rents on the resource inputs, the wage rate for labor, and the rate of return on capital. The example quantifies the indirect reliance of other sectors' products on raw coal and iron ore and the portions of the prices of the products that correspond to payments for these factors.

The A and F matrices for the hypothetical economy are shown in Table 2.1. Table 2.2 shows values for the exogenous variables (y and π) and the solution values for endogenous variables (x, p, f, and v), where factor use is calculated as $f = Fx$, and value-added is calculated as payments for all factors per unit of output, or $v = F'\pi$.

According to the F matrix (Table 2.1), raw coal is input only to the coal mining sector, which requires 1.25 t of resource input for each ton of commodity coal. Likewise, iron ore is input only to the iron mining sector, which requires about 1.07 t of resource input for each ton of iron pellets it delivers. The rent on land (see the vector of factor prices, π, in Table 2.2) is assumed to be \$15 per ha per year, the annual rents (or royalties) on raw coal and iron ore are \$5 and \$2 per t, respectively,

Table 2.1 A and F Matrices for a Hypothetical Economy

A matrix	Wheat	Coal mining	Iron mining	Machinery	Electricity
Wheat	0.020	0.000	0.000	0.000	0.000
Coal mining	0.000	0.023	0.214	0.259	0.833
Iron mining	0.000	0.000	0.286	0.556	0.139
Machinery	0.020	0.068	0.143	0.111	0.278
Electricity	0.049	0.045	0.179	0.370	0.056
F matrix	**Wheat**	**Coal mining**	**Iron mining**	**Machinery**	**Electricity**
Land	0.245	0.045	0.107	0.000	0.000
Raw coal	0.000	1.250	0.000	0.000	0.000
Iron ore	0.000	0.000	1.071	0.000	0.000
Labor	0.196	0.182	0.286	0.444	0.056
Capital	0.980	2.727	5.714	11.111	16.667

See text for units.

Table 2.2 Exogenous and Endogenous Variables

	Exogenous Y	Endogenous X	V	p
Wheat	100	102	6.23	9.28
Coal mining	0	44	9.66	15.23
Iron mining	0	28	8.32	35.99
Machinery	5	27	7.56	51.29
Electricity	12	36	4.00	38.06
Land	15	30		
Coal	5	55		
Iron	2	30		
Labor	12	50		
Capital	0.2	1,280		

See text for units.

and wages are \$12 per person-year. The capital stock, consisting of buildings and equipment, is measured in dollars' worth, and the rate of return on capital is 20% (Table 2.2).

To quantify the dependence of all sectors on the individual resource inputs, we calculate the $k \times n$ matrix $F(I-A)^{-1}$, where each entry measures the amount of one factor (corresponding to the row) required directly and indirectly to deliver a unit of final deliveries of the product (corresponding to the column). This matrix is shown as Table 2.3. According to the first and last entries in Table 2.3, 0.265 ha of land are required to deliver a ton of wheat and \$47 of capital to deliver a kilowatt-hour of electricity to final users.

Comparing this matrix with F element by element (Tables 2.1 and 2.3) shows that, even though not all factors are required directly in each sector (i.e., there are zeroes in F), every sector makes use of all factors at least indirectly (i.e., there are only non-zero entries in $F(I-A)^{-1}$). In particular, delivering 100 t of wheat to final users requires (reading down the first column in Table 2.3) 27 ha of land, of which

Table 2.3 Factor Requirements to Satisfy Final Deliveries ($F(I-A)^{-1}$)

	Wheat	Coal	Iron	Machinery	Electricity
Land	0.265	0.074	0.272	0.268	0.184
Raw coal	0.160	1.548	1.500	1.829	2.273
Iron ore	0.087	0.175	2.171	2.336	1.011
Labor	0.287	0.356	1.117	1.739	1.049
Capital	4.438	8.821	33.372	55.355	46.619

See text for units.

Table 2.4 Product Prices Disaggregated by Individual Factors ($\hat{\pi}F(I-A)^{-1}$)

	Wheat	Coal mining	Iron mining	Machinery	Electricity
Land	3.97	1.11	4.07	4.02	2.76
Raw coal	0.80	7.74	7.50	11.68	11.37
Iron ore	0.17	0.35	4.34	3.66	2.02
Labor	3.45	4.27	13.40	20.87	12.58
Capital	0.89	1.76	6.67	11.07	9.32
Unit Price	9.28	15.23	35.99	51.29	38.06

Unit prices as total payments to factors. Column headings refer to products and row headings to factors.

most (25) is used directly to grow the wheat, but also 16 t of raw coal and 9 t of iron ore, both of which are entirely attributable to their use in the production of machinery and electricity purchased by establishments in the wheat sector.

Following a similar logic, unit prices can be disaggregated, using Equation (2.8), into the portion paid, directly and indirectly, to each factor of production. Table 2.4 shows the matrix $\hat{\pi}F(I-A)^{-1}$, with the elements of the price vector (being the column totals) as the bottom row.[4]

Thus the income from a ton of wheat (column 1 of Table 2.4) is paid out mainly for land ($3.97) and labor ($3.45) for a total of $7.42 out of $9.28, of which most of the labor and almost all the land are used directly in the production of wheat (seen by comparing with the components of $\pi'F$). By contrast, about 30% of the price of a machine ($11.68 plus $3.66, or $15.34, out of $51.29) or a kWh of electricity ($11.37 plus $2.02, or $13.39, out of $38.06) goes to pay rents for resources, even though neither resource is directly exploited by these sectors.

Scenario About Resource Degradation

Now consider a simple scenario where the same economy is forced to extract iron ore with a lower metal content. The objective is to quantify how much this deterioration will cost the economy, in terms of the use of resources, the production

[4] From Equation (2.9) we know that $p' = \pi'F(I-A)^{-1}$; using $\hat{\pi}$ (a diagonal matrix) in place of π in the equation provides a disaggregation of p into individual factors.

of output, and price increases, relative to the baseline. We assume that this resource deterioration requires of the iron-mining sector 20% more machinery and electricity and 20% more labor and capital to convert a larger quantity of lower-grade ore (in order to achieve a given metal content) to a ton of iron pellets.

Redoing the calculations (using Equations (2.6–2.9) and the new input coefficients) shows higher sectoral output levels, factor use, and unit prices. Total factor payments increase 6% from $1,641 to $1,755 to deliver the same quantities of output to final users. Most outputs and most factor inputs, except for wheat and land, increase by about 10%. The unit price increase is steepest for the iron commodity (23%) and substantial for machinery (14%), since the latter makes intensive although indirect use of iron ore. It is lowest for wheat and the coal commodity (4% each), which make little use of iron ore either directly or indirectly.

Closure of the Basic Input-Output Model for Consumption, Investment, and Trade

"Closure" of the Basic Model

The basic input-output model is an "open" model for a single country or other geographic region and a single time period. The openness refers to the fact that consumption, investment, and exports are all columns of final deliveries whose levels are exogenous – that is, specified from outside the model – rather than being endogenously determined by the model. Thus there is no way to assure that, under alternative scenarios, outlays for consumption will be consistent with the endogenous earnings of labor, that investment will be consistent with earnings on capital stock, and that exports and imports will shift in consistent ways.

The basic model can be used to address many kinds of questions about economic interdependency that cannot be approached in other ways. This fact accounts for its continuing popularity. However, analyzing scenarios about sustainable development runs up against limitations of the basic model, notably the fact that consumption, investment, and trade levels are exogenous. The three extensions of the basic input-output model described in this section have been developed to meet this challenge. First, the input-output model is said to be closed for households when consumption and employment are made endogenous by relating them through one or more mathematical equations. In the simplest case, the earnings of labor are distinguished from other components of value-added and directly linked to household consumption, thus "closing" the model for households. Second, a dynamic input-output model is described that relates product flows to capital stocks. The dynamic model disaggregates the return on capital from other components of value-added and provides closure for investment outlays and the return on capital. Investment flows are associated with increases in the capital stock, and the price of the product includes a return on the capital stock required for its production. Finally, a world model results when the one-region model is closed for trade flows with all potential trade partners. An input-output model of the world economy with trade based on comparative advantage provides closure for a region's imports and exports by linking them to production and trade of all other regions. This trade model accords a prominent theoretical role to factor endowments, the total physical supply in each potential trade partner of each factor of production.

There are many ways of achieving closure for a model that contains an input-output matrix. The resulting model remains an input-output model only if the closure is multi-sectoral, that is, involves all sectors simultaneously. Thus in a dynamic input-output model the magnitude and composition of investment are determined at a sectoral level, and capital goods ordered by one sector are produced in the appropriate quantities and with designated time lags by the sectors producing those particular capital goods. This approach to closure is different from a dynamic model with an aggregate investment function for the economy as a whole or one with sectoral production functions that do not specify the sectoral composition of investment. It is also to be distinguished from the simplest kind of closure, described below for household consumption, where rows and columns are added to the coefficient matrix, which is then inverted.

The simplest closure for the basic input-output model retains the assumption of a linear relationship between output and final deliveries in the quantity model and between prices and value-added in the price model. This is the case in the closure for households described below. The second example of a dynamic input-output model makes use of a matrix difference equation with relationships that are no longer linear functions of final deliveries and value added. The final example utilizes a linear program, where production and consumption in each region are subject to constraints on the availability of the factors of production, inducing both trade flows in the quantity model and rents on scarce factors in the price model. In the linear program, both the objective function and the constraints are linear functions of the independent variables (as the name "linear program" implies), but the relationships between output and final deliveries, and between prices and value-added, are no longer linear.

These closures require additional information in the form of new variables and parameters as well as additional assumptions about the logic of the relations among these variables and between them and those of the basic model. While the three individual closures have been achieved and implemented, there is at this time no operational input-output model that is simultaneously closed for consumption, investment, and trade: this would be a dynamic world model closed for households.

Household Consumption

The closure of the basic input-output model for households provides the best example of a true conceptual extension to the basic model, but one that can still be represented with the same mathematical model, a linear relationship of the key variables involving a matrix inverse. This kind of model will be useful for the study of sustainable consumption. Industrial ecologists are concerned mainly with production and technology, but in the last few years they have turned increasing attention to the industrial ecology of household consumption (Hertwich 2005). This focus reflects the conviction that technological change cannot deliver sustainable development in the absence of changes in household lifestyles, mainly behaviors regarding diet, housing, and mobility. Changes in household consumption patterns have direct and indirect effects on factor use, including resources and employment, as well as on household income, and these in turn feedback on consumption. Closure of the basic input-output model for households captures this feedback loop and assures that household income and consumption outlays are consistent. The idea of extending an input-output table in this way is attributed to Stone, who made major contributions to national accounting (Stone 1975), with other particularly important contributions by Pyatt and Thorbecke (1976) and Keuning (1995) among others.

The simplest closure for households is achieved by starting from the $n \times n$ A matrix and adding one column and one row so that the resulting matrix is of dimensions $(n + 1) \times (n + 1)$. The new column of consumption coefficients is taken from final deliveries, and the new row of labor coefficients comes from factor inputs. If the output of households in the quantity model is number of workers, the row unit is workers per unit of each sector's output and the column unit is consumption per worker. In the price model, the unit price for the household sector is the wage rate. The matrix is manipulated in exactly the same way as its $n \times n$ counterpart, and a matrix inverse is calculated to provide a solution to the linear system. (If household output in the quantity model is measured in money values, the row unit is employee compensation per unit of sectoral output and the column unit is outlays for a given sector's product as a share of the total value of consumption.)

With the closure for household consumption, an important relationship has become endogenous. Now if changes are made in the A matrix, economy wide labor requirements, consumption quantities, the wage rate, and product prices will all adjust consistently. The quantity model using the expanded matrix now assures that enough labor is employed to satisfy consumption requirements, and the price model assures that wages are adequate to cover workers' costs of production, i.e., to purchase the consumption bundle.

The social accounting matrix (or SAM) is the name given to the extension of an input-output table that treats other categories of final deliveries in the way just described for households. (The name social accounting table would have been less confusing.) The SAM is converted to a coefficient matrix and manipulated like an input-output table. In this way it makes explicit the links between different categories of value-added (factors used and income earned) and corresponding categories of final deliveries (deliveries made and income spent). Today SAMs are compiled in many statistical offices, mainly in developing countries, as part of their National Accounts. They may contain several categories of households and different types of workers. Like input-output tables, they are generally compiled and analyzed in money values only. Duchin developed a mixed-unit SAM for Indonesia and constructed quantity and price models to analyze a scenario about technological changes (Duchin 1998). The analysis demonstrated that what may look like an increase in income for a certain category of household when analyzing only a money-value SAM may in fact be an increase in the number of such households coupled with not an increase but actually a decline in the average income per household.

Dynamic Model

The capital stock consists of infrastructure, buildings, machinery and equipment that are essential for production and consumption. These durable goods require energy, materials and other resources for their production, and after their economic or physical lifetime is exhausted, they are a major source of wastes and a secondary source for materials. The dynamic input-output model represents the demand for capital goods on the part of each producing sector and provides sectoral detail for the input requirements for resources and products to produce the capital goods.

Leontief formulated the dynamic input-output model shown in Equation (2.10) in terms of a difference equation with dated coefficient matrices, including a new matrix describing capital requirements (the B matrix), that distinguished technological structures at different points in time (Leontief 1970). The exogenous vector of investment, formerly part of final deliveries, was replaced by an expression where a matrix of stock-requirement coefficients is multiplied by the anticipated increase in output between the present time period and the subsequent period. This is written for the quantity model as a difference equation:

$$(\mathrm{I} - \mathrm{A}_t)\mathrm{x}_t - \mathrm{B}_{t+1}(\mathrm{x}_{t+1} - \mathrm{x}_t) = \mathrm{c}_t, \tag{2.10}$$

where c_t includes all final deliveries except investment goods. Interestingly, Leontief entitled the article "The Dynamic Inverse," stressing the fact that this was a linear system that could still be represented by a matrix and its inverse.

Unfortunately, this version of the model has features that limit its usefulness for empirical investigation: nonnegative solutions for the output vectors cannot in general be assured. Duchin and Szyld (1985) relaxed some of the unrealistic constraints in Leontief's model by defining two additional variables: each sector's production capacity and additions to capacity during a given time period. The new model introduced a non-linearity by allowing for unused capacity when output is falling: no expansion of capacity takes place if there is unused capacity, so a sector can fail to grow and still function normally (rather than having its capital stock turned back into raw materials when the investment term, $\mathrm{B}_{t+1}(\mathrm{x}_{t+1} - \mathrm{x}_t)$, becomes negative). This characteristic made the dynamic input-output model operational for empirical analysis and is particularly well suited for analyzing scenarios that focus on development and not on growth. The model was used in an empirical investigation of the impact of computer-based automation on employment in the US over the period from 1963 to 2000 (Leontief and Duchin 1986), and a related model was used by Edler and Ribakova (1993) in a study of technological change in the German economy. The first empirical study using both dynamic quantity and price models was carried out by Duchin and Lange (1992).

Time distinguishes stocks from flows: it takes time to accumulate capital stocks, and they are durable goods with a longer lifetime than other products. The dynamic input-output model described above deals with the time lags required to put new capacity in place: only a uniform 1-year lag is represented in the simple version of Equation (2.10). Leontief and Duchin (Duchin and Szyld 1985) also represented the replacement of existing capacity as durable goods become worn out or obsolete. No attempt has yet been made to use the dynamic input-output model to determine the potential of the depleted capital stock for reuse or for recycling of materials.

Trade

Challenges to sustainable development involving the extraction, processing, use, disposal, and reuse of resources are of a global nature. Many of the poorest economies are heavily dependent on agricultural production and resource extraction for export earnings. Their economic well-being depends upon the quantities of resources they can export and the prices of these exports relative to the cost of their manufactured imports (i.e., their terms of trade). Important influences are: barriers to trade in potential importers, including escalating tariffs (where the tariff is low on a raw material but progressively higher as the resource is more highly processed), and the amount of rent or royalty received by the owner of a resource relative to the profits earned by the industry that extracts and markets it – especially when the profits are earned in another country.

The first input-output model of the world economy was conceived by Leontief (1975) and implemented by Leontief et al. (1977) to analyze scenarios about future economic development. It required a massive data collection effort and represented a major computational challenge for that time. It was run as a mixed-unit quantity model with rudimentary elements of a price computation and rudimentary dynamics. There was no attempt to base trade flows on comparative costs. That model was subsequently refined and the database expanded and updated for more specialized empirical studies, including the projection of future mineral and energy use (Leontief et al. 1983) and evaluation of a scenario for sustainable development (Duchin and Lange 1994). This and many other models of the world economy can be used only by teams of researchers: they require a far larger number of exogenous assumptions and far more data than one-region models, and their use is cumbersome and labor-intensive. Such models have not been of much interest to theorists, including trade theorists, because they do not incorporate a concept of comparative advantage.

Recently Duchin revisited this framework in ways that should make it easier and more attractive to use. The new framework includes both a quantity model and a price model, and both are based on a fully general and operational conception of comparative advantage with production limited by resource availability (Duchin 2005b). It assigns a crucial role to resource endowments in different geographic regions as physical constraints on production and calculates scarcity rents even on unpriced resources, such as fresh water. These constraints introduce non-linearity into the model. Called the World Trade Model, it is a linear programming model of the world economy: the primal and dual correspond to the quantity and price input-output models, respectively, while the equality of the primal and dual objective functions corresponds to the income equation of a one-region model.

The World Trade Model offers several practical advantages. Because it has more theoretical structure about trade than its predecessor, the new model requires many fewer and simpler equations. Data requirements are also lower: for each country or region it requires only the information base of the basic input-output model plus a vector of total factor availability (e.g., coal reserves or the size of the labor force) and a vector of factor prices. The World Trade Model retains many features of the Leontief, Carter and Petri model, but in addition it makes a fully multisectoral determination of endogenous trade flows and product prices. In line with its intended use for analyzing scenarios about sustainable development, it minimizes factor use for given (exogenous) regional consumption rather than maximizing consumption for given factor use.

A country's requirements for resources, goods, and services may be met through domestic extraction and production or else through imports that are purchased in exchange for exports. In principle a country trades when it is cost-effective to do so, and changes in technologies and consumption patterns impact the calculation of cost-effectiveness. This calculation requires a direct comparison of the cost structures in all potential trading partners. Such comparisons cannot be achieved in a one-region framework.

Concluding Comments

Fuels, materials, other minerals, land and water are crucial for sustaining life both directly and indirectly through their roles in the production of goods and services. The ways in which we use resources are the single most important consideration for environmental degradation. Resource use is the common concern of input-output economists and industrial ecologists. The two groups have common interests in the availability of many types of data and mathematical models for analyzing the use of resources. But in both cases the inquiries need to be driven by the questions to be addressed rather than by what data have been collected or what techniques are in the toolkit. At the extreme, it is more useful to ask probing questions and address them in a preliminary way with scanty data and simple methods than to analyze trivial questions or carry out only formal exercises with highly massaged databases and elaborate techniques. All the better, of course, to address important questions with ample, high-quality data and relevant models.

Globalization today involves an unprecedented extent of transfer of technologies and emulation of institutions and lifestyles. The fact that resources are unevenly distributed over the globe lends critical importance to the terms on which they are obtained and the division of labor in processing them. The prospects for dramatic changes in building design and material use, the substitution prospects for specific resources in different uses, the magnitude of recycling that is practical to achieve – all these are questions to be addressed. We need to formulate the big questions to frame our subject and only then determine what data and methods may be needed to address them. I am optimistic that we can make striking progress at this time in these directions through the collaboration of industrial ecologists with input-output economists.

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Chapter 3
Industrial Ecology and Input-Output Economics: A Brief History

Sangwon Suh and Shigemi Kagawa

Introduction

It has been only a few hundred years since human society escaped from a constant cycle of ebb and flow of population changes. Famines and epidemics were mingled with preindustrial European and Asian history, repeatedly setting the human population of the region several decades to hundreds years back (Braudel 1979). It was industrialization, together with the green revolution, that enabled humans to manipulate the untamed nature, setting the humankind free from the famines and epidemics that kept its population at a much lower level throughout its history. The burst of human population in recent centuries, however, is not only a consequence of industrialization but in a sense also a cause of industrialization. Fulfilling the needs by the unprecedented number of people required intensification and efficiency in industrial and agricultural production, which in turn helped generate more economic surplus enabling consuming even more. The human kind seemed to have won an autonomy, of which the prosperity somehow self-catalyzes and works independently from the means that the nature provides.

Ironically, however, humans became more dependent upon the natural environment both as a source of natural resources and as a sink of wastes and pollution. Despite the remarkable technological developments, population growth and improvements in welfare demanded an unprecedented amount of natural resources withdrawal from and wastes and pollutants disposal to the nature. Global crude oil extraction, iron ore mining, and underground water withdrawal, to name a few, are at their highest to satisfy the needs of the ever wealthier and populous human-kind.

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Around 26 billion barrels of crude oil are extracted every year (EIA 2008), enough to fill over five Olympic-size stadiums every day (Suh 2004a). Per capita copper use until 1900 is estimated to be below 1 kg/year, which has become around 15 kg/year by 2000 (Gordon et al. 2006). The U.S. total materials use is estimated to be less 200 million metric tons at the dawn of the twentieth century, and it reached nearly 3,000 million metric tons by 1995 (Gardner and Sampat 1998).

All the non-renewable resources extracted from the environment are processed, transformed, used, and discarded; but after being discarded they persist somewhere in the nature or in the built environment in a variety of different physical forms. As a general pattern, stable chemicals, which had been safely isolated under the Earth's crust in the form of ores, crude oil and natural gas, are now present instead in more active and available forms. Many of the pollutants that are considered to be the causes of modern environmental problems, such as CO_2, heavy metals and other toxic substances, were extracted from the environment or synthesized thereof at an earlier stage of their life cycles. Thus, the extraction of natural resources for economic use is closely connected with the environmental problems by the intricate channels by which the modern economy transforms, uses and disposes of the inputs and outputs of the production system. Therefore, understanding the structure of the economy that governs material and energy flows between producing industries and consuming households is indispensable for solving the problems of both limited availability of natural resources and pollution.

Recognizing the inherent linkage between natural resource use and pollutant emissions, industrial ecology takes a systems approach that addresses the problems at both ends of the production chain. Industrial ecology aims at closing material cycles within the industrial system by developing symbiotic relationships among industries (Frosch and Gallopoulos 1989; Graedel and Allenby 1995; Ayres and Ayres 1996; Graedel 2002a).[1] In industrial ecology, an industrial system is viewed as a complex organism that processes energy and materials under its own metabolic rules (see, e.g., Kneese et al. 1970). How industrial systems are structured and how they transform, use and discard natural resources is therefore the major focus of industrial ecology.

Input-output economics describes and analyzes the structure of an economy in terms of the interactions among industries and between them and households. Thus, the relevance of input-output economics for industrial ecology seems evident. While this overlap of concerns was already recognized in the early years of the young field of industrial ecology (Duchin 1990, 1992; Lave et al. 1995), and some progress has certainly been made in exploiting it, widespread communication and effective collaboration between the two disciplines are still at an early stage.

[1] A discussion of the definition and goals of industrial ecology is provided by (Lifset and Graedel 2002).

History of Input-Output Analysis in Industrial Ecology

Industrial Ecology

As described in the previous section, industrial ecology seeks to close material cycles by developing symbiotic relationships among industries. One application of this concept is the so-called Eco-Industrial Park (EIP), such as Kalundborg in Denmark, where an industrial complex was evolved or designed to maximize the use of internal outputs and wastes from one establishment in another and to minimize the resource inputs and wastes associated with the entire complex (Ehrenfield and Gertler 1997; Chertow 1998). To our knowledge, such an idea was first articulated in the English-speaking world by Barry Commoner (Commoner 1971). In his book, *The Closing Circle*, Commoner simply but accurately described the origin of environmental problems as the lack of closing circles in the exchange of materials between society and the environment. If the 'circles' of material utilization indeed could be closed within the industrial systems by efficiently managing materials, environmental problems associated with virgin material inputs and waste outputs could be more systematically handled. His idea was not, however, widely hailed by the scientific community at that time. Besides Commoner's admonitions, several studies conducted in Belgium and Japan in the 1970s were concerned with the same issue, and they even used a term that would be translated as 'industrial ecology' in English (Erkman 1997).

It was clearly Frosch and Gallopoulos (1989), however, who coined the term 'industrial ecosystem' and drew broader international attention to the concept, providing critical momentum for developing industrial ecology as a distinct scientific field. Under the leadership of these authors, the National Academy of Engineering of the United States played an important role in hosting and further building industrial ecology discourses. Since then the field has not only diversified but also deepened in many respects embracing, e.g., Life Cycle Assessment (LCA), Material Flow Analysis (MFA), EIP development, sustainable production and consumption, earth systems engineering, policy analysis, etc. (Graedel and Allenby 1995; Ayres and Ayres 1996; Ehrenfield and Gertler 1997; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Allenby 1999a; Matthews et al. 2000; van der Voet et al. 2000; Graedel 2002a; Graedel 2002b; Hertwich 2005). To better facilitate communication within the growing industrial ecology community, the *Journal of Industrial Ecology* was launched in 1997. The first Gordon Research Conference in Industrial Ecology was held in 1998 and now takes place on a biennial basis. The International Society of Industrial Ecology (ISIE) was created in 2001, with its first biannual international conference held in Leiden in the same year.

Input-Output Analysis in Industrial Ecology: Historical Roots and its Propagation

Although it was the pioneering contributions by Duchin (1990, 1992) that explicitly made the link between input-output economics and industrial ecology, developments in input-output economics had previously touched upon the core concept of industrial ecology. Wassily Leontief himself incorporated key ideas of industrial ecology into an input-output framework. Leontief (1970) and Leontief and Ford (1972) proposed a model where the generation and the abatement of pollution are explicitly dealt with within an extended IO framework. This model, which combines both physical and monetary units in a single coefficient matrix, shows how pollutants generated by industries are treated by so-called 'pollution abatement sectors.' Although the model has been a subject of long-standing methodological discussions (Flick 1974; Leontief 1974; Lee 1982), its structure captures the essence of industrial ecology concerns: abatement of environmental problems by exploiting inter-industry interactions. As a general framework, we believe that the model by Leontief (1970) and Leontief and Ford (1972) deserves credit as an archetype of the various models that have become widely referred to in the field of industrial ecology during the last decade, including mixed-unit IO, waste IO and hybrid Life Cycle Assessment (LCA) models (Duchin 1990; Konijn et al. 1997; Joshi 1999; Nakamura and Kondo 2002; Kondo and Nakamura 2004; Kagawa et al. 2004; Suh 2004b). Notably, Duchin (1990) deals with the conversion of wastes to useful products, which is precisely the aim of industrial ecology, and subsequently, as part of a study funded by the first AT&T industrial ecology fellowship program, with the recovery of plastic wastes in particular (Duchin and Lange 1998). Duchin (1992) clarifies the quantity–price relationships in an input-output model (a theme to which she has repeatedly returned) and draws its implications for industrial ecology, which has traditionally been concerned exclusively with physical quantities.

Duchin and Lange evaluated the feasibility of the recommendations of the Brundtland Report for achieving sustainable development. For that, Duchin and Lange (1994) developed an input-output model of the global economy with multiple regions and analyzed the consequences of the Brundtland assumptions about economic development and technological change for future material use and waste generation. Despite substantial improvements in material efficiency and pollution reduction, they found that these could not offset the impact of population growth and the improved standards of living endorsed by the authors of the Brundtland Report.

Another pioneering study that greatly influenced current industrial ecology research was described by Ayres and Kneese (1969) and Kneese et al. (1970), who applied the mass-balance principle to the basic input-output structure, enabling a quantitative analysis of resource use and material flows of an economic system. The contribution by Ayres and Kneese is considered as the first attempt to describe the metabolic structure of an economy in terms of mass flows (see Ayres 1989; Haberl 2001).

Since the 1990s, new work in the areas of economy-wide research about material flows, sometimes based on Physical Input-Output Tables (PIOTs), has propelled this line of research forward in at least four distinct directions: (1) systems conceptualization (Duchin 1992, 2009), (2) development of methodology (Konijn et al. 1997; Nakamura and Kondo 2002; Hoekstra 2003; Suh 2004c; Giljum and Hubacek 2004; Dietzenbacher 2005; Dietzenbacher et al. 2009; Weisz and Duchin 2005), (3) compilation of data (Kratterl and Kratena 1990; Kratena et al. 1992; Pedersen 1999; Ariyoshi and Moriguchi 2003; Bringezu et al. 2003; Stahmer et al. 2003), and (4) applications (Duchin 1990; Duchin and Lange 1994; Duchin and Lange, 1998; Hubacek and Giljum 2003; Kagawa et al. 2004). PIOTs generally use a single unit of mass to describe physical flows among industrial sectors of a national economy. In principle, such PIOTs are capable of satisfying both column-wise and row-wise mass balances, providing a basis for locating materials within a national economy.[2] A notable variation in this tradition, although it had long been used in input-output economic studies starting with the work of Leontief, is the mixed-unit IO table. Konijn et al. (1997) analyzed a number of metal flows in the Netherlands using a mixed-unit IO table, and Hoekstra (2003) further improved both the accounting framework and data. Unlike the original PIOTs, mixed-unit IOTs do not assure the existence of column-wise mass-balance, but they make it possible to address more complex questions. Lennox Turner, Hoffman, and McInnis (2004) present the Australian Stocks and Flows Framework (ASFF), where a dynamic IO model is implemented on the basis of a hybrid input-output table. These studies constitute an important pillar of industrial ecology that is generally referred to as Material Flow Analysis (MFA).[3]

Although the emphasis in industrial ecology has arguably been more on the materials side, energy issues are without doubt also among its major concerns. In this regard, energy input-output analysis must be considered another important pillar for the conceptual basis of ‘industrial energy metabolism.’ The oil shock in the 1970s stimulated extensive research on the structure of energy use, and various studies quantifying the energy associated with individual products were carried out (Berry and Fels 1973; Chapman 1974). Wright (1974) utilized Input-Output Analysis (IOA) for energy analysis, which previously had been dominated by process-based analysis (see also Hannon 1974; Bullard and Herendeen 1975; Bullard et al. 1978). The two schools of energy analysis, namely process analysis and IO energy analysis, were merged by Bullard and Pilati (1976) into hybrid energy analysis (see also van Engelenburg et al. 1994; Wilting 1996). Another notable contribution to the area of energy analysis was made by Cleveland et al. (1984), who present a comprehensive analysis, using the US input-output tables, quantifying the interconnection of energy and economic activities from a biophysical standpoint (see

[2] Recent discussions have focused on the treatment of ‘disposal to nature’ in a PIOT. Interested readers are encouraged to consult Hubacek and Giljum (2003), Suh (2004c), Giljum and Hubacek (2004), Dietzenbacher (2005), Dietzenbacher et al. (2009), Weisz and Duchin (2006).

[3] The same acronym is sometimes used in the input-output domain to refer to Minimal Flow Analysis (see, e.g., Schnabl 1994 1995). In this text MFA means only Material Flow Analysis.

Cleveland 1999; Haberl 2001; Kagawa and Inamura 2004). These studies shed light on how an economy is structured by means of energy flows and informs certain approaches to studying climate change (see, e.g., Proops et al. 1993; Wier et al. 2001).

What generally escapes attention in both input-output economics and industrial ecology, despite its relevance for both, is the field of Ecological Network Analysis (ENA). Since Lotka (1925) and Lindeman (1942), material flows and energy flows have been among the central issues in ecology. It was Hannon (1973) who first introduced concepts from input-output economics to analyze the structure of energy utilization in an ecosystem. Using an input-output framework, the complex interactions between trophic levels or ecosystem compartments can be modeled, taking all direct and indirect relationships between components into account. Hannon's approach was adopted, modified and re-introduced by various ecologists. Finn (1976,1977), among others, developed a set of analytical measures to characterize the structure of an ecosystem using a rather extensive reformulation of the approach proposed by Hannon (1973). Another important development in the tradition of ENA is so-called environ analysis. Patten (1982) proposed the term "environ" to refer to the relative interdependency between ecosystem components in terms of nutrient or energy flows. Results of environ analysis are generally presented as a comprehensive network flow diagram, which shows the relative magnitudes of material or energy flows between the ecosystem components through direct and indirect relationships (Levine 1980; Patten 1982). Ulanowicz and colleagues have broadened the scope of materials and energy flow analysis both conceptually and empirically (Szyrmer and Ulanowicz 1987). Recently Bailey et al. (2004a, b) made use of the ENA tradition to analyze the flows of several metals through the US economy. Suh (2005) discusses the relationship between ENA and IOA and shows that Patten's environ analysis is similar to Structural Path Analysis (SPA), and that the ENA framework tends to converge toward the Ghoshian framework rather than the Leontief framework although using a different formalism (Defourny and Thorbecke 1984; Ghosh 1958).

Recent Progress

Recent developments have situated LCA, a key subfield of industrial ecology, as one of the areas that most extensively utilize IOA.[4] LCA is a tool for quantifying and evaluating the environmental impacts of a product over the course of its entire lifecycle (ISO 1998; Guinée et al. 2002). Similar to the energy analyses in the 1970s, LCAs have been generally based on so-called process-analysis, where information identifying and quantifying inputs and outputs of a product system is collected at the detailed unit-process level. As collecting process-level data is time-consuming

[4] In this chapter we use the term input-output analysis, or IOA, to denote concepts and methods first developed by input-output economists but now used extensively also by practitioners who are not economists.

and costly, it has been the general practice in conducting LCA to focus only on a selected set of processes causing so-called truncation errors (Lave et al. 1995; Lenzen 2000). Addressing the problem of truncation, Moriguchi et al. (1993) applied both IOA and process analysis in calculating the life-cycle CO_2 emissions of automobiles in Japan, forming a hybrid LCA approach. Nevertheless it was the series of studies at Carnegie Mellon University that provided a critical impetus in this direction of research under the banner of "Environmental Input-Output Life Cycle Assessment" or EIO-LCA (Lave et al. 1995; Flores 1996; Horvath and Hendrickson 1998; Hendrickson 1998; Joshi 1999; Hendrickson and Horvath 2000; Rosenblum et al. 2000; Matthews and Small 2001).[5] Lave et al. (1995) utilized the rich environmental statistics of the US and constructed a comprehensive environmental IO database for use in LCA. The tradition of input-output LCA in Carnegie Mellon University has been diversified addressing various issues, notably building materials and infrastructure (see, e.g., Horvath and Hendrickson 1998; Horvath 2004),[6] information infrastructure (Matthews et al. 2002), hybrid LCA (Joshi 1999; Matthews and Small 2001) and heavy metal flows in the US. Currently IOA is an important part of LCA practice and both methods and data for IO- and hybrid LCA are under rapid development (see Norris 2002; Lenzen 2002; Suh and Huppes 2002, 2005; Lenzen et al. 2004; Suh 2004b; Suh et al. 2004).[7]

The recent contributions of Faye Duchin and her colleagues situate studies based on both input-output economics and industrial ecology in a global framework. The World Trade Model developed by Duchin (2005) is a linear program that solves for both physical flows and associated prices on the basis of comparing physical stocks and technologies, and the associated cost structures, in all potential trade partners. The model has been used to examine the global implications of the changes in agricultural land yields due to future climate change (Juliá and Duchin 2005) and to evaluate the global trade-offs between cost-reduction and reduction in carbon emissions (Strømman et al. 2005).

Another area where IOA is widely used in conjunction with industrial ecology is the product policy field. The value of Integrated Product Policy (IPP) became widely acknowledged within European policy frameworks, notably the sixth Environmental Action Programme (EC 2001a). The product-oriented life-cycle approach taken by IPP was regarded as an important innovation in Environmental policy directives. In 2003, the European Commission adopted a Communication (EC 2003) that identifies products with the greatest potential for environmental improvement as a basis for implementing IPP. This involves quantifying environmental impacts of various products in an economy and investigating further the identified target products.

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[5] The heavily accessed web-based database of <www.eiolca.net> provide online LCA database based on 1992 and 1997 US benchmark IOTs.

[6] Acknowledging his achievements toward industrial ecology, including his contributions to EIO-LCA and industrial ecology of infrastructure, the ISIE awarded the second Laudise prize to Arpad Horvath in 2005.

[7] The International Journal of Life Cycle Assessment, which is the only international journal devoted entirely to the development of LCA, launched a section on IO- and hybrid LCA in 2004.

Naturally, IO-LCA has been recognized as one of the approaches well suited to IPP analyses. Weidema et al. (2004), for instance, compiled an international IO table with environmental extensions and utilized it for prioritizing environmentally important products in Denmark. Tukker et al. (2005) analyzed environmentally important products in EU25 using an environmentally extended input-output table where consumption is endogenous.[8]

IOA is rapidly broadening its scope of application in industrial ecology on other fronts as well. Ukidwe and Bakshi (2004) applied the second law of thermodynamics, or the entropy law, for the US economy using an input-output framework to analyze degradation of energy quality along the production chain of a product (see also Ukidwe et al. 2009). Many input-output tables are now supplemented with data on natural resource use and environmental emissions at an industry level of detail. Notable progress in this line of development includes the increasing number of natural resource accounts such as water accounts, land accounts and forestry accounts (see, e.g., Vincent 1997; Hellsten et al. 1999; Hubacek and Giljum 2003; Lange et al. 2003), which parallel the corresponding evolution in accounting systems such as Systems of Environmental and Economic Accounts (SEEA) and National Accounting Matrices including Environmental Accounts (NAMEA) (see, e.g., de Haan and Keuning 1996; EC 2001b; UN 2003).

Future of Input-Output Economics in Industrial Ecology

There are notable commonalities of intellectual grounds shared by Input-Output Economics and Industrial Ecology. In introducing Earth Systems Engineering and Management (ESEM), Braden Allenby advanced the idea that the world has become an artifact, by which he means that increasingly numerous aspects of the world have become part of engineered systems that are managed by humans (Allenby 1999b, 2000; see also Keith 2000). Whether such a change is desirable or not is debatable, the direction of change seems difficult to refute: as human influence over the physical, chemical and biological metabolism of the earth system becomes increasingly dominant, our $56 trillion economy needs a managerial ethos that matches the magnitude of the challenges, and industrial ecology undertakes to provide one. By contrast with other approaches to economics, which emphasize market competition based on self-interested, "rational" behavior on the parts of individual agents, input-output economics lends itself more readily to the analysis of alternative approaches to managerial and policy decision-making.[9]

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[8] Similar projects are currently being undertaken in Sweden (Wadeskog A. 2005, Personal communication).

[9] Karen Polenske has pointed out that compilation of input-output tables has been criticized in the US on the grounds that input-output analysis was a communistic idea, while it has been criticized in China on the grounds of its capitalistic orientation.

The strong emphasis on a systems view is another commonality between the two fields. One of Wassily Leontief's motivations in developing input-output theory was the recognition of the limitations of "partial" analysis. In his autobiography for the Nobel Foundation he noted: "[P]artial analysis cannot provide a sufficiently broad basis for fundamental understanding." The message, which points out that an analysis based on only part of a system may be misleading if it neglects strong interactions with the embedding system, is precisely the one industrial ecology endorses.

Both input-output economics and industrial ecology place strong emphasis on real-world data. Many of the research efforts in industrial ecology are devoted to developing sound empirical knowledge on how materials flow and accumulate around the globe (Lave et al. 1995; Matthews et al. 2000; Graedel 2002b; Nansai et al. 2003; Graedel et al. 2004; Suh 2004d). The importance of empirical grounding for an economic model has nowhere been stressed more than in input-output economics since its inception. In one of his speeches to the materials science community, Leontief stated (Leontief 1975):

> A model is essentially a theoretical construct which enables us, starting with some actual or hypothetical data, to arrive at some interesting empirical conclusions. It must start on the ground. It must end on the ground. In between, you can fly as high as you want, but land on the ground again. There are too many models which are still flying.

Given these common intellectual grounds between the two disciplines, what are the roles played by input-output economics in the field of industrial ecology? We choose to reflect on the main patterns of how IOA has been, and is being, utilized in the context of industrial ecology.

Most importantly, IOA has always had the ambition to facilitate interdisciplinary research by connecting different disciplines. Despite its conceptual and operational simplicity, the input-output framework encompasses price and quantity relationships, production factors and technology, income distribution, labor and capital investments, international trade, dynamics and structural change. This vast scope opens up the possibilities of integrating different fields of science using the input-output framework as a common medium. As it deals with problems at a systems level, many questions that industrial ecology poses demand close cooperation of engineers and natural scientists with economists and other social scientists. Input-output economics can provide a platform for industrial ecology where actors from different disciplines share a common ground and use it as a gateway to increasingly ambitious research agendas. Furthermore, as an efficient accounting structure, the formalisms for compiling input-output data are used, though sometimes in modified forms, in various applications including ENA, LCA and MFA, enabling common understandings and a ground for integration.

As compared to industrial ecology, input-output economics is a mature scientific field. Given the overlapping and adjoining areas of interests of the two disciplines, the rich understanding of productive systems accumulated over the long history of input-output economics can be a valuable knowledge base for approaching various issues in industrial ecology.[10] For instance, the discussions about allocation in LCA during the past 15 years mirror discussions that have taken place among input-output economists since the early 1960s under the banner of the "make" and "use" framework (Stone et al. 1963; Konijn 1994; Heijungs and Suh 2002; Kagawa and Suh 2009). The diverse analytical tools and models developed by input-output economists, which include but are not limited to structural path analysis, key sector analysis, structural decomposition analysis, and minimal flow analysis as well as dynamic input-output models, optimal choice-of-technology models, and models of the world economy, have direct relevance for conceptual representation and analysis of applied questions in industrial ecology as well (see, e.g., Treloar 1997; Lenzen 2002, 2003; Heijungs and Suh 2002; Hoekstra, 2003; Suh 2004b; Duchin 2009).

From a practical perspective, the input-output table provides valuable statistical information for industrial ecologists. The input-output table is one of the only publicly available statistics based on a well-established method of compilation that reveals the structure of inter-industry interdependence at a national level. One of the major difficulties in pursuing research in industrial ecology, as in many other disciplines, is the difficulty of obtaining reliable data from industry and the cost of collecting such data. In that regard, an input-output table is an important data source for industrial ecologists: hybrid LCA, for instance, utilizes an input-output table to describe the inter-industry exchanges of the background system that is connected to a more detailed engineering model describing inter-process exchanges (Joshi 1999; Suh 2004b; Suh and Huppes (2005).

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[10] In her Presidential Address to the 15th International Input-Output Conference, Duchin (2005) presented a vision about collaboration between input-output economists and industrial ecologists. She stressed resources as the main area of overlap and common interests and attempted to remove some remaining conceptual obstacles to more intensive and fruitful collaboration.

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Part II
Material Flow Analysis

Chapter 4
Conceptual Foundations and Applications of Physical Input-Output Tables

Stefan Giljum and Klaus Hubacek

Increasing empirical evidence suggests that current levels of anthropogenic environmental pressures on the world-wide level do not comply with requirements of environmental sustainability (for example, WWF et al. 2004). Especially industrialized countries, responsible for the largest share of pressures on the global environment, are demanded to significantly reduce the material and energy resources used for production and consumption and to achieve de-linking (or de-coupling) of economic growth from environmental degradation. The concept of de-linking was adopted by a large number of national, European and international environmental policies (for example, European Commission 2003; OECD 2004). While de-linking in relative terms decreases the resource intensity of economic processes, absolute de-linking is required from a sustainability point of view, in order to keep economic and social systems within the limits of the ecosphere (Hinterberger et al. 1997).[1]

Monitoring the transition of societies towards de-linking targets requires comprehensive and consistent information on the relations between socio-economic activities and resulting environmental consequences. In the past 15 years, a large number of approaches were developed providing this information in biophysical terms.[2] These methods proved to be appropriate tools to quantify "societal metabolism" (Fischer-Kowalski 1998) and to measure the use of "environmental space" (Opschoor 1995) by human activities.

On the macro level, several approaches of physical accounting (for example, economy-wide material flow accounting (MFA), energy accounting and land use accounting) can be directly linked to existing economic accounting schemes, such as the System of National Accounts (SNA). This enables consistent integration of

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[1] Hinterberger et al. (1997), see also the chapter by Giljum et al. in this handbook.

[2] See, for example, Daniels and Moore (2002) for an overview.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

monetary and physical information within one accounting framework and allows compiling comprehensive data bases for policy-oriented analyses of economy–environment interactions. The usefulness of these integrated accounting schemes is also increasingly highlighted on the international level, resulting for example in the publishing of the United Nations "System for Integrated Environmental-Economic Accounting (SEEA)" (for the latest version, see United Nations 2003).

With regard to assessing the material base and resource throughput (physical inputs on the one hand and outflows (waste and emissions) on the other hand) of national economies, MFA has established itself as a widely applied methodological approach and is recognized as a key tool for evaluating de-linking and eco-efficiency policies. Since the beginning of the 1990s, major efforts were undertaken to harmonize the various methodological approaches in the field of MFA, finally leading to standardization for economy-wide material flow accounting through a methodological guidebook published by the European Statistical Office (EUROSTAT 2001).

MFA is a powerful tool for quantifying aggregated resource inputs and outputs of economic systems with relatively low effort, as for many material categories considered in MFA accounts, data can be taken from available national or international statistics.[3] However, the usefulness of MFA for integrated environmental–economic assessments is limited. The concept of economy-wide MFA regards a national economy as a black box and only distinguishes domestic resource extraction and physical imports on the input side and physical exports and aggregated waste and emissions on the output side, with changes in the physical stock balancing these accounts (see Fig. 4.1).

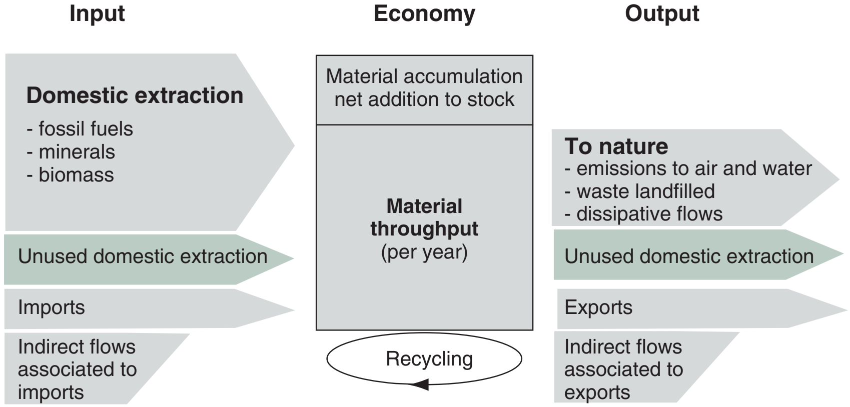

Fig. 4.1 General Scheme for Economy-Wide MFA, Excluding Water and Air Flows (EUROSTAT 2001)

[3] It must be emphasised, though, that the accurateness of MFA accounts depends to a large extent on quality and completeness of primary data used for their compilation. While most material categories concerning domestic material inputs (fossil fuels, metal ores, industrial and construction minerals and biomass) are covered by official statistics (with construction materials being the category with the most significant data gaps), data coverage is in general lower with regard to physical trade flows and outflows of waste and emissions.

This means that MFA accounts do neither provide information on material flows on the level of economic sectors, in particular on inter-industry relations, nor do they separate material inputs used for production processes from those directly delivered to final demand. Thus, MFA accounts and derived indicators by themselves do not allow analyzing implications for resource use of structural and technological change, of changes in consumption behavior and life-styles, and of migration and urbanization. From this perspective, physical input-output tables (PIOTs) can be regarded as a crucial further development of material flow accounts, erasing these deficits identified for aggregated MFA accounts.

The structure of this chapter is as follows. In the basic concept of physical input-output tables, we describe the basic structure of PIOTs and discuss differences between physical and monetary IO tables. State of the art provides a review of the state of the art and analyses differences between PIOTs compiled so far. In applications of the PIOT, the main areas of applications of PIOT-based analysis are presented. The chapter closes with an outlook on future work necessary to make PIOTs a more broadly applied tool for policy-oriented environmental–economic assessments.

The Basic Concept of Physical Input-Output Tables

Structure and Compilation of PIOTs

Physical input-output tables (PIOTs) provide a comprehensive description of anthropogenic material flows following the material balance principle, with the economic system depicted as being embedded in the larger natural system. A PIOT describes all material flows between the economic and the natural system (thus providing the same information as economy-wide material flow accounts described above). In addition, a PIOT opens the black box and illustrates the flows between the different sectors and to various types of final consumption within an economic system. Furthermore, the production sphere is separated from final demand and changes in physical stocks are accounted for on a sector level. In Box 4.1, we describe the general accounting structure of a PIOT.

Box 4.1 General Accounting Structure of a PIOT

Input-output tables take a meso-perspective to analyze the economy–environment relationship and disaggregate economic activities by sectors. Concerning the flows of intermediary products within the economy (first quadrant), PIOTs are directly comparable to monetary input-output tables (MIOTs), but with the products of the intra-industry trade listed in physical units (usually in tons) instead of monetary (value) terms (Fig. 4.2). The most wide-ranging extension of PIOTs compared to MIOTs is the inclusion of the environment as a source of raw materials on the input side (third quadrant) and as a sink for residuals (solid waste, waste water and air emissions) on the output side of the economy (second quadrant)

(continued)

Box 4.1 (continued)

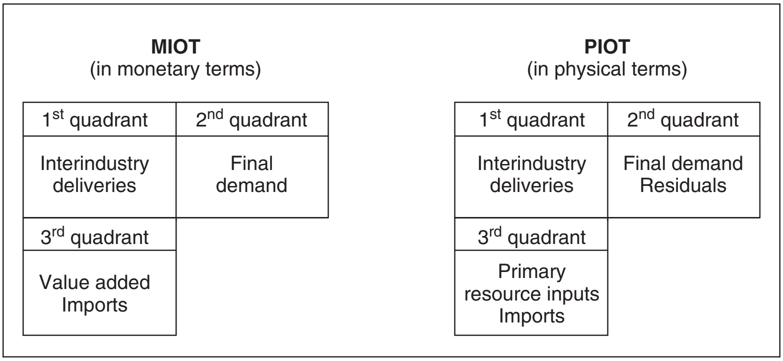

Fig. 4.2 Simplified Structure of MIOT and PIOT (Hubacek and Giljum 2003)

(Stahmer et al. 1996, 1997). Thus also resource flows that have no economic value and are therefore omitted in a MIOT are integrated into PIOTs. For each sector, the sum of all physical inputs has to equal the sum of all outputs to other economic sectors and to final consumption (e.g. private households), plus waste and emissions disposed to the environment. Concerning the changes in fixed assets and the interrelations with the rest of the world, the accumulation of materials (net-addition to stock) and the physical trade balance give information on the net difference. By definition, physical accumulation plus physical trade surplus or deficits have to be zero (Stahmer et al. 1997).

Another important difference between MIOT and PIOT is that domestic extraction of primary material inputs is no longer part of the intermediate use matrix as in a MIOT, but incorporated into the factor input matrix. In the logic of MIOTs environmental products (as long as there are monetary values attached to them) are generated within the economic system, whereas in a PIOT they are entering the economy from the natural system (Giljum et al. 2004).

Differences in construction make it impossible to have a simple unit conversion between MIOT and PIOT, i.e. the PIOT being derived only by multiplying the MIOT with a vector of prices per tons of material input for each cell. This is mainly due to aggregation of non-homogenous sectors (Weisz and Duchin 2005), differences in prices for different consumers of the products and different methods of establishing material versus money flows. In practice, however, physical quantities for some entries in a PIOT have to be estimated by dividing the monetary figures by appropriated prices using monetary supply and use tables (United Nations 2003).

It is also important to note that the basic identities of monetary values on the one hand and physical terms on the other hand for each of the sectors are different (Konjin et al. 1995). Whereas the identity

$$\textit{Total output} = \textit{total input of goods and services} + \textit{value added}$$
$$\text{(all in monetary terms)}$$

holds true for the MIOT, the identity concerning total physical inputs and outputs is not given, as – in the first quadrant – only inputs embodied in the output are accounted for. To enable a material balancing on the sectoral level, one thus has to add waste and emissions arising from production (third quadrant). The material balance is then equal to

$$\textit{Total output} = \textit{input of raw materials} + \textit{total input of goods and services} \\ - \textit{waste and emissions} \text{ (all in physical terms)}$$

A complete set of a PIOT comprises a number of sub-tables. The *physical input table* explains which materials (raw materials, goods or residuals) serve as inputs to which economic activity (production, private consumption, changes in stocks and exchanges with the rest of the world). The outputs (products and waste and emissions) of each of the economic activities are listed in the *physical output table*. Both physical input and output table are asymmetric, with the products or materials (inputs or outputs) listed on one axis and the different areas of economic activities (e.g. industries) on the other. The integration of these two sub-tables delivers the *symmetric physical input-output table*. A full PIOT can show the material flows between different sectors (industry by industry tables) or the materials required to transform other materials in the production process (materials by materials tables) (EUROSTAT 2001). The symmetric input-output table can again be composed of other sub-tables, which separately describe the flows of specific product groups, different materials or residuals (Gravgård 1999; Stahmer et al. 1996).

Most important data sources for compilation of PIOTs include production statistics, international trade statistics, energy accounts, accounts of material inputs and wastes and emissions statistics.

When establishing material balances and calculating total material inputs of economic activities, one has to distinguish between an economy-wide and a sector perspective. The input quadrant (third quadrant) contains all *primary material inputs* to the economic system. These consist of primary domestic extraction and physical imports. The processing quadrant (first quadrant) of the PIOT lists the flows of the intermediate products and thus comprises all material flows within the inter-industry part of the economic system. Within the reporting period (usually 1 year), all products of the first quadrant are made of materials, which before had to be (a) extracted from nature or being imported as primary inputs or (b) taken from physical stocks. *Total* material inputs to the economic system thus equals total primary inputs (quadrant 3) plus changes in stocks (shown in quadrant 2). On the *sector* level, however, material inputs are primary inputs *plus* secondary inputs from other sectors. In most of the PIOTs published so far, this distinction is not clearly drawn. Both in the PIOTs for Germany (Stahmer et al. 1997; Statistisches Bundesamt 2001) and Denmark (Gravgård 1999), primary and secondary inputs are misleadingly summed up to an aggregate, in the German PIOT called "total material use." However, in the methodological approach developed for the Austrian PIOT (called *O*perating

*M*atrix form material interrelations between *E*conomy and E*n*vironment, OMEN) the difference between sector and economy-wide material balances is most explicitly addressed (Weisz et al. 1999).

Comprehensive PIOTs disaggregate input, output and symmetrical IO tables into several material categories. The German PIOT contains separate supply and use tables for three major material groups: water, energy and other materials. Each of these tables further disaggregates nine categories of materials on the input side (overburden, energy carriers, soil minerals, excavation, other solid materials, water from nature, oxygen, carbon dioxide and other gases) and 17 categories of outputs, separating various flows of solid waste, waste water and air emissions. From these sub-tables aggregated symmetrical PIOTs are constructed in a bottom-up approach. This procedure is necessary to ensure the correct inclusion of material transformation processes, such as the transformation of a good (e.g. fossil energy carrier) into an emission (e.g. CO_2) during combustion processes (Statistisches Bundesamt 2001). In the PIOTs published for Denmark (Gravgård 1999), separate symmetrical IO tables for nine different material groups are presented: animal and vegetable products; stone, gravel and building materials; energy; wood and paper; metals and machinery; chemical products and fertilizers; packaging materials and the nitrogen content of products. Disaggregation into sub-PIOTs is of crucial importance for making PIOT a useful tool for policy analysis, as it allows carrying out separate IO calculations for material groups related to specific environmental problems (see also Hoekstra 2003).

Limitations of PIOTs

The major shortcoming of aggregated PIOTs is the fact that, such as in material flow accounting, all flows in a PIOT are accounted in one single unit, in most cases tons. The consideration of qualitative differences of material flows in terms of different potentials for environmental harm is therefore very limited. Weight-based aggregation has been criticized for a number of reasons:

- Big material flows dominate derived indicators and bias interpretations of aggregated results. However, small material flows, which might be neglected in aggregated indicators, can have large environmental impacts. Changes in the composition of aggregated indicators due to substitution between different materials thus are of crucial importance.
- Unweighted (emission) indicators do not tell anything about actual environmental impacts, which are determined by the use of materials with different environmental effects (e.g. toxicity) and the risks associated to different technologies (e.g. atomic energy versus decentralized renewable energy). These facts significantly reduce the usefulness of weight-based indicators for policy use (Hoekstra 2003).
- The sole focus on the reduction of aggregated resource use is a necessary but not sufficient precondition for achieving sustainability. The question remains of

what exactly we have to reduce to achieve a sustainable resource throughput (see, Reijnders 1998).

- Indicators relating material flows to economic data (e.g. material productivity and eco-efficiency indicators) have a strong economic component. Aggregation should therefore also reflect the economic usefulness of materials. Weight is no category to reflect economic values/decisions of end-users of materials (Cleveland and Ruth 1999).

Although the need to integrate qualitative aspects into evaluation of material flow analysis is increasingly recognized within the MFA community and first methodologies have been proposed (for an example how to link MFA data with evaluation methods from life cycle assessment (LCA) see van der Voet et al. 2003),[4] no standardized evaluation method exists so far. However, disaggregation of material flow accounts into a number of subcategories has been carried out by most material flow studies on the national level and is also recommended by the standardized methodology published by the EUROSTAT (2001). Also in PIOTs presented so far, input, output and symmetric IO tables are disaggregated into several material categories, most notably in the Danish PIOT (see above).

In some PIOTs, supplementary tables are presented to provide a better link to specific environmental issues. These additional tables are conceptually fully compatible with the corresponding PIOT tables in tons. In the German PIOT for 1990 (Stahmer et al. 1997), a separate table for energy in caloric values (terajoules) is presented. Information of energy carriers exclusively in weight units may lead to misleading conclusions, as different energy carriers are characterized by considerably different energy intensities per weight unit. Furthermore, specific tables for air emissions are presented, which weight various emissions with regard to their potential for climate change and for acidification. For example, concerning greenhouse gas emissions, 1 t of nitrogen oxide N_2O contributes 310 times, and 1 t of methane 21 times more to the greenhouse effect than 1 t of CO_2 (Statistisches Bundesamt 2001).

A major methodological weakness with regard to PIOTs compiled so far is that – unlike economy-wide MFA – there exists no standardized accounting methodology. Existing PIOTs differ significantly with regard to the number of sectors reported, the disaggregation into product groups, as well as the inclusion or exclusion of specific materials (see below for details). This fact complicates international comparisons of existing PIOTs and disables the use of different PIOTs on the national level to build aggregated international physical input-output models.

Finally, it must be emphasized that the compilation of a PIOT is a very work- and time-intensive task and requires the availability of highly disaggregated production and trade data as well as detailed data on domestic material extraction and water use. Therefore, only a few economy-wide PIOTs have been presented until today (see below) and it remains an open question, whether the compilation of PIOTs will be integrated into standard environmental statistics in the future.

[4] For an example how to link MFA data with evaluation methods from life cycle assessment (LCA) see van der Voet et al. (2003).

State of the Art

Existing PIOTs

The groundwork for physical input-output tables was laid by Kneese et al. (1970) and their application of the material balance approach to economic analysis. Precursors for physical IO tables have also been developed in ecology. Ecosystem models or "systems ecology" models emphasizing material and energy flows date back to the early 1960s (for example, Odum 1960) and have later been analyzed by applying input-output mathematics (Hannon 1973). These earlier approaches using energy or nutrient units are not further discussed in this chapter.

The first attempt to calculate a PIOT was carried out for Austria with input-output data for the year 1983 (Kratena et al. 1992; Kratterl and Kratena 1990). Up to now, for Austria a highly-aggregated PIOT (with three production sectors) exist (Weisz H 2000, unpublished). Full PIOTs were so far published for Germany for the years 1990 (Stahmer et al. 1997) and 1995 (Statistisches Bundesamt 2001) and for Denmark for the year 1990 (Gravgård 1999). Furthermore, aggregated PIOTs for Italy were presented by Nebbia (2000) and a detailed PIOT for Finland by Mäenpää (2002, see also the chapter by Mäenpää in this handbook),[5] both for the year 1995. For the UK a 76-sector PIOT is currently being developed (Wiedmann et al. 2004). In Japan, a regional PIOT is in construction as part of an evaluation tool for integrated resource and waste management (Niren and Yoshida 2004). Also in New Zealand, efforts are being undertaken to construct a PIOT on the economy-wide level.

In addition, PIOTs were compiled for specific materials (Konijn et al. 1997). These tables give a more detailed description of the entire production chain of specific materials, by distinguishing primary raw materials (e.g. iron ore) from materials, which have been physically transformed into secondary production materials (e.g. iron as a component of steel).

Methodological Differences

As mentioned above, no standardized accounting methodology for PIOTs exists so far. In the following, we list the most important issues concerning commons and differences between existing PIOTs.

Levels of Aggregation

First, differences occur with regard to the disaggregation level and the number of sectors reported. Whereas the German PIOT consists of 59 sectors, the Finish PIOT

[5] See also the chapter by Mäenpää in this handbook.

is based on 30 sectors, the Danish PIOT on 27 sectors, the UK PIOT on 76 sectors, and the Italian PIOT on 12 sectors. In the German and Italian PIOT, the waste treatment sector, which is the sector with the highest material inputs from other sectors, is separated from the other service sectors.

Concerning disaggregation into material and products groups, the Danish PIOT is especially illustrative as sub-tables for nine material groups are published (see above). The German PIOT is the only one to differentiate between several groups of primary inputs in domestic material extraction, such as energy carriers, minerals, stones, water and air. It also reports the category of unused domestic extraction (e.g. overburden from mining, excavation from construction and cooling water), which is not covered in other PIOT publications.

With regards to the compatibility to other data sources, the UK PIOT is very instructive. It was originally developed to account for 96 economic sectors but then aggregated to match the UK NAMEA (National Accounting Matrix including Environmental Accounts) data which allows linking the PIOT with some 20 different pollution factors on a sectoral level. In addition, the final demand sectors have been disaggregated using consumption data and the ACORN (A Classification of Residential Neighbourhoods) classification. This allows assessing different lifestyles with regards of their upstream environmental pollution and energy and material consumption.

System Boundaries

With regards to the representation of agricultural processes, the definition of system boundaries in some PIOTs differs from system boundaries known in economy-wide MFA. For example, in the German PIOT, plants and forests, which are directly ascribable to agricultural and forestry production, are considered part of the socio-economic system. Thus inputs from nature mainly comprise rainwater and carbon dioxide necessary for biomass growth. In contrast, economy-wide MFA considers plants and forests part of the natural system and counts harvest of timber and agricultural products as material inputs to the socio-economic system.[6] The varying definition of system boundaries significantly limits the comparability between results and the use of PIOTs for a sectorially disaggregated analysis of material flows, which are compiled following the standard MFA conventions (EUROSTAT 2001).

Consideration of Different Material Categories

As already mentioned above, it is a crucial factor, whether or not water and air are included in the tables, as these flows surpass all other (solid) materials by at

[6] We thank Helga Weisz, Institute for Social Ecology, University of Klagenfurt, Austria, for pointing this out to us.

least a factor of 10. Whereas the Danish PIOT only takes into account water that is added and included in products, the German PIOT also considers waste water and water for cooling. In addition, air components (like oxygen) are calculated as inputs for combustion processes. In economic analyses of production processes, the importance of throughput material flows such as cooling water is in general overestimated, when taking a weight-based approach. Therefore, these flows should be excluded, in order to allow focusing on materials, which actually remain within the economic system for further processing (Statistisches Bundesamt 2001). The inclusion or exclusion of water and air also leads to completely different physical technology matrices and thus shows significant implications for studies applying a physical multiplier for attributing factor inputs (such as primary material inputs or land use) to different categories of final demand (Giljum and Hubacek 2001; Moll and Acosta 2003).

Base Years

Finally, the reference years differ from study to study, with some being based on data from 1990 and others on data from 1995 or other years. The lack of several data points across a number of countries disables decomposition analysis or cross-country comparisons.

Applications of PIOT

Identification and Filling of Data Gaps

The PIOT structure acts as an accounting framework for a large number of different data sources reported in different units (tons, joules, monetary units, etc.). In the PIOT, the material balance principle must hold for each sector and for the economy as a whole, allowing a cross-check of data and the identification and possible removal of data gaps and errors in the primary data sources. This contributes to homogenization of classification schemes and data collection methods (Hoekstra 2003). The material balance principle can also be used for estimations of emissions of specific economic sectors, by combining data on energy inputs with emission factors (Statistisches Bundesamt 2001).

Material Intensities and Eco-Efficiency Indicators

PIOTs provide consistent information about the connections between raw material and energy inputs, produced goods and resulting waste and emissions in each economic sector. The analysis of material, energy and emission intensive production sectors and production chains helps identifying priority areas for resource management strategies. The compatibility of PIOTs with MIOTs enables direct relation of physical flow indicators with indicators of economic performance, such as GDP. These interlinkage indicators quantify the eco-efficiency (or resource productivity) of an economic sector or of the whole economy by calculating economic output (measured in monetary units) generated per material input (in physical units) and its development over time. Eco-efficiency indicators thus are suitable tools to monitor processes of de-linking or de-coupling of resource use from economic growth as one core strategy toward a more sustainable use of natural resources (Spangenberg et al. 1998).

Analysis of Specific Material Chains

A number of studies developed physical input-output tables based on specific materials. For example, Konijn et al. (1997) developed a PIOT describing all the production processes for products that contain iron, steel or zinc using the material balances for these materials. This table was then used to calculate the amount of rolled steel that is necessary to produce metal products (e.g. machinery and cars) and to evaluate the introduction of new production technologies in the steel sector (see also Hoekstra 2003).

Bailey et al. (2004) were interested in tracing the flows of six materials (aluminum, lead, magnesium, zinc, chromium, and nickel) through the industrial/economic system in the US in the 1990s. More specifically, they were tracing the two system inflows (i.e., domestic primary production and imports) forward through the system and to trace the two system outflows (i.e., exports and domestic disposal) backward through the system thus providing valuable information for groups within a domestic material flow system (e.g., scrap recyclers, metal primary producers, and importers/exporters) and policy makers.

However, compared with flow analysis or life-cycle analysis of particular materials or products, the use of PIOTs remains at a rather aggregate level and does not allow the calculation of specific energy requirements of, for example, glass bottles versus plastic bottles (Konijn et al. 1997).

Environmental Impacts and Links to LCA Methods

PIOTs (as well as MFAs) have been heavily criticized for neglecting important qualitative differences among various material flows regardless of their economic importance or environmental impacts (see above). Recent attempts by Hubacek et al. (2004) propose to overcome this limitation by linking physical information from a PIOT with evaluation approaches from life cycle assessment. Their analysis is based on the PIOTs for Denmark due to its most explicit representation of various materials. The main goal is to create a series of comprehensive PIOTs representing weighted environmental effects based on conversion factors derived from LCA. These applications use the Eco-Indicator 99 (EI99) methodology, an endpoint methodology leading to damage-oriented scores (such as for abiotic depletion or global warming).

Land Use

Physical input-output models can be extended by an additional vector of land area appropriated by each economic sector to assess direct and indirect land requirements ("ecological footprints" in terms of real used land) of different production and consumption patterns (Hubacek and Giljum 2003, see also the chapter by Dietzenbacher et al., in this handbook).[7] Especially for land related studies, using a physical multiplier is more appropriate than a monetary multiplier, since land appropriation and material intensity among sectors are highly correlated. Physical input-output analysis illustrates land appropriation in relation to material flows of each of the sectors, which is more significant from the point of view of environmental pressures than land appropriation in relation to the monetary flows of a MIOT.

Sustainable Consumption and Life Styles

In order to analyze changes in consumption patterns and lifestyles, PIOTs have been linked to NAMEA data and the household column has been extended to account for 55 different consumer groups (see also the chapters on sustainable consumption in this volume). For example, the Stockholm Environment Institute at York (SEI-Y), in collaboration with the Centre for Urban and Regional Ecology (Manchester University) and Cambridge Econometrics has recently been developing the Resource and Energy Analysis Programme (REAP) – an integrated resource–environment modeling tool based on a simplified "Physical Input-Output Table" for the UK, broken down by devolved countries and regions. With this tool, the key environmental impacts associated with material flows can be expressed by calculating the corresponding greenhouse gas emissions and ecological footprints (Birch et al. 2004; Wiedmann et al. 2004).

International Trade and Environmental Distribution

Physical IO tables and models can be used to calculate indirect material requirements of internationally traded products by quantifying direct and indirect material

[7] See also the chapter by Dietzenbacher et al. in this handbook.

and energy inputs required to produce the traded good (Giljum and Hubacek 2001; Weisz 2004). These analyses thus can contribute to the debate of a possible relocation of environmental burden on a global scale due to specialization of some world regions in resource intensive production and trade. The fact that domestic resource extraction or pollution is decreasing, as implied by the "Environmental Kuznets Curve (EKC)" (see Dinda 2004 for a survey) discussion, does not automatically indicate a transformation of economies towards a more sustainable development, if these resource inputs are only imported from or dirty production relocated to other world regions. For example, a recent material flow study analyzing the external trade relations of the European Union revealed that physical imports and associated indirect material flows are growing and increasingly substituting domestic material extraction, in particular with regard to fossil fuels and metal ores (Schütz et al. 2004).

Conclusions and Outlook

Physical input-output tables (PIOTs) can be regarded as an integration of input-output analysis and MFA and are a necessary next step in the development of material flow accounts, in order to widen their applicability for policy-oriented analyses. A number of elements of the mathematical tool kit of monetary input-output analysis have been transferred into the PIOT concept, thus making PIOTs a useful tool for assessments of environmental–economy interactions.

However, PIOTs share many points of critique expressed for MFA, in particular the aggregation of materials of different qualities, which ignores different effects on the environment and disables a reasonable evaluation of material substitutions in changing production and consumption patterns. Approaches to tackle these problems include focusing on specific materials and material transformation chains or providing separate economy-wide accounts for various materials, as done in the Danish PIOT. New approaches also aim at linking weight-based information with evaluation methods used in LCA, in order to come up with alternative aggregation procedures providing closer links to specific environmental problems.

Another major problem is the lack of standardization and therefore of comparability between existing PIOTs. This fact is observed with regard to base years, different materials included or excluded in PIOTs, definition of different systems boundaries, and different levels of sector aggregation. In order to ensure comparability of physical input-output tables of different economies it is paramount that further developments, especially within the UN initiative of establishing an internationally harmonized "System of Integrated Environmental and Economic Accounts (SEEA)" (United Nations 2003) focus on the definition of a standardized methodological procedure for setting up physical accounts on the national as well as supranational level. Resolving these issues will be a precondition for further development and more widespread application of the PIOT approach in the future.

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Chapter 5
Modelling Manufactured Capital Stocks and Material Flows in the Australian Stocks and Flows Framework

James A. Lennox and Graham M. Turner

Introduction

Manufactured capital stocks and their relationships to physical flows of materials and energy are of interest in the fields of industrial ecology and input-output analysis. Manufactured capital stocks embody technologies, which may be characterised by input-output (IO) relations. The rate and nature of technological and structural change in an economy are therefore related to the dynamics of these stocks. Certain capital stocks also act as substantial long-lived stores of materials in the anthroposphere. Additions to and scrapping of these stocks directly generate flows of new and used materials and wastes. This chapter is concerned with two relationships between manufactured capital stocks and material flows, and in particular, how they may be modelled in the field of industrial ecology. Examples are drawn from scenarios developed using the Australia Stocks and Flows Framework (ASFF) (Foran and Poldy 2002).

Section two of this chapter deals with methodological and practical issues encountered in accounting for and modelling manufactured capital stocks. Both commonalities and differences between economic and physical perspectives on capital stocks are discussed. An example is given of historical and projected vehicle stocks in Australia. Section three deals with input-output modelling of technologies embodied in capital stocks, focussing particularly on the 'bottom-up' or 'process modelling' approach employed in ASFF. An example of process-based IO models for steel production in Australia is provided. Section four is concerned with dynamic models of stocks and flows in Industrial Ecology. A dynamic physical IO model (Lennox et al. 2004) within ASFF is described and an example of material

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

flows associated with electricity generation capacity is given. Section 5 concludes the chapter, providing a brief discussion of key issues in modelling capital stocks in terms of material stores and/or embodied technologies within the field of industrial ecology.

Manufactured Capital Stocks

Economic and Physical Capital Accounting in Theory

Manufactured capital stocks have structural and functional dimensions – capital *qua* capital and capital *qua* productive capacity.[1] They can also be viewed from economic and physical perspectives. In economic terms, capital *qua* capital has a cost in terms of investment flows and depreciation. Capital *qua* productive capacity produces a stream of economic value over its lifetime. From a physical perspective, commodities are used in the processes of capital formation and maintenance, while capital stocks are employed in the transformation of commodities and the provision of services. The economic value of capital stocks can usually be observed via market prices for new and used capital goods. Equally, it is possible in principle to measure the physical size of capital stocks by some suitable metric (e.g. floor space of a building). However, capital *qua* productive capacity is in practice unobservable in either economic or physical terms. All that can be observed is the actual output of this capital, which may be less than its potential output.

Intrinsic characteristics of productive assets and the way in which they are employed in production may vary with age and time. From 1 year to the next, the technologies embodied in new capital assets may change. For example, the fuel efficiency of car engines has increased, while the average weight and power of cars has also increased. *Embodied technological change* within an asset stock results from the in-built technological differences between assets manufactured in different years. The year in which an asset was manufactured is known as its ‘vintage’. Embodied technological changes are likely to be more significant the more broadly each ‘technology’ is defined (i.e. with increasing aggregation). The intrinsic productivity of individual assets generally decreases monotonically with age and amount and type of use; however, this decay can be alleviated by maintenance and repair. The net result of these effects is known as e*fficiency decay*.[2]

The realised physical productivity of assets may also change because of improved methods of use. This is known as *disembodied technological change*, as it is independent of the built-in or embodied technology of tangible capital. Disembodied technological change may occur at various levels. At a micro level, improved

[1] The terms ‘production’ and ‘productive capacity’ are used very generally, to refer to production of market and non-market goods by in all sectors of the economy.

[2] Note that in SNA93, improvements to or extensions of capital must be classified as additions to stocks, whereas ‘normal’ maintenance activities must not be. In practice, such a distinction may be difficult to make.

practices may be developed for an individual capital asset, while at a higher level, generic techniques such as statistical quality control may be applied to almost any type of plant. The *potential productivity of capital* is then the product of embodied technological change, efficiency decay and disembodied technological change. The first and second of these are generally assumed to be functions of asset stock vintage, while disembodied technological change is assumed to apply proportionally to all vintages. Many types of capital are systematically used at less than full capacity, since a buffer of unused capacity is needed to allow for the relatively faster dynamics of requirements for output of goods and services. *Capacity utilisation* factors can be used to relate the potential productivity of capital to the realised productivity. These factors represent the result of a trade-off between flexibility and opportunity costs. Marginal and fixed costs of production are generally affected by technological as well as economic characteristics of capital stocks, and therefore will be a function of vintage. Again, the importance of vintage is likely to increase with the level of technology aggregation.

In theory, the multiplicative factors for capacity utilisation, efficiency decay, disembodied and embodied technological change relate capital stocks to the services derived from them in a simple and straightforward manner. In applied economics, they are difficult to define precisely, and impossible to estimate from the data sets usually employed in national accounting and macroeconomic analysis (Hulton 1999). The effects of specific innovations (e.g. statistical quality control) may be estimated in productivity studies and the effects of efficiency decay may be partially observable via markets in used equipment (US BEA 1999); however, systematic direct estimation of these factors and their dependence on time and vintage for all classes of tangible fixed capital appears to be impossible. Similar difficulties are encountered at corresponding scales of physical analysis. Specific items of new equipment often have nominal capacity ratings (generally less than maximal capacity). However, such data are impractical to collect and aggregate in large-scale studies. The physical productivity of capital can, by definition, be observed only in terms of throughput or similar measures of usage levels.

It is interesting to note that the value of stocks at the end of their productive lives is generally considered insignificant in economic terms (OECD 2001); however, end-of-life capital goods are often very important from an environmental perspective. Materials or components from end-of-life goods are either recycled or disposed of. End-of-life capital goods from capital stocks can therefore be seen as a material resource or an environmental burden. Furthermore, additional material and energy flows are mobilised in the processes of recycling or disposing of end-of-life goods. Recently, these issues have been dealt with in SEEA (UN 2003), so accounting practices in this area may improve in the future.

Capital Accounting in Practice

Actual stocks of manufactured capital can be estimated directly or indirectly. Census or sampling approaches may be applied to extant stocks, yielding direct estimates of stock sizes. Alternatively, additions to and deletions from stocks can be measured over time; again using census or sampling methods. Integrating these time series yields the cumulative net additions to stocks. Current stocks are then the sum of the initial stocks and the net accumulation to stocks. In the context of national accounting, the second approach has predominated. Investment flows are measured in monetary terms by all OECD countries, as they are an important element of national accounts.[3] Recent standards for measurement and accounting of economic capital are described by the OECD (2001).

Updating stock estimates based only on the current year's transactions appears very efficient. The major practical problem is that deletions from stocks are often unmeasured, or the available measurements are inappropriate to the task of capital stock estimation. Consequently, deletions from stocks are often estimated using the perpetual inventory method (PIM). While widely applied in capital accounting, the functional form and parameterisation of life-expectancy distributions used in the PIM are often of questionable accuracy (US BEA 1999). A further problem is that if net additions to stocks are relatively small in absolute value, the estimates of current stocks will be sensitive to the initial stock estimates. Reacting to the shortcomings of standard capital estimation methods, several countries have begun to make wider use of direct observation in national accounting, including observations of physical measures (Frenken 1992).

To aggregate individual assets into a capital stock, one must choose a common measure for both nominal and functional amounts of capital. Numeraires for nominal manufactured capital include number, mass and area. Discrete measures are more appropriate for relatively homogenous types of capital, while continuous measures are more appropriate for capital that may be added in essentially arbitrary quantities. Vehicles are often accounted for by number, with sub-classes distinguished according to the number of doors or seats, the engine size, or other characteristics. Floor area is a common measure of building stock size. The functional amount of capital may be expressed in terms of its potential output. In the case of industrial production, this may be the effective maximum output rate for the principle product. For capital items with multiple functions and/or functions that cannot be measured quantitatively, it is difficult to distinguish functional from nominal capital.[4] In Australia, systematic collection and publication of physical data is undertaken for only a few types of capital[5] by the Australian Bureau of Statistics (ABS) or other organisations.

Current practice in compilation of physical input-output tables (PIOT) treats manufactured capital stocks summarily or not at all. The Danish PIOTs (Gravgård

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[3] It should be noted that the number of sectors and commodities that are distinguished by different countries in relation to investment flows varies dramatically.

[4] It is worth noting the connection between physical accounting measures, and what is known as 'hedonic pricing' in economics. Hedonic prices are those inferred from observable characteristics of goods that are assumed to give them value (e.g. in a computer, one might value primarily speed, memory, hard disk space and screen size).

[5] These include but are not limited to houses, vehicles and power plants.

1999) include 'net additions to stocks' as an element of final demand, however there are no capital stock accounts associated with these tables. Even when physical capital stocks are accounted for, their functional dimension is not considered in either the Eurostat MFA methodology (EUROSTAT 2001) or in SEEA. This is presumed to be adequately captured by the economic accounts, with which physical accounts should ideally be harmonised. Indeed the Eurostat guide states that PIOT: should 'show the physical accumulation of materials in the economy, but not the stocks of man-made or natural capital' (EUROSTAT 2001).

Example: Motor Vehicle Stocks in Australia

In industrialised countries motor vehicle stocks significantly contribute to a range of environmental and resource problems. Australia is particularly reliant on both cars for personal mobility and on trucks for road freight transport. Both the number of vehicles and the kilometres travelled are very high by world standards, reflecting both the large size of Australia and the relatively low population densities of its cities and towns. Use of motor vehicles contributes to depletion of fossil energy resources and to atmospheric pollution. Motor vehicles also contribute significantly to societal stocks of steel and other metals. Finally, motor vehicle stocks are used in conjunction with major infrastructure stocks such as roads and parking facilities.

This section draws on modelling and scenarios developed in the Australian Stocks and Flows Framework (ASFF) (Foran and Poldy 2002) to illustrate the role of the motor vehicle stocks as a store of metals in society. Motor vehicle stocks are represented using a vintage model. In each period, a set proportion of each vintage survives and the residual stock is scrapped. The vintage model is driven by the quantity of motor vehicles demanded, which is derived from the population size and an assumed numbers of cars per household. In each period, the difference between the required and actual stock size must be made up with new vehicles. The model was calibrated to fit historical time series and other data. Within a scenario, variables controlling motor vehicle stocks are projected into the future. On this basis, vehicle stocks and additions to and deletions from them are projected. Several categories of motor vehicles are modelled in ASFF, but the following examples will focus on passenger cars. In the model, different sizes of car are not distinguished; however, parameters specify the average material intensity and composition of new cars in each vintage.

Figure 5.1 shows the historical and projected future growth in total car stocks under the 'base case' scenario from Foran and Poldy (2002). This stock trajectory is driven by population-related variables and a number of exogenous parameters. The corresponding additions to and deletions from stocks, shown in Fig. 5.2 below, are a function of the changing size and age distribution of the car fleet and the parameters determining the life-expectancies of cars of different vintages, which themselves

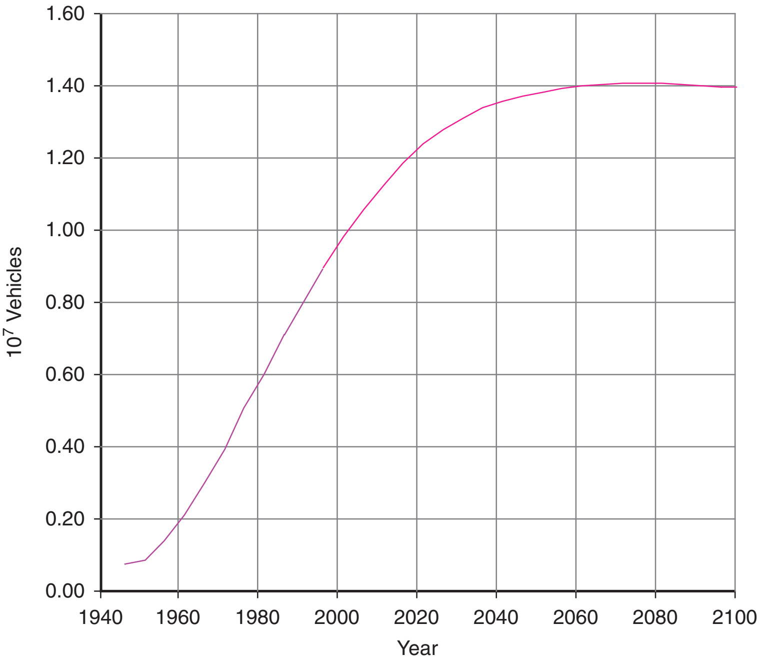

Fig. 5.1 History and Default Scenario Projections for Australian Car Stocks

change over time. The assumptions underlying the future projections shown above include (Foran and Poldy 2002):

- Cars will be manufactured for increased durability, causing the average age of privately owned cars to rise from 10.5 to 13.8 years by 2050.
- The number of cars per household has been increasing, but at a diminishing rate. It is assumed to saturate at 1.21 cars per household.

Under the base case scenario, the overall shape of the curve in Fig. 5.1 is similar to that of the projected population, but the modulating parameters associated with household size and cars per household make it steeper prior to saturation. The number of vehicles would peak around 40% above the present number. The number of new cars required per year would plateau much sooner, meaning that the domestic market would become relatively stable within a decade. By contrast, the number of scrapped vehicles will react much more slowly. It should be noted that subsequent data on new car registrations shows that the conditions for this scenario to be played out in Australia have not yet been met. The number of new passenger vehicle registrations increased by an average of 1.9% per year from 1997 to 2002 (Australian Bureau 2002). This compares to a 1.1% per annum increase from 1996 to 2001 in the base case scenario.

Historically, mass per vehicle rose until the oil crises of the 1970s and has since been falling with the introduction of smaller cars to the market. Design improvements and increasing use of plastics, aluminium and other light-weight materials

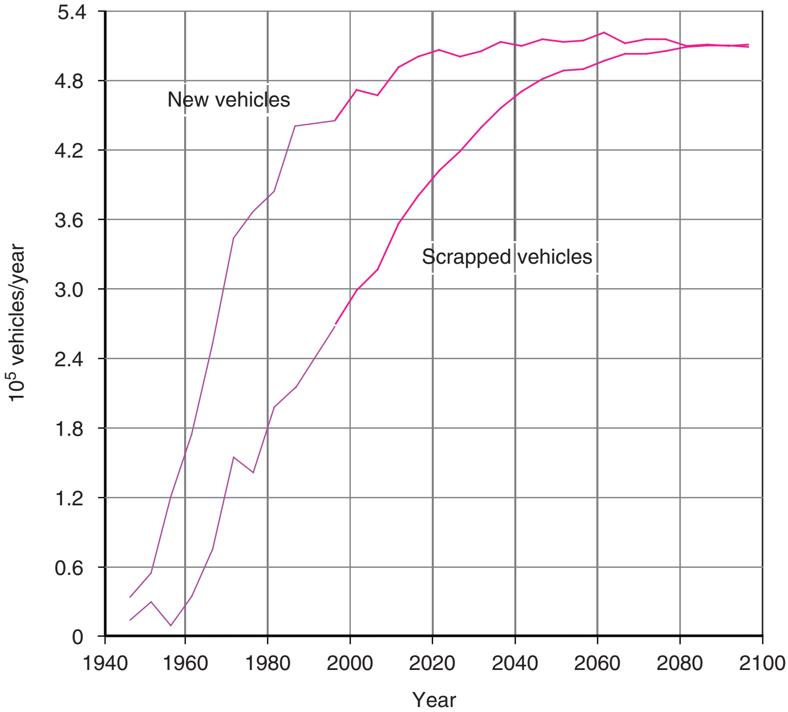

Fig. 5.2 Corresponding Numbers of New and Scrapped Cars (Right)

have also made vehicles lighter and should continue to do so for some time yet. It is assumed in the scenario that these factors outweigh counter-veiling trends towards the purchase of larger vehicles; although it is acknowledged that increased fuel efficiency might actually create a rebound effect by increasing the affordability of larger vehicles (Foran and Poldy 2002). The average vehicle weight is assumed to decrease until it plateaus at 1.2 t. The rapid decrease in average weight per vehicle partially cancels out the still rapid rise in vehicle numbers during the first decade of the twenty-first century. Consequently the masses of new and scrapped vehicles (Fig. 5.3) equilibrate more rapidly than do their numbers.

Modelling Technologies

One way of representing the technologies of production or consumption embodied in manufactured capital stocks is in terms of input-output relations. Input-output relations can be determined through a bottom-up modelling approach, in which an industry is seen as a system comprising a finite number of processes, each having its own input-output characteristics. Process analysis focuses on functional relationships between inputs and outputs that are determined by physical laws,

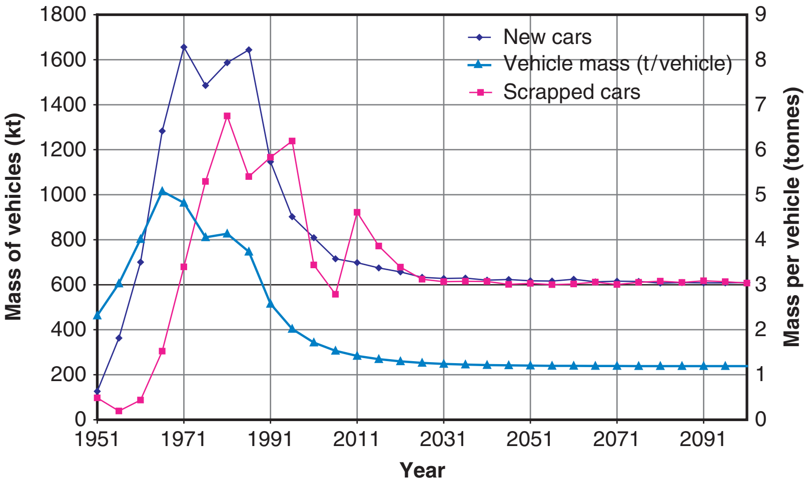

Fig. 5.3 Flows of Materials Associated with the Australian Vehicle Stocks

and/or are based on empirical engineering knowledge. Such relationships, which are frequently non-linear and multivariate, may be simplified for the purpose of constructing linear input-output relations. In the context of IO analysis, the possibility of describing 'generic' technologies is particularly appealing, since behind the IO coefficients will be clear physical interpretations. In principle then, each industry model (set of IO coefficients) can be seen as the composition of generic process models. In practice, inhomogeneity of nominally equivalent processes, as well as the existence of many auxiliary processes within industries (e.g. production of oxygen gas for own use by producers of metals) makes construction of economy-wide or even broad sector IO models a difficult and time-consuming task.

Process Analysis and Activity Analysis

Generic process descriptions can be built from both empirical and theoretical data. Observations of process inputs and outputs may be used directly to construct a model relating the two. Alternatively, descriptions of these relationships can often be found in the technical and scientific literature. Whichever of these methods is used, the validity of the resulting model must be assessed. Remaining within the bottom-up modelling paradigm, the representativeness of source data can be assessed qualitatively. For example, it would be inappropriate to use a model of clinker production by the 'wet process' to describe an industry where the 'dry process' was predominantly used. Quantitative validation requires the use of available 'top-down' statistical data. The latter can be used to validate process models individually and/or to validate a higher level model involving multiple process models. Cross-entropy techniques can be particularly useful for problems of this sort (Golan et al. 1996).

Box 5.1 Input-Output Tables in Australia

The Australian Bureau of Statistics has produced input-output tables for Australia since 1962–1963. In various periods, tables have been compiled annually, biennially or triennially. Since 1994–1995 tables have been compiled biennially with tables for 1998–1999 being published in 2004 (ABS 5209.0.55.001). This publication includes make and use tables for 106 industry sectors (see below) as well as input-output tables for both direct and indirect allocation of competing imports. A separate publication provides total domestic supply and trade data for detailed product items (ABS 5215.0.55.001).

Various State and other regional input-output tables have also been compiled by State Government agencies or researchers. For example the Queensland Office of Economic Statistics and Research has published State and regional input-output tables for Queensland. There is currently no official framework for the production and maintenance of regional input-output tables in Australia.

Input-Output Categories in the 1998–1999 Publication

0101	Sheep
0102	Grains
0103	Beef cattle
0104	Dairy cattle
0105	Pigs
0106	Poultry
0107	Other agriculture
0200	Services to agriculture; hunting and trapping
0300	Forestry and logging
0400	Commercial fishing
1100	Coal; oil and gas
1301	Iron ores
1302	Non-ferrous metal ores
1400	Other mining
1500	Services to mining
2101	Meat and meat products
2102	Dairy products
2103	Fruit and vegetable products
2104	Oils and fats
2105	Flour mill products and cereal foods
2106	Bakery products
2107	Confectionery
2108	Other food products
2109	Soft drinks, cordials and syrups
2110	Beer and malt
2111	Wine and spirits
2112	Tobacco products
2201	Textile fibres, yarns and woven fabrics

(continued)

Box 5.1 (continued)

2202	Textile products
2203	Knitting mill products
2204	Clothing
2205	Footwear
2206	Leather and leather products
2301	Sawmill products
2302	Other wood products
2303	Pulp, paper and paperboard
2304	Paper containers and products
2401	Printing and services to printing
2402	Publishing; recorded media, etc.
2501	Petroleum and coal products
2502	Basic chemicals
2503	Paints
2504	Medicinal and pharmaceutical products, pesticides
2505	Soap and detergents
2506	Cosmetics and toiletry preparations
2507	Other chemical products
2508	Rubber products
2509	Plastic products
2601	Glass and glass products
2602	Ceramic products
2603	Cement, lime and concrete slurry
2604	Plaster and other concrete products
2605	Other non-metallic mineral products
2701	Iron and steel
2702	Basic non-ferrous metal and products
2703	Structural metal products
2704	Sheet metal products
2705	Fabricated metal products
2801	Motor vehicles and parts; other transport equipment
2802	Ships and boats
2803	Railway equipment
2804	Aircraft
2805	Photographic and scientific equipment
2806	Electronic equipment
2807	Household appliances
2808	Other electrical equipment
2809	Agricultural, mining, etc. machinery
2810	Other machinery and equipment
2901	Prefabricated buildings
2902	Furniture
2903	Other manufacturing
3601	Electricity supply
3602	Gas supply

3701	Water supply; sewerage and drainage services
4101	Residential building
4102	Other construction
4501	Wholesale trade
5101	Retail trade
5401	Mechanical repairs
5402	Other repairs
5701	Accommodation, cafes and restaurants
6101	Road transport
6201	Rail, pipeline and other transport
6301	Water transport
6401	Air and space transport
6601	Services to transport; storage
7101	Communication services
7301	Banking
7302	Non-bank finance
7401	Insurance
7501	Services to finance, investment and insurance
7701	Ownership of dwellings
7702	Other property services
7801	Scientific research, technical and computer services
7802	Legal, accounting, marketing and business management services
7803	Other business services
8101	Government administration
8201	Defense
8401	Education
8601	Health services
8701	Community services
9101	Motion picture, radio and television services
9201	Libraries, museums and the arts
9301	Sport, gambling and recreational services
9501	Personal services
9601	Other services

Attempts to systematically describe large suites of generic industrial technologies are reviewed by Gault et al. (1985). Most such efforts have related to energy analysis (Boustead and Handcock 1979) and greenhouse gas emissions modelling (Gielen et al. 1998), which is to be expected, given the intensity of research in these areas over several decades. Gault et al. developed the 'Design Approach' methodology for modelling socio-economic systems. The Design Approach views socio-economic systems form a hierarchical multilevel perspective. It relies heavily on the use of process analysis method, as described by Gault (Gault et al. 1987). The Design Approach has been adopted in the CSIRO's 'Australian Stocks and Flows Framework' (Foran and Poldy 2002; Poldy et al. 2000).

Bottom-up approaches to modelling input-output functions are now frequently applied in the field of IO analysis. However, historically, bottom-up approaches were more widely employed in the related field of activity analysis. Activity analysis was developed by Koopmans and his colleagues in the 1950s ‘to study and appraise criteria, rules and practices for the allocation of resources’ (Koopmans 1953). ‘Methods of production’ and ‘the elementary activity, the conceptual atom of technology’ (Koopmans 1951, 1953) defined technologies at a finer scale than that permitted by Leontief’s input-output analysis. An additional differentiating feature of activity analysis was the use of linear (and later, non-linear) programming techniques to find optimal configurations of technologies. The Design Approach adopts on the one hand the detailed technological representation of activity analysis but on the other, the deliberative approach to modelling and the emphasis on economic planning espoused by Leontief.

More recently, the concept of activities has been employed in an input-output context by Konijn and Steenge (Konijn 1994; Konijin et al. 1995). Their method for disaggregating industries and commodities in make and use tables to generate ‘activity-by-activity’ input-output tables has been adopted by Statistics Netherlands (Algera 1999). In this method, bottom-up information can be used to complement top-down information (make and use tables) in the process of disaggregating frequently inhomogeneous ‘industries’ into more homogeneous ‘activities’. In particular, secondary activities common to a number of different industries are distinguished (e.g. consulting services provided by manufacturing companies).

Example: Technological Change in the Australian Steel Industry

In this section, a study of energy use in the Australian iron and steel industry will illustrate how top-down and bottom-up information can be combined to extract information with the aid of generalised cross-entropy techniques (Golan et al. 1996). For the Australian iron and steel sector, production data exist for iron and steel in total and also with subtotals for the basic oxygen furnace (BOF) versus the electric arc furnace (EAF) route and for ingot casting (IC) versus continuous casting (CC) (Fig. 5.4).

It can be seen that continuous casting replaces (less efficient) ingot casting and that the share of EAF production increases, but is quite small. The energy used by Australia’s iron and steel sector is also known (Fig. 5.5). Note that these data include consumption of self-produced energy (coke and thermal energy). The consumption data constrain the energy input coefficients for individual process steps. Specifically, consumption of each energy type by each process must add up to the total consumption of each energy type. Better estimates of input coefficients would be obtained if data for the total energy used by each process were also available; however, they are not. It was expected that efficiency improvements had occurred in the industry, due both to shut-down of old units and to new units brought on-line in later years. This

Table 5.1 Prior Estimates (Bracket) and Calibrated Energy Input Coefficients for 96/97 (GJ/t)

	Coal	Coke	Liq HC	Nat gas	Electric	Other	COG/BFG
Coke	35.1	0	0(1.285)	0.88	0.10	0.18(0)	5.68
Ovens (coke)	(38.5)			(0.1)	(0.095)		(4.18)
Sinter +	2.44	8.67	0.15	1.87	0.42	0.03(0)	5.67
BF (iron)	(3.05)	(10.8)	(0.23)	(0.14)	(0.43)		(2.26)
EAF	0.08	0	0.12	0.28	4.59	0.06(0)	0
(steel)	(0.085)		(0.12)	(0.25)	(1.53)		
BOF (hot steel)	0.01	4.49	0.04	0.23	0.17	0.01(0)	0.31
	(0.025)	(6.98)	(0.038)	(0.038)	(0.16)		(0.085)
Contin	0	0	0.00	0.01	0.09	0	0.01
Cast (crude steel)	(0.005)		(0.005)	(0.005)	(0.09)	(0.005)	
Ingot Cast	1.27	0	0.01	0.20	0.56	0	0.01
(crude steel)	(1.26)		(0.007)	(0.13)	(0.49)	(0.005)	
Rolling,	1.11	0	0.01	0.99	1.23	0	0.02
finishing, misc.	(1.38)		(0.008)	(0.14)	(0.35)	(0.006)	
(finished steel)							

COG = coke oven gas, BFG = blast furnace gas.

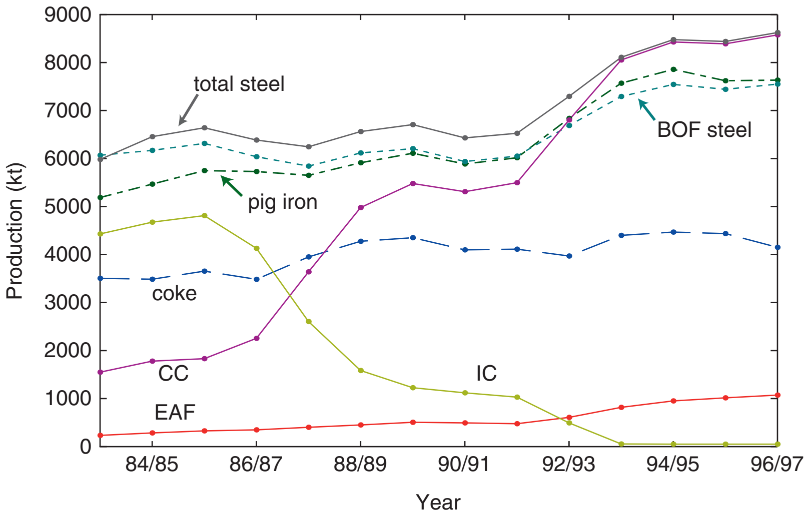

Fig. 5.4 Production of Iron and Steel with Breakdown of Key Processes (Ferber 2002)

is because the Australian industry suffered from world over-capacity in the early 1980s, but more recently has invested several billion Australian dollars in capital works.

Energy input coefficients for the iron and steel industry were calibrated using the cross-entropy methodology for each year from 1981/92 through 1996/97. Prior upper and lower bounds and prior coefficient estimates were specified for each coefficient based mainly on information in (European Integrated Pollution

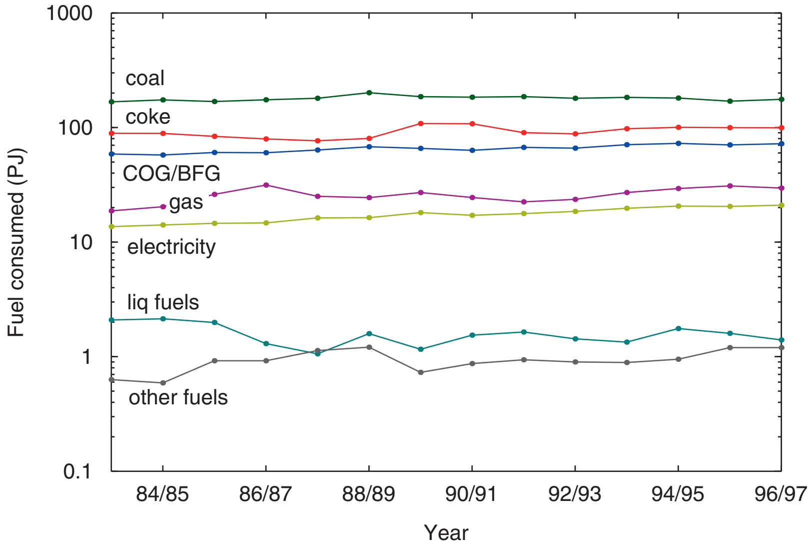

Fig. 5.5 Total Consumption of Fuels and Electricity by the Iron and Steel Sector

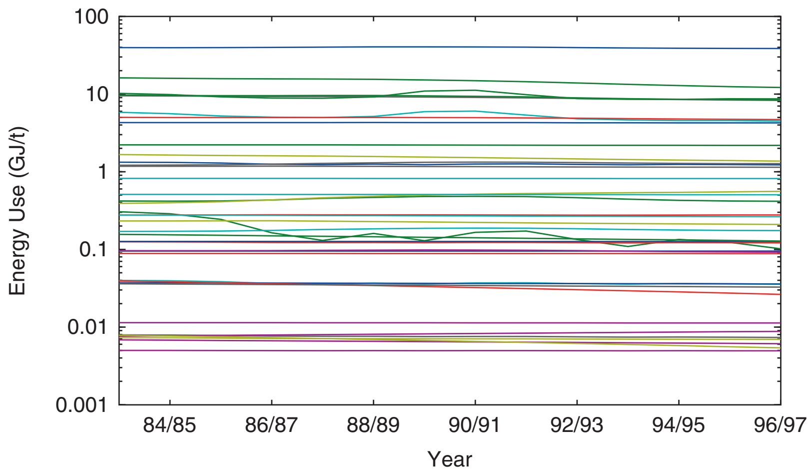

Fig. 5.6 Input Coefficient Trajectories by Process and Energy Type

Prevention and Control Bureau 2001). As an example, the 1996/97 coefficients, along with the prior estimates (which were the same for all years) are shown in Table 5.1 Inputs are given per tonne product of each process (for lack of statistical data, sintering and BF were aggregated and coefficients are per ton pig iron). The shaded coefficients were assumed to be identically zero.

The trajectories of the 40 non-zero coefficients are plotted in Fig. 5.6.

Coefficients for coal and coke use decline slightly over time, but for coke, the decline is interrupted by a large peak from 1989–1992. The peak matches features in overall production and use data, so is not an artefact, but is otherwise hard to explain. Coefficients for COG/BFG use also tend to decline, although it should be noted that the production of COG/BFG increases over time as a proportion of total consumption, indicating improving efficiency. Coefficients for natural gas fluctuate while those for electricity tend to go up until the 1990s, when they begin to decline. Total (gross) energy input to each process declines in most cases – for the aggregated sintering/blast furnace operations, from 23.8 to 20.7 GJ/t. No strong trends were distinguished for less energy-intensive processes, and an increasing trend was observed for the EAF process. This might have been caused by decreasing quality of feed material. In all cases, results such as these cannot be treated as conclusive, since the process of cross-entropy minimization ought to be seen as something between interpolation and regression. The more data are used, the more reliable the results. It is also a characteristic of this method that large changes tend to accrue to large coefficients. This results in conservative, but not necessarily accurate values for the smallest coefficients.

Relating Capital Stocks and Material Flows

Dynamic Input-Output and Process Models

Tying together models of capital stocks and technologies requires the construction of dynamic models. In the IO literature, dynamic IO models make capital investments a function of expected future demands (Leontief 1970a; Sonis and Hewings 1998; Duchin and Szyld 1985). Thus they consider the capacity of each industry and the commodities required to maintain and form new capacity. A few authors have also linked capital investments to technological change within industries via marginal IO coefficients (Tilanus 1967; Azid 2004). In the MFA literature on the other hand, the function of manufactured capital stocks is not usually considered at all. The focus is purely on capital stocks as reservoirs of bulk materials or specific substances of interest.

Environmentally extended input-output models can be traced back to Leontief's work on air pollutants in the 1970s (Leontief 1970b, 1972). Subsequently, similar extended input-output models (i.e. static ones) have been widely applied to environmental and resource issues. Environmental extensions of dynamic IO models have been far less common (consistent with the limited applications of dynamic IO models more generally). Physical input-output models have appeared in recent years, derived from the physical input-output tables (PIOT) now available for a number of European countries and static IO models have been derived from these by various authors. However, as yet there does not appear to be sufficient empirical data to support the construction of dynamic input-output models based only on physical flows statistics. The highly aggregate representation of capital stocks in current PIOTs may also be a barrier to creating dynamic physical models (see above).

Konijn, de Boer and Lange (1997) present a hybrid-unit IO model that includes consumption of selected materials for capital formation. They estimate materials embodied in exports, consumption and fixed capital formation. Duchin, Lange and co-workers (1994) built on the original multi-regional World Model (Leontief et al. 1977) to examine 'relationships among increasing affluence, pollution and technological choices' (Duchin et al. 1994). In particular, they assess the feasibility of 'sustainable development' as envisaged in the Brundtland Report (World Commission 1987). Their dynamic IO model includes capital stock dynamics and exogenous technological change. The latter is derived from extensive bottom-up data and analysis. The model is used to simulate an 'Our Common Future' scenario with technological change and a reference scenario with no technological change post 1990. Idenburg and Wilting (2000; Idenburg 1998) use a dynamic IO model to study the technological change and eco-efficiency in The Netherlands. A multi-sectoral equilibrium model for Norway, extended to describe total material inputs and specific waste flows was developed by Bruvoll and Ibenholt (1997). They use the model to assess the links between material and energy intensities of production and waste flows.

Process analysis has been widely used to construct bottom-up multi-sectoral models in the energy and climate policy fields.[6] These models are often used within an economic optimisation framework to identify solutions achieving policy objectives whilst minimising costs, subject to technological and other constraints (Löschel 2002). Technological change can be modelled in terms of substitution between different technologies and/or changes in individual technologies. Input substitution possibilities are generally reduced as one moves from more generic to more specific and detailed representations of technologies.

Capital vintages are frequently distinguished in bottom-up models. The possibility of substituting intermediate inputs for labor and (less commonly) of substitution between intermediate inputs may differ for new capital and existing capital stocks. The most extreme assumptions are often referred to as 'clay' (non-substitutability) and 'putty' (full substitutability), leading to three basic types of model (Kónya 1994)[7]:

Clay–clay
Putty–clay
Putty–putty

Assumptions of limited substitutability are also possible (e.g. putty–semi-clay) (Ruth et al. 2004). Clay models assume that technological change is entirely embodied in capital stocks, whilst putty models assume that technological change is entirely disembodied. The theoretical appropriateness of these assumptions depends

[6] Top-down approaches based on macro-economic modeling have also been widely used, and have often produced very different results (IEA 1998).

[7] The fourth possibility of clay–putty does not have a logical interpretation, since substitutability *ex post* is not likely to be greater than *ex ante*.

on the level of technological aggregation (Ruth et al. 2004; Davidsdottir 2002). In practice, it may be difficult to identify the many parameter values required in more 'realistic' but complicated models.

Dynamic IO Modelling in ASFF

In ASFF, hierarchically linked sectoral/thematic modules describe different parts of the economy and employ various model structures. One such module, the 'materials model' describes flows of material and energy, as well as capital stocks within 'basic industries' using a dynamic IO structure (Lennox et al. 2003). 'Basic industries' are defined as those transforming raw materials (ores, concentrates, harvested materials, etc.) into bulk industrial materials and energy forms (cement, steel, electricity, etc.) (Lennox et al. 2003). The model is driven by the requirements for processed materials and energy in all other parts of the economy – i.e. those modelled in the other modules of ASFF. Adjustments to these requirements are made to account for materials recycling and international trade in processed materials.

The materials model consists of a set of process-based input-output relations, each of which is associated with a capital stock. Input-output coefficients are exogenously specified for each process and may vary over time. Technological change of individual processes is therefore modelled as being entirely disembodied. On the other hand, multiple processes may produce the same product and the existing capital stocks of each process partly determine the combination of technologies employed. In this respect, technologies are represented as embodied and technological change can be modelled in terms of substituting alternative processes.

Evolution of capital stocks is modelled using vintages and life tables that determine the proportion of each vintage that survives from one period to the next. Physical depreciation of productive capital and capital maintenance are assumed to be factored into life tables. Additions to capital stocks are determined as a function of output requirements, stock scrapping and several decision variables. There is no forecasting of outputs for future years as in Duchin and Syzld's model (1985), partly because the ASFF model deals with longer time steps of 5 years. Processes of capital stock formation and scrapping are associated with material flows through material embodiment parameters. These describe the mass of materials that compose a functional unit of capital. It must be said that flows associated with production equipment are generally small when compared both with either production throughput or materials embodied buildings and civil works. Thus in ASFF, the bulk of industrial capital stocks are industrial buildings or civil works such dams.

Example: Electricity Generation in Australia

The representation of capital stocks and associated material flows in ASFF is illustrated with reference to the electricity generation industry. A number of different

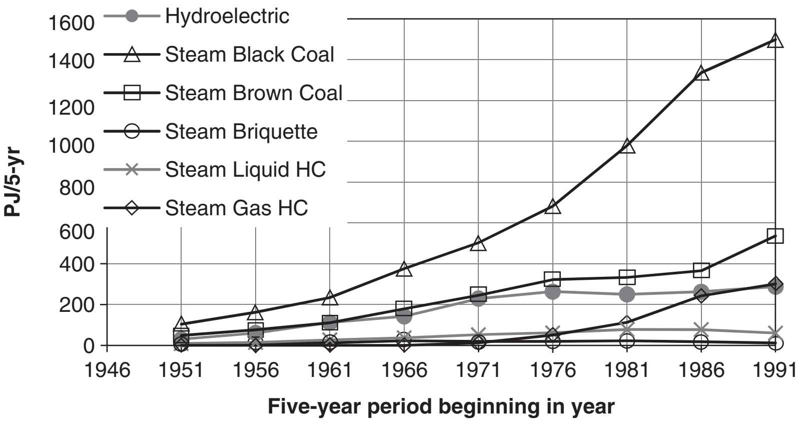

Fig. 5.7 Electricity Production by Process

Table 5.2 Material Composition Coefficients

t/MW nominal capacity	Concrete	Steel
Hydroelectricity	4,100	36
Steam-fired	370	73
t/MW nominal capacity	74	11

generation processes are represented in ASFF including different types of coal, oil and gas firing, as well as hydroelectric generation. Figure 5.7 shows the historical output for each of these processes over historical time. Note that the values shown are in PJ/5-year and are summations over spatial regions represented in the model.

The process models used for electricity generation activities are simpler than those for steel-making (above). As a first approximation it is assumed that the only inputs to generating processes are electricity (for self-use and internal losses) plus the fuel consumed in thermal generation processes. However, in additional to these direct inputs, there are the indirect inputs of materials required for the construction of new capital. By mass, the main constituents of these stocks are steel and concrete. Embodied materials coefficients for hydroelectric, steam and gas turbine generation process capital stocks are shown in Table 5.2 (CISS 2001). Note that hydro-electric works vary greatly in their materials requirements, so these values should be treated with caution.

Using these coefficients, the corresponding endogenous requirements for steel and concrete are computed and are shown in Fig. 5.8. To put the requirements for steel and concrete in perspective, the total supply of steel is illustrated on a second axis in Fig. 5.8, the majority of which is used domestically.

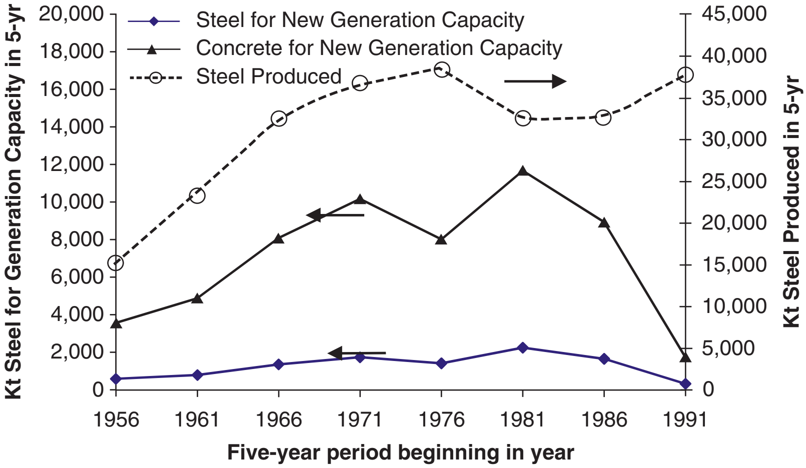

Fig. 5.8 Steel and Concrete for Endogenous Growth of Electricity Supply (Left Axis) and Steel Production (Right Axis)

Discussion and Conclusions

In the IO literature, manufactured capital stocks have primarily been considered as a component of final demand. Few models of the technologies embodied in these stocks have been developed. While technological change is frequently considered in this literature, it is usually implemented in terms of exogenous changes to IO parameters. On the other hand, there are many examples of bottom-up multi-industry and multi-sectoral models that represent embodied technologies. Clay–clay, putty–clay and putty–semi-clay vintage models make an explicit link between capital stocks and technological characteristics. The dynamic physical IO model of industries within ASFF includes vintaged stocks, but does not link these to IO coefficients, which are exogenously specified. The field of activity analysis provides an obvious link between general bottom-up or process-based modelling approaches and the field of IO analysis, which is dominated by top-down approaches.

In the material flow analysis (MFA) literature, capital stocks have mainly been considered as stores of materials/substances and hence, as temporary sinks and sources of material/substance flows. 'Bulk MFA' studies in particular, are rarely concerned with process and are essentially descriptive. ASFF shares the aim of describing physical flows into and out of an economy; however, the bottom-up approach taken with ASFF leads to a much more detailed description of the physical economy and a strong interest in process. Physical IO models generally provide more detail than does MFA, but much less than do bottom-up models or some economic IO models. Physical IO modelling still faces a considerable constraint in terms of data availability. The most promising route forward then appears to be with the various possibilities for 'hybrid' input-output modelling, whereby top-down and bottom-up methods and/or physical and economic components are combined.

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Chapter 6
An Input-Output Framework to Enhance Consistency in Hybrid Modeling

Susanne Kytzia

Introduction

Input-Output Tables (IOT) have long attracted interest from researchers in Industrial Ecology (IE) for two reasons. First, they provide an easily accessible data base to analyze networks of economic processes or activities on national scale. This data base is used to allocate environmental impacts and physical flows to economic activities in Life Cycle Assessment (LCA) (Hendrickson et al. 1998; Matthews and Small 2001; Suh and Huppes 2002, 2005; Suh 2004a, b) and Material Flow Accounting (MA Accounting) (see contributions of Giljum and Nathani in this handbook, also Meyer and Bockermann 1998; Bringezu 2002; Daniels and Moore 2002). Second, IOT is integrated into the general framework of national accounting and therefore provide an interface between MF Accounting on national scale and economic indicators such as GDP. This interface is used to set up Physical Input-Output Tables (PIOT) following the system definitions and partly the procedures of data compilation commonly used in IOT (Weisz and Duchin 2006; Gravgård 1999; Stahmer et al. 1998). But, also more general attempts to integrate physical flow and stock accounting into national accounting rely on system definitions commonly used in IOT to ensure compatibility within the overall accounting scheme (Weisz et al. 2005; Voet et al. 2005; Spangenberg et al. 1999). This is of paramount importance for using mixed indicators from physical and economic accounting such as DMC per GDP to analyze processes of dematerialization.

For numerous research questions, however, an analytic approach based on the system definition given by national IOT is not appropriate. IOT on national scale only provide highly aggregated data, use a given industry classification and measure commodity flows in monetary units. Household activities and capital formation

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are only partly covered. Such a system definition is insufficient to compare environmental performances of different products (e.g. cars), to evaluate waste management strategies for specific materials (e.g. electronic waste) or identify pathways of substances (e.g. chlorine). The system definition is a key step in any LCA or Material Flow Analysis (MFA) and researchers in IE are naturally reluctant to start with a "pre-defined" system which might not cover all important aspects of the problem under study.

One solution to meet both needs for (a) compatibility with IOT and (b) using a problem specific system definition are hybrid models. According to Haes et al. (2004) "a hybrid model means that the tools that constitute the model are connected with one another by data flows, but without full compatibility between the models at stake. (. . .) Its main purpose is to enlarge the scope and/or detail of a single tool analysis in a practical and yet science based way" (p. 25). Hybrid models using IOT as one core model were introduced for LCA (Suh et al.) as well as for MFA (see Chapter 10 by C. Nathani). They use the IE tool – LCA and MFA – for a detailed and problem specific analysis of physical flows and environmental burdens. According to Haes et al. (2004) these analysis can be considered as the "foreground". IOT in contrast provides the "background" used to extent system boundaries or to link physical and economic modeling. Yet, a foreground–background distinction is not constitutive for hybrid models. It is rather the aim for consistency in the overall model framework, in which all models "must to a sufficient degree have the same model structure" (Haes et al. 2004, p. 26) with full consistency as a prospect for further research (p. 29).

In this chapter I argue, that one step towards full consistency is to use the methodological framework of Input Output Analysis (IO) as a common basis for both physical and economic analysis. IO is a general tool which can be used on different scales: company, region, industry or nation. The pre-defined system definition is given by national accounting standards not by IO itself and IO are flexible to adapt to alternative system definitions (e.g. including household activities). They can be used for demand driven as well as supply driven modeling approaches (Suh 2005). Physical models can easily be fit into the IO terminology, represented as matrices and the matrix inversion can be used as the key algorism (Heijungs and Suh 2002; Voet 1996; Baccini and Bader 1996a). Thus, the IO methodology is most promising for the development of "economic–physical" models at all scales of investigation ranging from national economies to technical processes.

In the following second section, a general framework of input output modeling is introduced including economic IO as well as LCA, MFA and SFA. It outlines similarities and differences between these methods and shows how they can be combined in "economic–physical" models. This framework is illustrated by two case studies in the third section. In the first case study, I use an IO modeling framework to combine an analysis of flows of heavy metals in cement production with cost calculation data. In the second case study, a MFA for products related to food production and consumption in a Swiss region is used as a physical IO model and combined with the Leontief price model. In the final section, I sum up what we gain by using the proposed modeling framework and discuss the shortcomings and limitations we are faced with.

General Framework for IO Modeling

Figure 6.1 shows a simple production system which consists of three processes, primary production, processing and trade, linked by flows of material with a market price (raw material and processed goods) and without a market price (emissions).

This system may have different properties of interest to researchers in the field of IE, each property by itself or in combination with the others. Such properties are (i) the distribution of substances in an anthropogenic system, (ii) the resource consumption to satisfy a specific human need or (iii) an economic activity generating factor income. A combined investigation of these properties might reveal how much factor income is generated by satisfying a specific human need or how the distribution of substances is related to factor income. Such considerations are important to IE in its desire to enhance economic and technological development in line with the notion of sustainability.

Models Investigating Different System Properties

Most models investigating these properties are based on input output approaches.

Distribution of Substances

The distribution of substances is analyzed with **Substance Flow Analyses (SFA)**. It is a method for investigating pathways of specific substances through anthropogenic and natural systems (Baccini and Brunner 1991; Baccini and Bader 1996a, b; Voet 1996). The term "substance" is defined according to its use in chemistry as an "entity of identical atoms or molecules that is an element or a defined chemical compound (Brunner et al. 1998, p. 5). Most SFA studies are motivated by a specific environmental problem associated with the substance under study such as heavy metals (Bergbäck 1992; Jonsson 2000; Sörme 2003), nitrogen (Voet 1996) or chlorine (Ayres and Ayres 1998/99). The use of SFA helps to relate critical emissions of these substances to processes, products and material inputs in the system. Most SFA studies are based on a static input output model, relating the

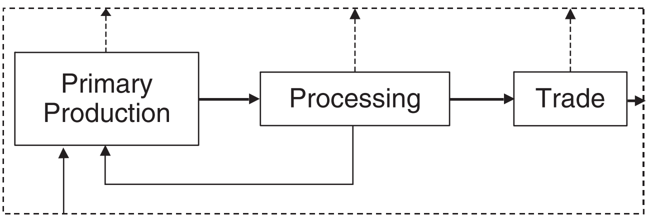

Fig. 6.1 Simplified Production Chain. Material Flows without a Market Price are Shown in Dotted Lines

input into the system measured in mass units of the substance to the output of this substance in each process.

$$\mathbf{x}_{\mathbf{sub}}^{(\mathbf{r})} = (\mathbf{I}\text{-}\mathbf{B}_{\mathbf{sub}}^{(\mathbf{r})})'^{-1}\mathbf{pa}_{\mathbf{sub}}^{(\mathbf{r})} \tag{6.1}$$

$\mathbf{x}_{\mathbf{sub}}^{(\mathbf{r})}$: vector of outputs of each process in mass units of substance r (e.g. chlorine)

$\mathbf{pa}_{\mathbf{sub}}^{(\mathbf{r})}$: vector of primary inputs of each process from outside the system boundaries in mass units of the substance r

$\mathbf{I}$: identity matrix

$\mathbf{B}_{\mathbf{sub}}^{(\mathbf{r})}$: matrix of input-output coefficients for substance r (transfer coefficients in the SFA terminology)

Consumption of Resources and Generation of Emissions

The consumption of resources can be analyzed with a **Material Flow Analysis (MFA)**. From a methodological perspective, it is closely related to SFA (Baccini and Bader 1996a, b; Bringezu 2000). The term "materials" in MFA generally includes goods, defined as "materials with a positive or negative economic value" (Brunner et al. 1998, p. 5). Examples are studies analyzing the use of land, energy and non-renewable resources (MFA for biomass, food products or construction materials). MFA studies link the use of natural resources to consumer needs, economic structures or technological development (Müller 1998; Redle 1999; Faist 2000; Faist et al. 2001; Hug and Baccini 2002). Natural processes (e.g. forests or soil) can be included in the studies to additionally assess the reproductive potential of the system or the range of the remaining resource deposits (see e.g. Müller 1998). A large number of MFA studies are based on static output input models, relating the output of a system (e.g. final demand of private households) measured in mass units of the studied material to the input of this material into each process.

$$\mathbf{x}_{\mathbf{mat}}^{(\mathbf{k})} = (\mathbf{I}\text{-}\mathbf{A}_{\mathbf{mat}}^{(\mathbf{k})})^{-1}\mathbf{y}_{\mathbf{mat}}^{(\mathbf{k})} \tag{6.2}$$

$\mathbf{x}_{\mathbf{mat}}^{(\mathbf{k})}$: vector of inputs of each process in mass units of material k (e.g. biomass)

$\mathbf{y}_{\mathbf{mat}}^{(\mathbf{k})}$: vector of outputs of each process to the target process in mass units of material k

$\mathbf{I}$: identity matrix

$\mathbf{A}_{\mathbf{mat}}^{(\mathbf{k})}$: matrix of output-input coefficients for material k (transfer coefficients in the MFA terminology)

In order to analyze the emissions caused in this system, the approach can be extended with emission coefficients formulating a linear relationship between the total material input into each process (which equals its production volume) and its emissions.

$$\mathbf{u} = \mathbf{x}_{\mathbf{mat}}^{(\mathbf{k})}\,\mathbf{e}^{(\mathbf{k})} = (\mathbf{I}\text{-}\mathbf{A}_{\mathbf{mat}}^{(\mathbf{k})})^{-1}\mathbf{y}_{\mathbf{mat}}^{(\mathbf{k})}\mathbf{e}^{(\mathbf{k})}$$

u : vector of emissions caused by each process in mass units of the emission used for environmental assessment (e.g. carbon dioxide)

$\mathbf{e}^{(\mathbf{k})}$: vector of emission coefficients defined as the amount of emissions (in mass units of the chosen emission) related to the input into each process in mass unit of material k

(6.3)

This approach is very similar to **Life Cycle Assessment (LCA)**, a tool for environmental impact assessment of product chains (Heijungs 1997a, b; Frischknecht 1998; Heijungs and Suh 2002). In contrast to the approach shown in Equations (6.2)–(6.3), LCA proposes a mixed unit approach allowing for input and output flows in different physical units (e.g. energy and mass units). In consequence, it does not confirm with the principle of material balancing. In addition, resource consumption and emissions are assessed according to their environmental impacts (impact assessment). LCA is generally applied to compare different alternatives in corporate or public environmental management (product development and procurement) or for consumer information. It delivers indicator values for environmental impacts related to the alternative systems (e.g. Global Warming Potential, Resource Depletion or Toxicity).

Generation of Factor Income

The generation of factor income is analyzed with an economic **Input Output Analysis (IO)** as introduced by Leontief in 1936. IO is an economic tool with a long tradition in economic and environmental assessment of policies on national scale as well as regional scale. It was originally developed for empirical analysis of commodity flows between the various producing and consuming sectors within a national economy (e.g. in Miller and Blair 1985). The core model is a matrix of output input coefficients (technology matrix) describing commodity flow between processes in the economic system over a stated period of time. The direction of flows represents the physical structure of the system. Yet, they are generally measured in monetary units.

$$\mathbf{x_{mon}} = (\mathbf{I}\text{-}\mathbf{A_{mon}})^{-1}\mathbf{y_{mon}}$$

$\mathbf{x_{mon}}$: vector of inputs of each process in monetary units
$\mathbf{y_{mon}}$: vector of outputs of each process to the target process in monetary units (6.4)
$\mathbf{I}$: identity matrix
$\mathbf{A_{mon}}$: matrix of output-input coefficients (technology matrix in IO terminology)

IO can also be extended with emission coefficients to evaluate environmental effects of environmental policies and technological development (e.g. Meyer and Bockermann 1998).

$$\mathbf{u} = \mathbf{x_{mon}}\ \mathbf{e} = (\mathbf{I}\text{-}\mathbf{A_{mon}})^{-1}\mathbf{y_{mon}}\mathbf{e}$$

u : vector of emissions caused by each process in mass units of the emission used for environmental assessment (e.g. carbon dioxide)
$\mathbf{e}$: vector of emission coefficients defined as the amount of emissions (in mass units of the chosen emission) related to the amount of input of each process in monetary units
(6.5)

Joint Investigation of Different System Properties

The core model in all input output approaches introduced in the previous section is the matrix of input output (IO) or output input (OI) coefficients (technology matrix or matrix of transfer coefficients). It represents the structure of the studied system. In combining models for different system properties we have to ask whether the same structure – or the same IO/OI matrix – can represent different system properties or not. This decision leads to the degree of model integration that we will finally achieve.

(i) *Different system properties represented in different sub-model*: Obviously, the distribution of substances is not represented by a system structure equal to the system structure depicting the generation of factor income. It is based on coefficients estimated with the knowledge and the methods of natural sciences whereas the generation of factor income is based on economic production chains. In this case, we end up with two core models which are linked by additional equations converting the monetary flows into material flows (via prices) and the material flows into substance flows (via substance concentrations). With help of these additional equations in combination with the models introduced in previous sections we can for example estimate how much phosphorus is emitted and how much factor income is generated by the daily food consumption of an average Swiss person. The resulting model framework, however, is partly redundant because the different system properties are represented independently although they may be more closely related. Example: the flow between processing and trade in Fig. 6.1 may be represented independently as substance, material and money flow in three different submodels, $A^{(r)}_{sub}$, $A^{(k)}_{mat}$ and A_{mon}. Yet, it is evident that these flows are related through the substance concentration and the material price. As this interrelation is lost in the model presented above, it does not help to ensure the model's consistency. In our example, a scenario calculation based on wrong assumptions may show a rising amount of material flowing between processing and trade combined with a decreasing amount of substances flowing between these two processes although the substance concentration of this material remains constant. This obvious error is not revealed by the model itself but has to be depicted in the interpretation of results by the researchers.

(ii) *Different system properties represented in a common core-model*: Differences in the system *structures* representing the generation of factor income, the generation of emissions and the consumption of resources are less evident. On the one hand, we could argue that in systems where every economic activity can be defined by a specific output or input flow of material, both monetary and physical flows will show an equivalent system structure. And, a system structure based on physical flows would be more accurate as changes in relative prices tend to distort its representation. Following this argumentation, we can combine the models introduced in earlier sections on consumption of resources and generation of emissions and on generation of factor income on the basis of the Leontief price model (Duchin 1992). We end up with a matrix of OI coefficients based on the ratios of output and input flows in mass units, $A^{(k)}_{mat}$, as core model (see also the Chapter 2 in this handbook by Faye Duchin).

On the other hand, we could argue that the description of the system structure with monetary flows is preferable because (i) it is a better representation of the economic production function and (ii) it allows for including service industries. Following this line of argumentation we end up with a model equivalent to Equation (6.5) with a matrix E including coefficients for emissions as well as resource consumption (see also Chapter 4). The core model then is the Leontief inverse.

Case Studies

The following two case studies illustrate two options for a joint investigation of different system properties: first, their representation in different sub-models with a low level of model integration (cement production), and second their representation in one common core model which is highly integrated (food production chain). The case studies are based on data from Brodbeck and Kytzia (1999),[1] Faist (2000) and Kytzia et al. (2004).

[1] Data of cement production could not be used directly but had to be modified for this publication. The heavy metal concentrations in the case study are higher than the concentrations found in the study.

Cement Production

Cement industries are one of the world's largest producers of carbon dioxide emissions due to fossil fuel incineration and carbon dioxide emissions from the process itself. An interesting option to reduce them on national scale is to substitute fossil fuels in cement industries with waste of high energy content such as plastics, waste tires or solvents. These waste flows can be used as secondary fuels in the cement production process instead of being burned in waste incineration plants or deposited in landfills. The substitution saves fossil fuels as well as carbon dioxide emissions. At the same time, it is most interesting for cement industries as prices for secondary fuels are lower than prices for fossil fuels. For some waste flows like sewage sludge, cement industries can even sell their incineration capacity and, thereby, earn money both from waste incineration and substitution of fossil fuels.

In Switzerland, cement industries have pursued this strategy for many years. To ensure the quality of their product and the compliance to environmental regulations, production plans have to ensure that the content of heavy metals in cement and exhaust air does not exceed certain standard concentrations. SFA is an appropriate tool to support this process of controlling and monitoring. In combination with cost planning, it helps to answer the key question of how much secondary fuels of a certain quality should be used in cement production to minimize production costs without violating any quality or environmental standard.

In the first case study, we introduce an input output model that combines SFA with cost calculation.

System Definition and Modeling Approach

Figure 6.2 shows the system definition of a cement production plan that we use in our model. The main characteristics of the system from a technical point of view,

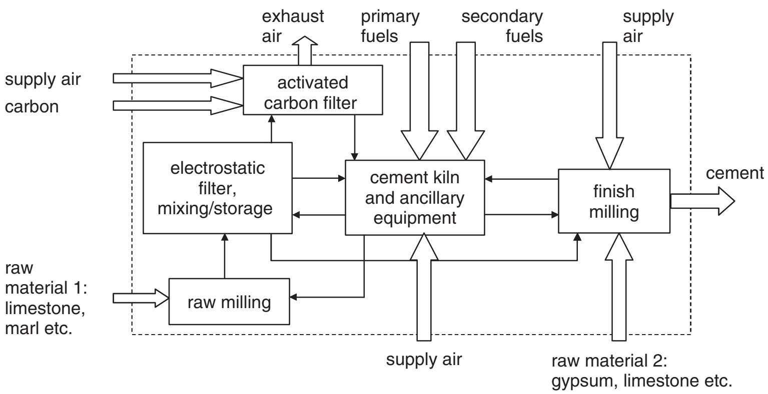

Fig. 6.2 System Definition of Cement Production. The Data for Flows of Money, Quick Silver and Material is Given in Appendix (Tables 6.5–6.7)

are the inner circles of material flows: the first from raw milling to the electrostatic filter to the cement kiln back to raw milling, the second from the electrostatic filer to the activated carbon filter to the cement kiln back to the electrostatic filter and the third from the electrostatic filter to the finish milling back to the cement kiln back to the electrostatic filter. These circles mainly consist of streams of air carrying the materials from process to process and making sure that the heat from the cement kiln is used as efficiently as possible.

These circles are most relevant for the substance flows within the system. Yet, they have no meaning in cost calculation. For this reason, the two system properties, distribution of substances and cost allocation, cannot be represented in the same model structure. We, therefore, formulate three separate input output models according to Equation (6.1) for substances for the example of quick silver (Hg) (Equation (6.6)), production costs (Equation (6.7)) and material flows (Equation (6.8)). The input output model for material flows is used to calculate the production volume in tons needed to show the costs of production as well as the concentration of quick silver per ton of cement (see Fig. 6.3). These three models are linked via their vectors of primary input which are linear dependent as shown in Equations (6.9) and (6.10).

$$\mathbf{x}_{\mathbf{sub}}^{(\mathbf{Hg})} = (\mathbf{I}\text{-}\mathbf{B}_{\mathbf{sub}}^{(\mathbf{Hg})})'^{-1}\mathbf{pa}_{\mathbf{sub}}^{(\mathbf{Hg})} \tag{6.6}$$

$$\mathbf{x}_{\mathbf{mat}}^{(\mathbf{cement})} = (\mathbf{I}\text{-}\mathbf{B}_{\mathbf{mat}}^{(\mathbf{cement})})'^{-1}\mathbf{pa}_{\mathbf{mat}}^{(\mathbf{cement})} \tag{6.7}$$

$$\mathbf{x}_{\mathbf{mon}}^{(\mathbf{cement})} = (\mathbf{I}\text{-}\mathbf{B}_{\mathbf{mon}}^{(\mathbf{cement})})'^{-1}\mathbf{pa}_{\mathbf{mon}}^{(\mathbf{cement})} \tag{6.8}$$

$$\mathbf{pa}_{\mathbf{sub}}^{(\mathbf{Hg})} = \mathbf{pa}_{\mathbf{mat}}^{(\mathbf{cement})}\mathbf{k}^{(\mathbf{Hg})} \tag{6.9}$$

$$\mathbf{pa}_{\mathbf{mon}}^{(\mathbf{cement})} = \mathbf{pa}_{\mathbf{mat}}^{(\mathbf{cement})}\mathbf{p}^{(\mathbf{cement})} \tag{6.10}$$

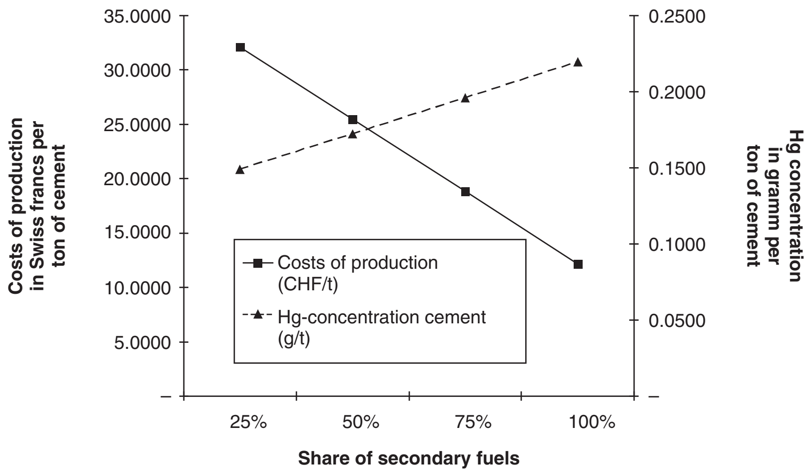

Fig. 6.3 Effects of Changes in the Share of Secondary Fuels in Total Fuel Requirements in Cement Production from 25% to 100% on Costs of Production Per Ton of Cement and Concentration of Quick Silver (Hg) Per Ton of Cement

where,

$\mathbf{x}_{\mathbf{sub}}^{\mathbf{(Hg)}}$: vector of sum of outputs and intermediate flows of substance Hg in each process

$\mathbf{B}_{\mathbf{sub}}^{\mathbf{(Hg)}}$: matrix of input output coefficients for substance flows

$\mathbf{pa}_{\mathbf{sub}}^{\mathbf{(Hg)}}$: vector of primary input of substance Hg in each process

$\mathbf{x}_{\mathbf{mat}}^{\mathbf{(cement)}}$: vector of sum of outputs and intermediate flows of materials needed in cement production in each process

$\mathbf{B}_{\mathbf{mat}}^{\mathbf{(cement)}}$: matrix of input output coefficients for material flows

$\mathbf{pa}_{\mathbf{mat}}^{\mathbf{(cement)}}$: vector of primary input of materials in each process

$\mathbf{x}_{\mathbf{mon}}^{\mathbf{(cement)}}$: vector of sum of outputs and intermediate flows of material values (costs) in cement production in each process

$\mathbf{B}_{\mathbf{mon}}^{\mathbf{(cement)}}$: matrix of input output coefficients for cost flows

$\mathbf{pa}_{\mathbf{mon}}^{\mathbf{(cement)}}$: vector of primary input of costs in each process

$\mathbf{k}^{\mathbf{(Hg)}}$: vector of concentration of substance Hg in materials needed in cement production

$\mathbf{p}^{\mathbf{(cement)}}$: vector of prices for materials needed in cement production in each process

The three different IOTs for each material, money and substance flow in the status quo are shown in the Appendix (Tables 6.5–6.7).

Parameter Variation

On this basis, we evaluate the effects of a change in the share of secondary fuels in the primary input of fuels. We assume that the cement plant increases the amount of sewage sludge from 25% to 100% of the total fuel requirements. As a result, the cost for raw material and fuels fall drastically (see Fig. 6.3) and the concentration of quick silver in cement and exhaust air rises.

The cement industry can now introduce their quality standard for a maximum Hg concentration in cement and decide on the share of secondary fuels they can use to reach this maximum concentration. They can also use the model to evaluate changes in the production process that will reduce the amount of quick silver which finally ends up in the cement.

Discussions on the Case Study

This case study illustrates how a combination of input output models which describe different system properties can be used in production planning on corporate scale.

Such models have been used for some time (see e.g. Renz 1979) but are not very much discussed in the field of industrial ecology. Yet, they are a good example for the options we have using a weakly integrated model, namely: (i) the representation of different system characteristics within the same model framework and (ii) the combined evaluation of the effects of optimization measures on different system properties. The consistency of the overall model, however, has to be ensured in the process of modeling and inconsistencies are not necessarily revealed in a model based data analysis.

Food Production Chain

Food production in industrialized countries uses natural resources inefficiently. The consumption of 1 MJ of food requires approximately 5 MJ of primary energy used for food production and preparation, mostly fossil fuels. This negative energy balance is not sustainable on global scale, moreover, as the need for food is likely to grow in the next decades with growing population. In addition, food production needs arable land. In most European countries the average diet includes a comparatively high portion of meat and milk products. Their production requires a higher amount of land per mass unit dry matter than the production of cereals, vegetables or fruit. The availability of arable land, however, is limited in Switzerland itself as well as on global scale.

In order to improve resource efficiency in food production and consumption, we can change today's diets, current practices in agricultural production or design new food products requiring less packaging, less conservation or less cooling. But, which is the most promising strategy? This question can be answered by considering the effectiveness of each single strategy with regard to reducing resource consumption. In addition, we can take economic and social parameters into account to analyze which strategy is favorable from a more comprehensive perspective. To this aim, we analyze resource consumption and factor income in the Swiss food production chain.

System Definition, Modeling Approach and Scenarios

System boundaries are given by the system's function to provide food for private households in the case study region. We assess all relevant processes in the life-cycle of food products which are consumed in a Swiss Lowland region by approximately 185,000 inhabitants, which represents approximately 3% of the population in Switzerland (see Fig. 6.4). Only essential food products are studied (meat, dairy, cereals, vegetables, fruit including fruit juices).

The study focuses on food products and all major products used to produce and to distribute consumer food. It includes food products, fodder, pesticides, and

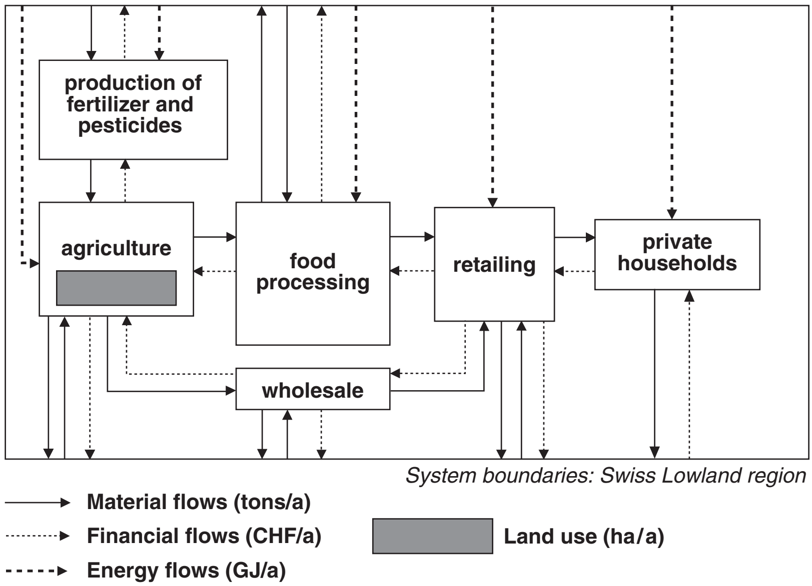

Fig. 6.4 System Definition for the Analysis of the Chain of Food Production and Consumption in Switzerland

fertilizer and packaging materials. In addition, we analyze in which way food production and consumption contributes to the resource demand of the study region. For this purpose resource consumption is described with the indicators primary energy consumption and land use.

The general model structure is shown in Equations (6.11), (6.13) and (6.17). In addition, we include primary energy consumption and land use of private households (Equation (6.16)) as well as primary energy consumption and land use cause by imports of food products in other regions (Equation (6.15)). These indirect impacts are estimated by multiplying the coefficient vectors for primary energy consumption and for land use vectors with the Leontief inverse (Equation (6.14)). The resulting vectors contain "multipliers" for each process that express how much energy or land was needed in the food production chain up to this specific process (vector of cumulative energy or land use). We then multiply the amount of food products imported in one process with the coefficient of cumulative energy or land use belonging to the processes supplying these products in the domestic economy, e.g. the import of fodder in milk production is multiplied with the coefficient for cumulative energy or land use for the process of fodder production. We thereby assume that imported products are produced with the same energy and land efficiency as products in the studied system. This assumption does not hold for products which cannot be grown in Switzerland, like bananas, or which can be produced more efficiently in other countries, like cereals. In consequence, Equation (6.15) only allows for a rough estimation of indirect impacts.

$$\mathbf{x}_{\mathbf{mat}}^{\mathbf{(food)}} = (\mathbf{I}\text{-}\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}})^{-1}\mathbf{y}_{\mathbf{mat}}^{\mathbf{(food)}} \tag{6.11}$$

$$\mathbf{u}_{\mathbf{total}} = \mathbf{u}_{\mathbf{food\_IOT}} + \mathbf{u}_{\mathbf{food\_cum}} + \mathbf{u}_{\mathbf{food\_PHH}} \tag{6.12}$$

$$\mathbf{u}_{\mathbf{food\_IOT}} = \mathbf{x}_{\mathbf{mat}}^{\mathbf{(food)}}\mathbf{e}^{\mathbf{(food\_IOT)}} \tag{6.13}$$

$$\mathbf{e}^{\mathbf{(food\_cum)}} = \mathbf{e}^{\mathbf{(food\_IOT)}}(\mathbf{I}\text{-A}_{\mathbf{mat}}^{\mathbf{(food)}})^{-1} \tag{6.14}$$

$$\mathbf{u}_{\mathbf{food\_cum}} = \mathbf{imports}_{\mathbf{mat}}^{\mathbf{(food)}}\mathbf{e}^{\mathbf{(food\_cum)}} \tag{6.15}$$

$$\mathbf{u}_{\mathbf{food\_PHH}} = \mathbf{y}_{\mathbf{mat}}^{\mathbf{(food)}}\mathbf{e}^{\mathbf{(food\_PHH)}} \tag{6.16}$$

$$\mathbf{p}^{\mathbf{(food)}} = (\mathbf{I}\text{-A}_{\mathbf{mat}}^{\mathbf{(food)}})'^{-1}\mathbf{v}^{\mathbf{(food)}} \tag{6.17}$$

where,

$\mathbf{x}_{\mathbf{mat}}^{\mathbf{(food)}}$:	vector of inputs of food products and all major products used to produce and to distribute consumer food into each process in mass units (wet weight)
$\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}}$:	matrix of output input coefficients for food products
$\mathbf{y}_{\mathbf{mat}}^{\mathbf{(food)}}$:	vector of food products consumed by approx. 185'000 inhabitants in a Swiss Lowland region in mass units (wet weight)
$\mathbf{u}_{\mathbf{total}}$:	vector of total primary energy consumption and total land use
$\mathbf{u}_{\mathbf{food\_IOT}}$:	vector of primary energy consumption and land use caused by of each process in the input output matrix $\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}}$ in giga joule and hectars
$\mathbf{u}_{\mathbf{food\_cum}}$:	vector of primary energy consumption and land use in other regions caused by import of food in each process in $\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}}$ in giga joule and hectars
$\mathbf{u}_{\mathbf{food\_PHH}}$:	vector of primary energy consumption and land use caused by private households in giga joule or hectars
$\mathbf{e}^{\mathbf{(food\_IOT)}}$:	vector of coefficients for primary energy consumption and land use for each process in $\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}}$ in Giga joule or hectar per ton
$\mathbf{imports}_{\mathbf{mat}}^{\mathbf{(food)}}$:	imports of food in each process in $\mathbf{A}_{\mathbf{mat}}^{\mathbf{(food)}}$ in mass units (wet weight)
$\mathbf{e}^{\mathbf{(food\_PHH)}}$:	vector of coefficients for primary energy consumption and land use for private households in giga joule or hectars per ton
$\mathbf{p}^{\mathbf{(food)}}$:	vector of prices for food products in each process
$\mathbf{v}^{\mathbf{(food)}}$:	vector of the value of primary input into from outside the system boundaries into each process per ton of input

The data for vector $X_{\text{mat}}^{\text{(food)}}$ is derived from the corporate information system of regional branch of a nationwide operating retailer with a market share of 24%. A comparison with data from a market research institute and national statistics on food consumption showed that the data is representative for food consumption in Switzerland. Various data sources were used to assess the energy and material requirements of the products along their life cycles and their prices (Faist 2000; Carlsson-Kanyama and Faist 2000; Kytzia et al. 2004). Primary data were available for packaging quantities, processing and retailing, whereas for the other processes secondary data were used.

The scenario calculation is used to evaluate the effect of single improvement strategies. We define the following two scenarios:

(i) *Vegetarian diet*: The scenario evaluates a lacto-ovo-vegetarian (no meat) diet. Meat and milk are substituted with grain and vegetables, maintaining the actual calorie and protein consumption. This scenario is calculated with the model presented above with a modified vector $Y^{(food\_veg)}{}_{mat}$ (see Appendix Table 6.8). All other parameters in the model remain constant.

(ii) *Organic agriculture*: This scenario assumes an overall change in agriculture towards organic cultivation methods. Data on fertilizer and pesticide in organic and conventional agriculture as well as food prices are mostly Swiss. The calculation uses actual producer prices for organic products and assumes that processing industries and retailers try to maintain an absolute margin. This means that the following parameters in the model presented above are modified: $A^{(food\_org)}{}_{mat}$, $E^{(food\_org)}$ and $v^{(food\_org)}$ (see Appendix Table 6.9). All other parameters remain constant.

Results

(i) *Status quo*: Primary energy consumption in the status quo is presented in Table 6.1. It shows that the total energy consumption is evenly distributed between agriculture, households and industrial processes (processing, wholesale and retailing) with a share of approximately 25% each. Fifteen percent is needed for the production of imported products outside Switzerland.

While milk and meat products dominate primary energy consumption in the domestic system with 54% of total domestic production, primary energy consumption of imports is dominated by fruit (44% of total imports) and vegetables (29% of total imports).

Land use is dominated by agriculture accounting for 99% of the total, 84% domestic and 16% abroad (see Table 6.2). Meat and milk need by far the largest share of the total land consumption (86%) followed by cereals (9%).

The value of primary input (factor income + imports) is evenly distributed between agriculture (30%), food processing (30%) and retailing (22%). And again, milk and meat are the two dominant product categories with 50% of the total value of primary input (see Table 6.3).

(ii) *Scenarios*: In both scenarios, the relative effects on land use surpass changes in energy demand (see Table 6.4). With a complete change to a full vegetarian diet we could reduce land use by around 70%. Organic agriculture, however, results in an increase in land use by 21% due to reduced yields per hectare. None of the scenarios

Table 6.1 Total Energy Consumption in Gigajoule (GJ)

Energy consumption	Milk	Meat	Fruits	Vegetables	Cereals	Total	In % of total
Production of fertilizer and pesticides	112,200	37,400	10,200	6,800	20,400	187,000	5
Agriculture	390,500	152,900	58,900	220,100	48,800	871,000	24
Wholesale	0	0	11,200	20,600	0	31,800	1
Food processing	33,700	71,000	20,300	17,800	79,900	222,700	6
Retailing	177,100	114,900	198,300	106,000	85,900	682,200	19
Private housholds	500,400	39,000	203,000	207,500	89,100	1,039,000	29
Total domestic	1,214,000	415,200	501,900	578,700	324,100	3,033,800	85
Imports	43,200	35,400	234,900	153,400	62,700	529,600	15
Total (domestic + imports)	1,257,200	450,500	736,900	732,100	386,700	3,563,500	
In % of total	35	13	21	21	11		

Table 6.2 Land Use in Hectare (ha)

Land use	Milk	Meat	Fruit	Vegetables	Cereals	Total	In % of total
Domestic In % of total domestic	17,700 69	5,900 23	160 1	430 2	1,570 6	25,760 100	84
Imports In % of total imports	1,880 37	1,000 20	530 11	290 6	1,330 26	5,030 100	16
Total In % of total	19,580	6,900	690	720	2,900	30,790	
domestic + imports	64	22	2	2	9	100	4

represents a strategy to reduce energy consumption by more than 15%. Again, only a complete switch to full vegetarian diet results in significant efficiency gains whereas the organic agriculture scenario results in minor improvements. Changes in the value of the primary input (factor income plus imports) amount to plus 10% for organic agriculture and minus 21% for a full vegetarian diet. Yet, they are unevenly distributed. With a shift to a full vegetarian diet, the domestic agriculture practically breaks down with a loss of value of primary input of over 60%. In the organic agriculture scenario, agriculture gains most (30% by assumption) whereas all other processes suffer losses in factor income. Consumer prices rise by 10% due to increased production costs in agriculture.

Table 6.3 Value of Primary Input in Swiss Francs (CHF)

Value of primary input		Milk	Meat	Fruit	Vegetables	Cereals	Total	In % of total
Production of fertilizer and pesticides	Value of imports	835,000	278,000	76,000	51,000	152,000	1,392,000	0
Agriculture	Domestic	66,524,000	56,976,000	8,003,000	20,714,000	9,324,000	161,541,000	30
	Value of imports	2,760,000	920,000	–	–	–	3,680,000	1
Wholesale	Domestic	–	–	17,593,000	8,570,000	–	26,163,000	5
	Value of imports	–	–	25,852,000	12,742,000	–	38,594,000	7
Food processing	Domestic	33,007,000	63,901,000	7,271,000	17,984,000	39,420,000	161,583,000	30
	Value of imports	–	–	1,616,000	1,298,000	6,317,000	9,231,000	2
Retailing	Domestic	21,760,000	27,022,000	21,955,000	25,264,000	21,722,000	117,722,000	22
	Value of imports	5,428,000	14,299,000	–	–	6,135,000	25,862,000	5
Total domestic		122,125,000	148,176,000	54,898,000	72,584,000	70,618,000	468,401,000	86
Total imports		8,188,000	15,219,000	27,467,000	14,040,000	12,452,000	77,366,000	14
Total		130,313,000	163,395,000	82,365,000	86,624,000	83,070,000	545,767,000	

Table 6.4 Results of the Scenario Calculation

		Status quo	Organic agriculture	Vegan diet
Energy	GJ	3,563,500.00	3,518,800.00	3,039,500.00
	% of status quo		−1	−15
Land use	Ha	30,790.00	37,350.00	8,230.00
	% of status quo		21	−73
Value of primary inputs	CHF in thousand	545,800.00	602,000.00	433,300.00
	% of status quo		10	−21

Discussions on the Case Study

We describe three different characteristics of the food production chain (land use, energy consumption and generation of factor income) with a physical IO model augmented with a number of coefficient vectors for energy, land use and factor income. This results in a consistent model based on a limited set of data which reveals how the different characteristics are interrelated. As primary income and energy consumption are both evenly distributed among the main processes in the production chain, the effects of drastic changes in one process (in our case agriculture or private consumption) are attenuated. Land use, in contrast, is dominated by one process and is, therefore, more sensitive to changes pertaining to this particular process. For all three system characteristics, the consumption of meat and milk seems to be of utmost importance. Most resources are required by and most money is earned with animal production.

From a methodological point of view, a substitution of the physical IO model by a monetary one would change neither the structure of the model nor the results of the model calculation. The model is strictly linear and every process is defined as a one-product-process. The choice of the physical IO model can, therefore, only be explained by the fact that the study was carried out by researchers from the field of MFA who – naturally – started of with a tool well known to them. It could, in theory, just as well have been carried out by input output economists using a monetary IOT based on bottom up data collection.

Conclusions

The proposed modeling framework enhances consistency in hybrid models which are used to combine models from natural scientists, engineers and economists. Such interdisciplinary research is paramount in Industrial Ecology because of its interest in different properties of industrial systems, out of scientific curiosity and being obliged to so by the triple bottom line of sustainable development. Hybrid models can promote the collaboration between scientists with different disciplinary background because they provide a common language, ensure consistency and enable the clear definition of interfaces. If they are used as proposed in this article, it encourages researchers to clearly state which system property they are interested in and carefully choose an appropriate model structure. This helps to relate a model to the theoretical framework providing concepts for better understanding of the studied system property and may reveal interesting parallels or contradictions from a theoretical point of view (see, e.g. Suh 2004, S. 158ff).

The proposed modeling framework, however, is only the smallest common denominator between the SFA, MFA, LCA and IO. There are much more sophisticated modeling approaches in every single field which should be further pursued e.g. equilibrium models or dynamic SFA. And, there are a number of most interesting research questions for which the overlap between SFA, MFA and IO is much smaller, e.g. SFA with an emphasis on natural systems or IO for service economies. In these cases, one model will clearly take the lead in defining the system.

However, the "smallest common denominator" still deserves some further attention from the IE research community. First, we still do not have a "common language" free of inconsistencies and misperceptions as shown in the contribution of Faye Duchin in this handbook and Weisz and Duchin (2006). Second, the potential of the proposed modeling framework as a basis for hybrid models in interdisciplinary research has not yet fully been exploited. A better understanding of different system properties and their interdependencies is likely to broaden our perspective on industrial systems and reveal solutions for a better management of natural resources.

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Appendix

Table 6.5 Input Output Tables for Material Flow for 1 Year in the Status Quo

Material flows (in tons per year)	Raw milling	Electrostatic filter, mixing/storage	Activated carbon filter	Cement kiln and auxillary equipment	Finish milling	Output (Y)	Sum of output and intermediate flows (X)
Raw milling		1,260,000					1,260,000
Electrostatic filter, mixing/storage			772,200	790,000	11,800	0	1,574,000
Activated carbon filter				2,120		1,208,200	1,210,320
Cement kiln and auxillary equipment	439,000	314,000			512,000		1,265,000
Finish milling				344,000		607,771	951,771
primary fuels				42,900			
Secondary fuels				23,980			
raw material 1	821,000						
supply air			436,000	62,000	373,000		
Carbon			2,120				
raw material 2					54,971		
Sum of input (PA)	821,000		438,120	128,880	427,971		
Sum of input and intermediate flows (X)	1,260,000	1,574,000	1,210,320	1,265,000	951,771		

Table 6.6 Input Output Tables for Production Costs for 1 Year in the Status Quo

Production costs (in thousand CHF per year)	Raw milling	Electrostatic filter, mixing/ storage	Activated carbon filter	Cement kiln and auxillary equipment	Finish milling	Output (Y)	Sum of output and intermediate flows (X)
Raw milling	0	2,100	0	0	0	0	2,100
Electrostatic filter, mixing/storage	0	0	0	4,820	0	0	4,820
Activated carbon filter	0	2,670	0	0	0	0	2,670
Cement kiln and auxillary equipment	0	0	0	0	14,800	0	14,800
Finish milling	0	0	0	0	0	19,500	19,500
Raw material	130		820	200	1,750		
Electricity	1,070		290	1,060	1,400		
Fixed costs	900	50	1,560	6,700	1,550		
Primary fuels				4,570			
Secondary fuels				−2,550			
Sum of input (PA)	2,100	50	2,670	9,980	4,700		
Sum of input and intermediate flows (X)	2,100	4,820	2,670	14,800	19,500		

Table 6.7 Input-Output Tables for Substance Flows (Hg) for 1 Year in the Status Quo

Substance flows (in gram per year)	Raw milling	Electrostatic filter, mixing/ storage	Activated carbon filter	Cement kiln and auxillary equipment	Finish milling	Output (Y)	Sum of output and intermediate flows (X)
Raw milling		434,000					434,000
Electrostatic filter, mixing/storage			116,000	497,000	88,000		701,000
Activated carbon filter		0		114,000		**2,100**	116,100
Cement kiln and auxillary equipment	374,000	267,000					641,000
Finish milling						**90,500**	90,500
Primary fuels				10,500			
Secondary fuels				19,500			
Raw material 1	60,000						
Supply air			0				
Carbon							
Raw material 2			100				
Sum of input (PA)					2,500		
Sum of input and intermediate flows (X)	**60,000**	**0**	**100**	**30,000**	**2,500**		

Table 6.8 Parameters for Food Consumption for the Scenario "Vegetarian Diet" in 1,000 t. To Balance the Nutritive Value and the Protein of the Diet of Vegetarians in Relation to Status Quo, a Slightly Higher Food Quantity Is Needed

	Status quo	Scenario full vegetarian
Animal product	41	0
Vegetable and potato	22	28
Fruit	20	25
Fruit juice	5	10
Cereal (incl. leguminous)	19	41
Total	131	128
Difference		+2%

Table 6.9 Parameters for the Scenario "Organic Agriculture". In Addition, the Demand of Pesticide and Fertilizer Decreases to 10% of the Status Quo Value

		Land use		Energy		Value of primary inputs	
		Status quo	Szen: Organic	Status quo	Szen: Organic	Status quo	Szen: Organic
		$E^{(food\_IOT)}$	$E^{(food\_IOT)}$	$E^{(food\_IOT)}$	$E^{(food\_IOT)}$	PA	PA
Pesticide and fertilizer production				340	340	1391500.00	139150.00
Agriculture	Fodder	0.0316	0.0379	0.3	0.4	67518800.00	89076884.00
	Milk			2.8	2.8	18645, 000.0	24238500.00
	Meat			5.7	5.7	41016, 000.0	53320800.00
	Fruit	0.0252	0.0290	9.5	10.2	8002700.00	10492313.00
	Vegetables	0.0255	0.0313	13.1	13.2	20714200.00	26987662.00
	Cereals	0.1706	0.2398	5.3	6.4	9324200.00	12299066.00
Wholesale	Fruit			0.5	0.5	43444640.00	43444640.00
	Vegetables			1	1	21312327.27	21312327.27
Processing	Milk			1.2	1.2	33006820.00	33006820.00
	Meat			7.5	7.5	63900700.00	63900700.00
	Fruit			5.2	5.2	8886540.00	8886540.00
	Vegetables			4	4	19282080.00	19282080.00
	Cereals			5.3	5.3	45737620.00	45737620.00
Retailing	Milk			6.3	6.3	27187205.00	27187205.00
	Meat			10.9	10.9	41320726.76	41320726.76
	Fruit			8.4	8.4	21955043.00	21955043.00
	Vegetables			4.7	4.7	25264421.45	25264421.45
	Cereals			5.4	5.4	27856357.41	27856357.41

Chapter 7
Physical Input-Output Analysis and Disposals to Nature

Erik Dietzenbacher, Stefan Giljum, Klaus Hubacek, and Sangwon Suh

Introduction

The enormous increase in interest – in the last 2 decades – for environmental issues has led to a markedly upsurge in the collection of data. One of the new types of data sources that have become available is the physical input-output table (PIOT). The production sector in an economy distinguishes industries and the intermediate flows between the industries are measured in the same physical unit, such as billion tons (bt). This is in contrast to the usual monetary input-output tables (MIOTs) that measure the intermediate deliveries in money terms, such as billion dollars. Examples of published PIOTs can be found in Kratterl and Kratena (1990), Kratena et al. (1992), Konijn et al. (1997), Stahmer et al. (1997), Pedersen (1999), Nebbia (2000), Mäenpää (2002), and Hoekstra (2003).[1]

On the one hand, PIOTs can be regarded as a natural extension of the so-called hybrid input-output tables, as far as their numerical implementation is concerned.[2]

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[1] See Konijn et al. (1997), Stahmer (2000) and Strassert (2001) for analyses of PIOTs.

[2] See, e.g. Miller and Blair (1985). From a theoretical point of view, hybrid tables are a mix of purely monetary and purely physical tables. Considering the data availability, however, monetary tables are widespread while also hybrid tables have been used issued frequently, whereas physical tables are relatively new and still scarce.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

Whereas hybrid tables record several rows in physical terms (not necessarily in the same units), PIOTs cover all industries in physical units. In general, the PIOT (or the hybrid table) cannot be obtained from the MIOT by dividing all deliveries in the same row by a single price. If this were true, the analyses based on a MIOT and its corresponding PIOT would yield the same answer (see Appendix 1). There are two reasons why a uniform price within a row is very unlikely to occur in published input-output tables. The first is that it is very common that certain customers can buy products at a preferential rate, while others have to pay much more (e.g. we may think of discounts that are provided when large amounts are bought). The second reason is that published input-output tables always contain aggregated data. The consequences may be illustrated by a simple example. Suppose that industry i consists of two subindustries, i_1 and i_2. Suppose further that both subindustries do sell their products at uniform prices, p_1 and p_2 respectively. Consider the case that deliveries of industry i to industry j consist entirely of deliveries by subindustry i_1, while the deliveries from i to another industry h are entirely supplied by subindustry i_2. In that case, the appropriate prices to convert the MIOT would be p_1 for the deliveries from i to j, and p_2 for the deliveries from i to h. So, even if uniform prices do hold at a disaggregated level, they will no longer apply once industries are aggregated.

On the other hand, PIOTs are very different from a hybrid (or any other type of) input-output table in the sense that they include detailed information with respect to the generation of disposals to nature (solid wastes, waste water and air emissions). Usually different types of information (all per industry) are appended to MIOTs, such as employment figures, SO_2 emissions, land use and solid wastes. The distinction between appending disposals to nature to a MIOT and their inclusion in a PIOT, is that the material balance holds for each industry or sector in a PIOT. This is due to the fact that disposals to nature are part of a consistent accounting framework in physical terms.

The advantages of PIOTs are thus twofold. First, they better reflect the physical aspects of the production process and, second, they consistently integrate the generation of disposals to nature, which have become a relevant point of environmental concern. The disadvantage of using PIOTs is that our usual input-output techniques are of limited value and have to be adapted so as to cope with disposals. This paper discusses how we may do so with regards to land appropriation as a specific example; but the following discussion would hold for any type of resource use or pollution expressed in physical units. The section below describes the analytical framework and defines the problem. Recently two approaches have been suggested, leading to entirely different answers (see the discussion in Hubacek and Giljum 2003; Giljum and Hubacek 2004; Giljum et al. 2004; Suh 2004; Dietzenbacher 2005;). The first is based on reallocating disposals to nature to the final demand categories proportionally and is dealt with as Approach A. The second (Approach B) considers disposals to nature as a necessity for production (as if it were an input). The third method (Approach C), reconciles the Approaches A and B. That is, it adopts the idea of Approach A to redistribute disposals to nature over final demand categories but arrives at the answers of Approach B.

The Analytical Framework

The starting-point of our analysis is the PIOT as given in Table 7.1. All entries in this table are measured in physical units (e.g. bt). We distinguish n industries and the element z_{ij} of the $n \times n$ matrix $\mathbf{Z}$ indicates the intermediate material flows from industry i to industry j. For simplicity, we take only two final demand categories into consideration. Domestic and foreign final demands are indicated by the vectors $\mathbf{d}$ and $\mathbf{e}$ respectively.[3] The final demands cover the material flows for private consumption, government expenditures, and investments. The vector with disposals to nature (which, for convenience, we will term waste hereafter) in each industry is given by $\mathbf{w}$. Summing the intermediate material flows, the flows for final demands and the generated waste for industry i (i.e. summing over row i) gives the industry's total material outflow x_i as element of vector $\mathbf{x}$. The columns of the PIOT give the material inputs of each industry j. These are the intermediate material flows z_{ij} obtained from industry i and the primary material inputs r_j obtained from domestic extraction and imports. The material balance is reflected by the equality between the column sum (i.e. total material inputs) and the row sum (i.e. total material outflow), for each industry i.

We have appended the PIOT with an additional row vector $\mathbf{s}'$. Its element s_j gives the amount of land appropriated by industry j. Note that this gives us the land use *in* industry j. The central question that we address in this paper is how much land use can be attributed to each of the final demands? In this way we know to what extent for example the domestic consumption of product i can be held "responsible" for the current land use. Answering this type of question is relevant for policy issues, such as the design of land use management systems; the interrelations between socio-economic driving forces (economic growth, structural change, lifestyle change); and changes in land cover and land use. A similar question is whether one extra billion ton of exports of product i requires more land to be used than the same amount of extra exports of product h.

Table 7.1 The PIOT Appended with Land Use

	Industries	Final demand		Waste	Total output
		Domestic	Exports		
Industries	$\mathbf{Z}$	$\mathbf{d}$	$\mathbf{e}$	$\mathbf{w}$	$\mathbf{x}$
Primary material inputs	$\mathbf{r}'$				
Total input	$\mathbf{x}'$				
Land appropriation	$\mathbf{s}'$				

[3] Matrices are indicated by bold, upright capital letters; vectors by bold, upright lower case letters, and scalars by italicized lower case letters. Vectors are columns by definition, so that row vectors are obtained by transposition, indicated by a prime (e.g. $\mathbf{x}'$). A diagonal matrix with the elements of vector x on its main diagonal and all other entries equal to zero is indicated by a circumflex (e.g. $\hat{\mathbf{x}}$).

Let us consider first how the question is approached in the absence of waste. That is, we assume that $\mathbf{w} = 0$. In this case, the approach for the PIOT is the same as it would have been for an MIOT. First, the input coefficients are defined as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, so that $a_{ij} = z_{ij}/x_j$ gives the material input from industry i that is required per unit of material outflow in industry j. In the absence of waste, the accounting equations yield $\mathbf{x} = \mathbf{Zu} + (\mathbf{d} + \mathbf{e})$, where $\mathbf{u}$ is the summation vector consisting entirely of ones. Using the definition for the input coefficients, this gives $\mathbf{x} = \mathbf{Ax} + (\mathbf{d} + \mathbf{e})$. For given final demands $\mathbf{d} + \mathbf{e}$, the solution is obtained as $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{d} + \mathbf{e}) = \mathbf{M}(\mathbf{d} + \mathbf{e})$. Here, the matrix $\mathbf{M}$ is the Leontief inverse or multiplier matrix. Its element m_{ij} gives the material outflow in industry i that is necessary to satisfy one unit of material flows for final demands (domestic or foreign) in industry j. Hence, $m_{ij}e_j$ – that is the element (i, j) of matrix $\mathbf{M}\hat{\mathbf{e}}$ – gives the material outflow in industry i that is required directly or indirectly for the exports e_j of industry j. In other words, the material outflow in industry i that can be attributed to the exports of industry j amounts to $m_{ij}e_j$.

The land use coefficients are defined by the row vector $\mathbf{c}' = \mathbf{s}'\hat{\mathbf{x}}^{-1}$. Its typical element $c_j = s_j/x_j$ gives the land use in industry j required per unit of its material outflow. Therefore, the typical element $c_i m_{ij} e_j$ of the matrix $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{e}}$ gives the land use in industry i that can be attributed to the exports e_j of industry j. The ith row sum of $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{e}}$, i.e. element i of the vector $\hat{\mathbf{c}}\mathbf{Me}$, gives the land use in industry i necessary for all the exports. In the same way, the jth column sum of $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{e}}$, i.e. element j of the row vector $\mathbf{c}'\mathbf{M}\hat{\mathbf{e}}$, gives the land use in all industries that can be attributed (i.e. contributing as inputs) to the exports of industry j. Note that it must be true that if we calculate the land use in industry i required for all *actual* domestic and foreign final demands, the answer should equal this industry's actual land use s_i. It is easily verified that this holds when waste is absent, because $\hat{\mathbf{c}}\mathbf{M}(\mathbf{e} + \mathbf{d}) = \hat{\mathbf{c}}\mathbf{x} = \mathbf{s}$.

In the presence of waste, however, this is no longer true. Now the model changes into $\mathbf{x} = \mathbf{Ax} + (\mathbf{d} + \mathbf{e} + \mathbf{w}) = \mathbf{M}(\mathbf{d} + \mathbf{e} + \mathbf{w})$. The immediate consequence of using the standard procedure as described above for attributing land use to final demand categories is that the answers induce a gross underestimation. This is because $\hat{\mathbf{c}}\mathbf{M}(\mathbf{e} + \mathbf{d}) = \mathbf{s} - \hat{\mathbf{c}}\mathbf{Mw} < \mathbf{s}$, if $\mathbf{w} > 0$. In the input-output model that we have used, the final demand categories are the drivers of the model in the sense that satisfying these final demands is the ultimate goal of the production process. Therefore, all the actual land use should somehow be attributed to the actual final demands. The generation of waste requires land (reflected by $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{w}}$) but is not a goal of producing, i.e. waste is not a final demand category. The problem to be tackled is how to treat waste in the context of a physical input-output study?

The calculations in this paper are essentially meant to illustrate the approaches and are based on the 1995 PIOT for Italy, which has been aggregated to three industries for convenience and which is given in Table 7.2. Carrying out the standard procedure above indicates that we are not just dealing with an academic puzzle. It turns out that the land use attributed to the actual domestic and foreign final demands amounts to 28,300 and 5,900 km^2, respectively. This is only 23% of the actual land appropriation of 147,000 km^2, indicating a serious underestimation.

Table 7.2 The Three-Industry PIOT for Italy, 1995 (in billion tons) (Nebbia 2000)

	Industries			Final demands		Waste	Total
	A	*M*	*S*	Dom	Exp		
Agriculture	153	190	30	0	20	477	870
Manufacturing	66	845	74	585	73	667	2,310
Services	33	29	10	67	0	97	236
Primary inputs	618	1,246	122				
Total	870	2,310	236				
Land	112	19	16				147

Land appropriation is in thousand square kilometers

Approach A: A Reallocation of Waste over the Final Demand Categories

The first approach is to reallocate the waste over the final demand categories. The idea is simple and intuitively very appealing. If Manufacturing generates 667 bt of waste, while the domestic final demands are 585 bt and the exports are 73 bt, then it seems reasonable to split the land use that is involved in this waste generation and attribute it to the two final demand categories. This reallocation (or redistribution) approach was introduced by Hubacek and Giljum (2003) and further refined by Giljum and Hubacek (2004), Giljum et al. (2004) and Suh (2004). The reallocation of waste, results in extended vectors of domestic and foreign final demands. In general, we have for industry i

$$d_i^{ext} = d_i + \alpha_i w_i, \text{ and } e_i^{ext} = e_i + (1 - \alpha_i) w_i \tag{7.1}$$

with $0 \leq \alpha_i \leq 1$. The land use in industry i that can be attributed to, for example, the exports of industry j are then given by the element (i, j) of the matrix $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{e}}^{ext}$.

Note that the reallocation in Equation (7.1) solves the problem of underestimation. We will use the term consistent to indicate that the land use in industry i that is attributed to the final demands, exactly equals the actual land use in industry i. This immediately follows from $\hat{\mathbf{c}}\mathbf{M}(\mathbf{d}^{ext} + \mathbf{e}^{ext}) = \hat{\mathbf{c}}\mathbf{M}(\mathbf{d} + \mathbf{e} + \mathbf{w}) = \hat{\mathbf{c}}\mathbf{x} = \mathbf{s}$.

The general formulation in Equation (7.1) allows for many different choices for the reallocation parameter α_i. The obvious choice seems to distribute the waste proportional to the sizes of the domestic and foreign final demand in each industry. Other ways to allocate waste to the various demand categories is to use life cycle analysis or other technical information. This proportional distribution yields[4]

[4] This approach corresponds to Approach 2 in Suh (2004) and to the alternative approach in Giljum and Hubacek (2004).

$$\alpha_i = \frac{d_i}{d_i + e_i}, \text{ and } 1 - \alpha_i = \frac{e_i}{d_i + e_i}. \tag{7.2}$$

So, for the example in the beginning of this section, the land use attributed to the exports of Manufacturing is based on an extended export of $73 + 667 \times 73/(585 + 73) = 147$ bt.

Approach B: Waste Generation as an "Input" for Production

In Section "The Analytical Framework", we have already indicated that the generation of waste should not be seen as part of the final demands, because final demands are the ultimate goal of production in the input-output model, and therefore its drivers. In contrast, waste generation is a necessity for production, in the same way as intermediate and primary inputs are. At the same time, the System of National Accounts – SNA (see CEC/IMF/OECD/UN/WB 1993), which provides guidelines for the construction of national accounts and input-output tables – uses a well-defined concept of production. Goods and services are considered as outputs whenever their production is destined for the market, which in most cases implies that a price is charged. According to this definition, the generation of waste should, although being an outflow of the production process, clearly not be accounted as part of the output of an industry.

Approach *B* was introduced by Suh (2004) and is based on the view that waste is not part of the output but should be treated as if it were an input (or at least the permission to generate waste).[5] This implies that we remove the column vector of waste in Table 7.1 and insert it as a row (with minus signs), which gives us Tables 7.3 and 7.4.

Subtracting the waste from the outflows yields $\bar{\mathbf{x}} = \mathbf{x} - \mathbf{w}$, which will be termed "usable" output. It should be stressed that the accounting equations that are central in Table 7.1 remain valid in Table 7.3. This holds also for the material balance. In the case of Agriculture, we find that the intermediate material inputs are 252 bt and

Table 7.3 The PIOT with Waste as an "Input"

	Industries	Final demand		Total output
		Domestic	Exports	
Industries	$\mathbf{Z}$	$\mathbf{d}$	$\mathbf{e}$	$\bar{\mathbf{x}}$
Primary material inputs	$\mathbf{r}'$			
Waste	$-\mathbf{w}'$			
Total input	$\bar{\mathbf{x}}'$			
Land appropriation	$\mathbf{s}'$			

[5] This approach corresponds to the Approach 1 in Suh (2004).

Table 7.4 The Italian PIOT with Waste as an "Input"

	Industries			Final		Total
	A	*M*	*S*	Dom	Exp	
Agriculture	153	190	30	0	20	393
Manufacturing	66	845	74	585	73	1,643
Services	33	29	10	67	0	139
Primary inputs	618	1,246	122			
Waste	−477	−667	−97			
Total	393	1,643	139			
Land	112	19	16			147

the primary material inputs are 618 bt. This yields an outflow of 870 bt, of which 393 bt is usable output and 477 bt is waste. The usable output is sold as intermediate input to the industries (373 bt) and as final goods for exports (20 bt) as shown in Table 7.4.

The next steps in Approach B are the same as those for Approach A. That is, first the input coefficients are defined as $\overline{\mathbf{A}} = \mathbf{Z}\hat{\overline{\mathbf{x}}}^{-1}$, where an overbar is used to indicate that we are working with usable outputs. The interpretation is still the same, $\bar{a}_{ij}$ gives the intermediate material input from industry i required per unit of usable output in industry j. In the same way we may define the primary material input coefficients and the waste coefficients. If we consider, for example, the production process for Agriculture, it follows that the production of 1 t of usable output requires that $477/393 = 1.21$ t of waste are generated. This means that producing 1 t of usable output, yields an outflow of $1 + 1.21 = 2.21$ t. The inputs for producing a ton of usable outputs in the service industry are $(153 + 66 + 33/393 =)$ 0.64 t of intermediate inputs and $(618/393 =)$ 1.57 t of primary material inputs. Note that when producing 1 t of usable output, the outflow and total amount of inputs are equal (2.21 t), reflecting the material balance.

The multiplier matrix is obtained as $\overline{\mathbf{M}} = (\mathbf{I} - \overline{\mathbf{A}})^{-1}$ and the land use coefficients as $\bar{\mathbf{c}}' = \mathbf{s}'\hat{\overline{\mathbf{x}}}^{-1}$. The land use in industry i that is attributed to the exports by industry j is then given by the element (i, j) of the matrix $\hat{\bar{\mathbf{c}}}\overline{\mathbf{M}}\hat{\mathbf{e}}$.

Note that also Approach B is consistent, i.e. the land use in industry i that is attributed to the final demands, exactly equals the actual land use in industry i. This follows from $\hat{\bar{\mathbf{c}}}\overline{\mathbf{M}}(\mathbf{d} + \mathbf{e}) = \hat{\bar{\mathbf{c}}}\bar{\mathbf{x}} = \mathbf{s}$.

An Empirical Evaluation of the Differences and Approach C

We have now discussed the two original approaches for treating waste in a physical input-output analysis. Table 7.5 gives the results for the attribution of land use to each of the final demands. For Approach A, the numbers in the column domestic are obtained as the elements of the (row) vector $\mathbf{c}'\mathbf{M}\hat{\mathbf{d}}^{ext}$, with $\mathbf{d}^{ext}$ as given by Equations (7.1) and (7.2), and the numbers in the column foreign are obtained from

Table 7.5 Attribution of Land Use (in thousand square kilometers), Approaches A and B

	Approach A		Approach B	
	Domestic	Foreign	Domestic	Foreign
Attributed to				
Agriculture	0	81.7	0	11.2
Manufacturing	42.8	5.3	99.7	12.4
Services	17.1	0	23.6	0
Total	60.0	87.0	123.3	23.7

$\mathbf{c}'\mathbf{M}\hat{\mathbf{e}}^{ext}$. For Approach B, the elements of $\bar{\mathbf{c}}'\overline{\mathbf{M}}\hat{\mathbf{d}}$ and $\bar{\mathbf{c}}'\overline{\mathbf{M}}\hat{\mathbf{e}}$ are given in the columns domestic and foreign respectively. It is clear that the two approaches lead to entirely different answers. For example, in Approach A, 56% of the total land use is attributed to Agriculture, 33% to Manufacturing, and 12% to Services. For Approach B, however, we find 8%, 76% and 16%, respectively.

To get an idea which answer might be more correct from an intuitive point of view, consider Table 7.2 again. Note that in terms of material flows, waste generation is 67% larger than the sum of all final demands. Also note that 38% of all waste is generated in Agriculture. Of the final demands, 88% is for Manufacturing products, which is therefore a major driver of the production process and triggers the production in this industry. Almost 18% of the intermediate inputs of Manufacturing are delivered by Agriculture. Indirectly, also the production of Agriculture is boosted and leads to a substantial outflow of material (and roughly 55% of this is waste). Hence, much of the waste generated in Agriculture should be attributed to the final demands of Manufacturing. Next, it should be noted that 1 bt of material outflow in Agriculture requires 15.7 and 1.9 times as much land as the same amount of outflow in Manufacturing and Services, respectively, requires. Summarized, the final demands in Manufacturing are "responsible" for a lot of waste in Agriculture which is very intensive in its land use.

It thus seems that the answer provided by Approach B better reflects the situation. On the other hand, Approach A to reallocate the waste over the final demands is intuitively very attractive. Synthesizing these two approaches, we will now introduce Approach C. Waste is reallocated over the final demand categories, but according to who is responsible for the waste generation. As we have seen, a large part of the waste in Agriculture needs to be attributed to the final demands in Manufacturing.

Define the waste coefficients as $\bar{q}_i = w_i/\bar{x}_i$ (or $\bar{\mathbf{q}}' = \mathbf{w}'\hat{\bar{\mathbf{x}}}^{-1}$), indicating the amount of waste generated in industry i per unit of its usable output. The usable output in industry i necessary for the export in industry j equals $\bar{m}_{ij}e_j$ (that is, element (i, j) of the matrix $\overline{\mathbf{M}}\hat{\mathbf{e}}$). The waste generated in industry i for the export in industry j then amounts to $\bar{q}_i\bar{m}_{ij}e_j$ (as typical element of the matrix $\hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{e}}$). The results for the matrices $\hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{d}}$ and $\hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{e}}$ are given in Table 7.6.

Note that approximately 30% of all waste is generated in Agriculture but should be attributed to the final demands in Manufacturing. This is 79% of the waste generated in Agriculture. In reallocating the waste over the final demands, it seems

Table 7.6 Imputation of Waste (in billion tons) to Final Demands

	Waste imputed to						Total
	Domestic final demand in			Foreign final demand in			
	A	*M*	*S*	*A*	*M*	*S*	
Generated in							
A	0	333	57	45	42	0	477
M	0	550	41	7	69	0	667
S	0	35	55	3	4	0	97
Total	0	918	153	55	115	0	1,241

appropriate to attribute the waste in the different industries to the "responsible" final demand. For example, attribute the 333 bt of waste in Agriculture, 550 in Manufacturing, and 35 in Services, to the domestic final demand in Manufacturing (which is 585 bt). Since we are interested in the land use, also the land use that is (directly and indirectly) involved in generating the various wastes should be attributed to the "responsible" final demand.

If we continue this example, the land use attributed to the 585 bt of domestic final demand in Manufacturing amounts to

$$\mathbf{c\hat{M}}\begin{pmatrix}0\\585\\0\end{pmatrix}+\hat{\mathbf{c}}\mathbf{M}\begin{pmatrix}333\\550\\35\end{pmatrix}=99.7 \tag{7.3}$$

which is the answer that was also reported in Table 7.5 for Approach B. The first part in expression (7.3), gives the land use (in each of the three industries) necessary to satisfy the final demand itself and the second part gives the land use necessary for the waste generation that was attributed to the specific final demand. In contrast, the 42,800 km^2 in Table 7.5 for Approach A are obtained from

$$\hat{\mathbf{c}}\mathbf{M}\begin{pmatrix}0\\585\\0\end{pmatrix}+\hat{\mathbf{c}}\mathbf{M}\begin{pmatrix}0\\593\\0\end{pmatrix}=42.8,\ \text{with } 593=667\times\frac{585}{585+73} \tag{7.4}$$

Approach C is obtained by formalizing the example above and was proposed in Dietzenbacher (2005). Consider the domestic final demand d_j in industry j. The land use in industry i involved in this outflow of material equals $c_i m_{ij} d_j$. But d_j is also "responsible" for the generation of waste in industry k to the amount of $\bar{q}_k \bar{m}_{kj} d_j$, with $k = 1, 2, 3$. So the land use in industry i that is involved in the generation of waste in industry k, which is attributed to the domestic final demand in industry j then becomes $c_i m_{ik} \bar{q}_k \bar{m}_{kj} d_j$. The total amount of land use attributed to d_j then yields

$$c_i m_{ij} d_j + \Sigma_k c_i m_{ik} \bar{q}_k \bar{m}_{kj} d_j$$

which is element (i, j) of matrix

$$\hat{\mathbf{c}}\mathbf{M}(\hat{\mathbf{d}} + \hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{d}}). \tag{7.5}$$

Appendix 2 shows that Approach C is (just like Approaches A and B) consistent, in the sense that the land use in industry i that is attributed to the final demands, exactly equals the actual land use in industry i. Also in Appendix 2, it is shown that Approaches B and C are equivalent.

Approach C thus arrives at the same answer as Approach B does (which was found to be the intuitively correct answer), but adopts the reallocation principle of Approach A (which was found to be intuitively appealing). The difference between Approaches A and C is that in Approach A the vector $\mathbf{d}$ is replaced by an extended vector $\mathbf{d}^{ext}$. Or, equivalently, the diagonal matrix $\hat{\mathbf{d}}$ is replaced by $\hat{\mathbf{d}}^{ext}$, which is still a diagonal matrix. In Approach C, however, the diagonal matrix $\hat{\mathbf{d}}$ is replaced by $\hat{\mathbf{d}} + \hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{d}}$ which is no longer a diagonal matrix.

The advantage of using Approach C (instead of B) is that it allows to obtain additional information. That is, just like we did in expression (7.3) for a particular case, we may split Equation (7.5) into $\hat{\mathbf{c}}\mathbf{M}\hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{d}}$ and $\hat{\mathbf{c}}\mathbf{M}\hat{\mathbf{d}}$. The first term can be interpreted as the land use that is involved in generating the waste that can be attributed to the specific final demands (the so-called waste part). The second term can be interpreted as the non-waste part of the land use. The full set of results is given in Table 7.7 and according to this line of interpretation, 77% of all land use is due to the generation of waste, and 45% of all land use is the land used in Agriculture that is involved in generating the waste that is attributed to the domestic final demand in Manufacturing.

Table 7.7 Land Use (in thousand square kilometers) for Approach C

	Non-waste part				Waste part				
	A	*M*	*S*	Total	*A*	*M*	*S*	Total	Total
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Land use in:					Attributed to domestic final				
Agriculture	0.0	12.4	1.9	14.3	0.0	65.8	11.5	77.3	91.6
Manufacturing	0.0	7.7	0.3	8.1	0.0	7.9	0.9	8.8	16.8
Services	0.0	1.1	4.8	5.9	0.0	4.7	4.2	8.9	14.8
Total	0.0	21.3	7.0	28.3	0.0	78.4	16.6	95.0	123.3
Land use in:					Attributed to exports				
Agriculture	3.2	1.6	0.0	4.7	7.4	8.2	0.0	15.6	20.4
Manufacturing	0.0	1.0	0.0	1.0	0.2	1.0	0.0	1.2	2.2
Services	0.1	0.1	0.0	0.2	0.4	0.6	0.0	0.9	1.2
Total	3.3	2.7	0.0	5.9	8.0	9.8	0.0	17.7	23.7

(4) = (1) + (2) + (3); (8) = (5) + (6) + (7); (9) = (4) + (8).

A point of discussion in using Approach C is that it uses two different assumptions at the same time, which may raise a consistency issue. For instance, the interpretation on 'waste part' of land use introduced above is only possible by following and accepting the assumption that factor inputs can be distributed over the products and wastes based on their mass, that is used in Approach A, while the calculation of direct and indirect waste in Approach C is done following the assumption that only products are responsible for the whole factor inputs, that is used in Approach B.

Concluding Remarks

In the series of discussion – notably by Hubacek and Giljum (2003), Dietzenbacher (2005), Giljum and Hubacek (2004), Giljum et al. (2004), and Suh (2004) – the treatment of waste in a PIOT has been the main methodological issue. In these articles, several different approaches are proposed and applied, which are summarized and denoted as the approaches A (Approach 2 in Suh 2004, and "the alternative approach" in Giljum and Hubacek 2004), B (Approach 1 in Suh 2004) and C (Dietzenbacher 2005) in the current chapter. We provided an analysis of the approaches proposed and tried to assemble our efforts to gain a common understanding of the issue.

We also showed that the results from an MIOT and corresponding PIOT will have the same results if the price per mass of output in each sector is homogeneous over the consuming sectors. In other words, PIOTs and MIOTs generally produce different results under the situation of price inhomogeneity.

As for the separate approaches, Approach A rests on the idea of reallocating the waste generated in some sector to the domestic and foreign final demands in that sector. Approach B adopts the viewpoint that usable products of a productive process (goods) are responsible for the entire use of factor inputs and the generation of wastes (bads). The results obtained from B were clearly better to interpret and seemed more correct than those obtained from A. Approach C applies the reallocation principle of A and arrives at the same results as B, using that the (direct and indirect) generation of wastes is attributed to the final demands. It should be stressed that Approach C uses two apparently different assumptions at the same time, which may raise the question of its methodological consistency. On the one hand, it adopts the land use per mass of outflow (including wastes) of Approach A to attribute land use to final demands and disposals to nature. On the other hand, it uses the waste per mass of usable output of Approach B to attribute the generation of waste to the final demands.[6] Overall, Approach B seems to be the simplest solution for treating waste disposal in PIOTs at the moment.

[6] Derivation of $\bar{\mathbf{q}}$, $\bar{\mathbf{M}}\hat{\mathbf{d}}$ and the operation, $\hat{\bar{\mathbf{q}}}\bar{\mathbf{M}}\hat{\mathbf{d}}$ follows the assumption used by the Approach B, while the rest of the operation follows the assumption used by the Approach A.

For the empirical evaluation of the Approaches A and B, we have used an aggregated PIOT for Italy in 1995. It was found that the outcomes may exhibit large differences (see Table 7.5). Similar findings were reported in Suh (2004) and Dietzenbacher (2005), using the aggregated PIOT for Germany in 1990. It should be stressed, however, that this need not always be the case. Appendix 3 presents (and briefly discusses) the results for the 1990 PIOT for Denmark, for which the Approaches A and B generate quite comparable outcomes.

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Appendix 1

In this Appendix we will show that the analysis as based on a MIOT yields the same answer as the analysis on the basis of a PIOT after conversion of the result, if all sales by industry i are delivered at a single price. In the case of a MIOT, let the matrix of intermediate deliveries, and the vectors of outputs and final demands be denoted as $\mathbf{Z}_M$, $\mathbf{x}_M$ and $\mathbf{f}_M$ respectively, where the subscript M indicates that the numbers are in monetary terms. The accounting equation yields $\mathbf{x}_M = \mathbf{Z}_M\mathbf{u} + \mathbf{f}_M$. The "monetary" input coefficients are obtained as $\mathbf{A}_M = \mathbf{Z}_M\hat{\mathbf{x}}_M^{-1}$, or $a_{ij}^M = z_{ij}^M / x_j^M$. The model then becomes $\mathbf{x}_M = \mathbf{A}_M\mathbf{x}_M + \mathbf{f}_M$.

Let $\mathbf{p}$ denote the vector of prices for each of the products and it is assumed that the same price holds no matter whether the product is sold to industry j, to industry h, or to final demands. For the intermediate deliveries in physical terms we thus have $\mathbf{Z} = \hat{\mathbf{p}}^{-1}\mathbf{Z}_M$ or $z_{ij} = z_{ij}^M / p_i$. In the same way, we have $\mathbf{x} = \hat{\mathbf{p}}^{-1}\mathbf{x}_M$ for the outputs and $\mathbf{f} = \hat{\mathbf{p}}^{-1}\mathbf{f}_M$ for the final demands. The accounting equations then yield

$$\mathbf{x} = \hat{\mathbf{p}}^{-1}\mathbf{x}_M = \hat{\mathbf{p}}^{-1}(\mathbf{Z}_M\mathbf{u} + \mathbf{f}_M) = \hat{\mathbf{p}}^{-1}\mathbf{Z}_M\mathbf{u} + \hat{\mathbf{p}}^{-1}\mathbf{f}_M = \mathbf{Z}\mathbf{u} + \mathbf{f}.$$

The physical input coefficients become

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} = (\hat{\mathbf{p}}^{-1}\mathbf{Z}_M)(\hat{\mathbf{p}}^{-1}\hat{\mathbf{x}}_M)^{-1} = \hat{\mathbf{p}}^{-1}\mathbf{Z}_M\hat{\mathbf{x}}_M^{-1}\hat{\mathbf{p}} = \hat{\mathbf{p}}^{-1}\mathbf{A}_M\hat{\mathbf{p}},$$

which yields $\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f}$ for the physical input-output model.

The typical exercise in input-output analysis is to find the output levels necessary to satisfy an exogenously specified final demand vector, assuming that the input coefficients remain fixed. So let us take $\tilde{\mathbf{f}}$ as the new physical final demands. Using the physical input-output model, the outputs are given by $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{A})^{-1}\tilde{\mathbf{f}}$. Alternatively, we could have used the monetary model. That is, first convert the final demands $\tilde{\mathbf{f}}$ into money terms, i.e. $\hat{\mathbf{p}}\tilde{\mathbf{f}}$. Then calculate the monetary outputs, i.e. $\tilde{\mathbf{x}}_M = (\mathbf{I} - \mathbf{A}_M)^{-1}(\hat{\mathbf{p}}\tilde{\mathbf{f}})$. Finally, convert the monetary solution back to physical units, i.e. $\tilde{\mathbf{x}} = \hat{\mathbf{p}}^{-1}\tilde{\mathbf{x}}_M = \hat{\mathbf{p}}^{-1}(\mathbf{I} - \mathbf{A}_M)^{-1}(\hat{\mathbf{p}}\tilde{\mathbf{f}})$. It is easily seen that these two alternative answers for $\tilde{\mathbf{x}}$ are the same, because $\mathbf{A} = \hat{\mathbf{p}}^{-1}\mathbf{A}_M\hat{\mathbf{p}}$ implies $(\mathbf{I} - \mathbf{A}) = \hat{\mathbf{p}}^{-1}(\mathbf{I} - \mathbf{A}_M)\hat{\mathbf{p}}$, which in its turn yields $(\mathbf{I} - \mathbf{A})^{-1} = \hat{\mathbf{p}}^{-1}(\mathbf{I} - \mathbf{A}_M)^{-1}\hat{\mathbf{p}}$. So, the input-output model is not sensitive to the choice of units, provided the same unit is applied within an entire row of the table (see also Fisher 1965, for a seminal contribution to this discussion).

Appendix 2

First, we show that Approach C is consistent. The land use in industry i that is attributed to the final demands is given by

$$\hat{\mathbf{c}}\mathbf{M}(\mathbf{d} + \hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\mathbf{d}) + \hat{\mathbf{c}}\mathbf{M}(\mathbf{e} + \hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\mathbf{e}) = \hat{\mathbf{c}}\mathbf{M}(\mathbf{d} + \mathbf{e}) + \hat{\mathbf{c}}\mathbf{M}[\hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}(\mathbf{d} + \mathbf{e})] \tag{7.6}$$

Note that $\hat{\bar{\mathbf{q}}}\bar{\mathbf{M}}(\mathbf{d}+\mathbf{e}) = \hat{\bar{\mathbf{q}}}\bar{\mathbf{x}} = \mathbf{w}$. The right hand side of Equation (7.6) thus becomes $\hat{\mathbf{c}}\mathbf{M}(\mathbf{d} + \mathbf{e} + \mathbf{w}) = \hat{\mathbf{c}}\mathbf{x} = \mathbf{s}$, which is the actual land use in industry i.

Second, we show the equivalence of the Approaches B and C. That is, for any vector $\mathbf{d}$ it is required that

$$\hat{\mathbf{c}}\mathbf{M}(\hat{\mathbf{d}} + \hat{\bar{\mathbf{q}}}\overline{\mathbf{M}}\hat{\mathbf{d}}) = \hat{\bar{\mathbf{c}}}\overline{\mathbf{M}}\hat{\mathbf{d}}.$$

Postmultiplying both sides by $\hat{\mathbf{d}}^{-1}(\mathbf{I} - \bar{\mathbf{A}})\hat{\bar{\mathbf{x}}}$ yields

$$\hat{\mathbf{c}}\mathbf{M}(\mathbf{I} - \overline{\mathbf{A}} + \hat{\bar{\mathbf{q}}})\hat{\bar{\mathbf{x}}} = \hat{\bar{\mathbf{c}}}\hat{\bar{\mathbf{x}}}. \tag{7.7}$$

Note that $\hat{\bar{\mathbf{q}}}\hat{\bar{\mathbf{x}}} = \hat{\mathbf{w}}$, and $(\mathbf{I} - \overline{\mathbf{A}})\hat{\bar{\mathbf{x}}} = \hat{\bar{\mathbf{x}}} - \mathbf{Z} = \hat{\mathbf{x}} - \hat{\mathbf{w}} - \mathbf{Z} = (\mathbf{I} - \mathbf{A})\hat{\mathbf{x}} - \hat{\mathbf{w}}$. Substituting this in the left hand side of (7.7) gives $\hat{\mathbf{c}}\mathbf{M}(\mathbf{I} - \overline{\mathbf{A}} + \hat{\bar{\mathbf{q}}})\hat{\bar{\mathbf{x}}} = \hat{\mathbf{c}}\mathbf{M}(\mathbf{I} - \mathbf{A})\hat{\mathbf{x}} = \hat{\mathbf{c}}\hat{\mathbf{x}} = \hat{\mathbf{s}}$, which equals the right hand side because $\hat{\bar{\mathbf{c}}}\hat{\bar{\mathbf{x}}} = \hat{\mathbf{s}}$.

Appendix 3

Table 7.8 gives the three-industry PIOT for Denmark in 1990 and the results for applying Approaches A and B are given in Table 7.9 (which is comparable to Table 7.5). Whereas we found that the outcomes are very different for the case of Italy, the two approaches yield rather similar results for Denmark. Recall that in Italy a substantial part of the waste is generated in Agriculture (with very high land use coefficients) but should essentially be attributed to the final demands in

Table 7.8 The Three-Industry PIOT for Denmark, 1990 (in million tons) (Pedersen 1999)

	Industries			Final demands		Waste	Total
	A	*M*	*S*	Dom	Exp		
Agriculture	6,149	52,686	428	722	9,873	4,652	74,510
Manufacturing	5,073	27,002	2,328	63,604	13,110	24,233	55,620
Services	–	42	1	692	237	2,815	3,787
Primary inputs	63,288	55,620	1,030				
Total	74,510	135,350	3,787				
Land	41,532	2,916	1,331				45,779

Land appropriation is in square kilometer.

Table 7.9 Attribution of Land Use in Denmark (in square kilometers), Approaches *A* and *B*

	Approach *A*		Approach *B*	
	Domestic	Foreign	Domestic	Foreign
Attributed to				
Agriculture	657	8,985	498	6,804
Manufacturing	28,010	5,773	29,748	6,132
Services	1,754	601	1,935	663
Total	30,420	15,359	32,181	13,598

Manufacturing. This is what is done in Approach C (which gives the same results as Approach B). In Approach A, however, all waste in Agriculture is attributed to the final demands in Agriculture, which explains the differences in the outcomes.

In the Danish table, we see that relatively little waste is generated in Agriculture. Manufacturing provides 87% of all final demands and generates 76% of all waste. Although the final demands in Manufacturing do boost production in Agriculture it has relatively minor effects in terms of waste (and thus land use). As a consequence, the bulk of the waste is generated in Manufacturing and should be attributed to the final demands in Manufacturing. This is what is done in both approaches, which explains why their outcomes are much closer to each other in the Danish case.

The purpose of this paper is to examine the methodological aspects of treating disposals to nature in the context of PIOTs. The case that leads to large differences in results is therefore much more interesting. The case of Denmark shows, however, that the two approaches *may* lead to similar results, despite their methodological differences.

Chapter 8
Accounting and Modelling Global Resource Use

Stefan Giljum, Friedrich Hinterberger, Christian Lutz, and Bernd Meyer

Introduction

Monitoring the transition of modern societies towards a path of sustainable development requires comprehensive and consistent information on the relations between socio-economic activities and resulting environmental consequences. In the past 15 years, several approaches have been developed providing this information in biophysical terms (see, for example, Daniels and Moore 2002 for an overview). These methods of physical accounting are applied to quantify "societal metabolism" (Fischer-Kowalski 1998) and to measure the use of "environmental space" (Opschoor 1995) by human activities. Within the system of physical accounts on the national level (for a classification see United Nations 2003), material flow accounting and analysis (MFA) and land use accounting are regarded as appropriate tools to provide a comprehensive picture of environmental pressures induced by and interlinked with the production and consumption of a country.

In the European Union (EU), a large number of policy documents address high levels of resource use and production of huge amounts of waste and emissions as one major obstacle for the realisation of an environmentally sustainable development in industrialised countries. The sustainable management of natural resources, in order to keep anthropogenic environmental pressures within the limits of Earth's

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

carrying capacity, is highlighted as one central objective for the implementation of a sustainability strategy within Europe (for example, European Commission 2001a). De-coupling (or de-linking) economic growth from the use of natural resources and environmental degradation is defined as the core strategy to achieve sustainable levels of resource use; raising the resource productivity of production and consumption activities should help producing the same or even more products with less resource input and less waste (European Commission 2003).

In 2001, the European Council at Gothenburg agreed on a "European Strategy for Sustainable Development". In the European Commissions' (2001b) background document for the EU sustainability strategy, it is emphasised that production and consumption activities within EU borders would have environmental impacts in other world regions and would increase the pressure on the environment (particularly in developing countries). Thus the links between trade and environment would have to be taken into account in order to guarantee that the goal of achieving sustainability within Europe fosters sustainability on a global scale at the same time.

This becomes particularly relevant, as the externalisation of environmental burden through international trade might be an effective strategy for industrialised countries to maintain high environmental quality within their own borders, while externalising the negative environmental consequences of their production and consumption processes to other parts of the world (see, for example, Ahmad and Wyckoff 2003; Giljum and Eisenmenger 2004; Muradian and Martinez-Alier 2001; Tisdell 2001).[1]

An evaluation of the economic activities of one country or world region within the context of the urgently due transformation of societies towards sustainability on the global level can therefore only be carried out by extending the domestic physical accounts and including so-called indirect resource requirements (or "ecological rucksacks") associated with imports and exports. The declining material use per unit of GDP ("relative dematerialisation") in countries of the western hemisphere (see for example Adriaanse et al. 1997) does not automatically lead to lower overall consumption of material-intensive goods, but results to some extent from higher imports of these products from other world regions (Muradian and Martinez-Alier 2001; Schütz et al. 2004). Physical accounting studies, which comprehensively integrate international trade aspects, can clarify whether relative dematerialisation in the North is going along with a de-intensification of trade flows or is linked to increased physical inputs of natural resources from the global South.

While input-output (IO) models have been used for assessments of economy–environment relationships since the late 1960s, in particular in the field of energy and pollution studies (see, for example, Bullard and Herendeen 1975; Victor 1972), the integration of material flow and land use accounts with monetary IO models is a relatively young, but rapidly developing research field. With regard to integrated

[1] An extensive body of literature exists on this issue, also discussed under the notion of the "pollution haven hypothesis" (see, for example, Grether and de Melo 2003 and Neumayer 2001 for summaries of this debate).

sustainability scenario simulation and policy evaluation, these models are powerful tools, in particular for applications on the international level.

This chapter has three main objectives: it aims (a) at providing the methodological foundations for performing parallel accounting of material flows and land appropriation of economic activities within a framework of input-output models, (b) at describing necessary properties and the state of the art of global environmental–economy models and most important data sources for their construction and (c) at presenting policy applications of such an integrated modelling approach with regard to sustainability scenarios and assessments on the global level.

Physical Accounting introduces the basic concept of material flow accounting and analysis (MFA) and land use accounting. Methodological foundations for linking resource input accounts to monetary IO models are presented next. In State of the Art we review the state of the art with regard to global simulation models and summarise necessary properties of a global sustainability model and most important data sources. Global Policy Scenario describes the main areas of applications of this approach for world-wide sustainability policy-oriented assessments. Finally, the chapter concludes with discussion and summary.

Physical Accounting: MFA and LUA

The basic concept underlying the MFA approach is a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and – similar to living beings – dependent on a constant throughput of materials and energy. Raw materials, water, and air are extracted from the natural system as inputs, transformed into products and finally re-transferred to the natural system as outputs (waste and emissions). To highlight the similarity to natural metabolic processes, the terms “industrial” (Ayres 1989) or “societal” (Fischer-Kowalski 1998) metabolism have been introduced. Since the beginning of the 1990s, MFA has been a rapidly growing field of scientific interest and major efforts have been undertaken to harmonise the different methodological approaches developed by different research teams (Bringezu et al. 1997; Kleijn et al. 1999), resulting in the publication of a standardised methodological guidebook for economy-wide material flow accounting by the Statistical Office of the European Community (EUROSTAT 2001).

Material Flow Accounting and Analysis (MFA)

The main purposes of economy-wide material flow accounts are to provide insights into structure and change over time of the physical metabolism (resource throughput) of national economies, to derive a set of aggregated indicators for the material basis and resource productivity of production and consumption patterns, and to permit analytical uses, including assessments of resource flows induced by international trade as well as decomposition analyses separating technological, structural and final demand changes (see Chapter 34 by Stocker in this handbook). Today, MFA is recognised as a key tool for evaluating resource use and eco-efficiency policies, for example by the European Union (European Commission 2003) and the OECD (OECD 2004; see also Board on Earth Sciences and Resources 2004 for a summary of the use of MFA in the United States; 2004).

Material flow-based indicators for direct material flows (including domestic material extraction and direct import and export flows) can, to a large extent, be calculated using published national or international statistics. Assessing material flows on a sector level and calculating indirect resource requirements of internationally traded products within a macro-economic framework requires extending the standard MFA accounting method. In this chapter we focus on applications of IO analysis for material flow accounting and modelling.

A large number of national MFA studies have been presented for developed countries (for example, Adriaanse et al. 1997; EUROSTAT 2002, 2005; Matthews et al. 2000) and transition economies (Hammer and Hubacek 2002; Mündl et al. 1999; Scasny et al. 2003). Concerning countries in the global South, economy-wide MFAs have been compiled for Brazil and Venezuela (Amann et al. 2002), for Chile (Giljum 2004) and for China (Chen and Qiao 2001). A first estimation of the material basis of the global economy was presented by Schandl and Eisenmenger (2004) for the year 1999. A time series for resource extraction of all countries of the world from 1980–2002 was recently compiled by Giljum et al. (2004). The availability of detailed material input accounts is necessary for building global economic–environmental accounting and simulation tools.

Land Use Accounting

Together with energy and material flows, land use is the third important natural resource input category of economic activities (see for example, Spangenberg and Bonnoit 1998). Changes in land use and land cover are among the issues central to the study on environmental and socio-economic impacts of global environmental change (for example, Fischer et al. 2002).

The most influential physical accounting method focusing on land appropriation is the ecological footprint (EF) (Wackernagel and Rees 1996). The EF method is a tool to perform natural capital assessments on the national level and provide indicators for overall land (and water) appropriation related to production and consumption patterns in different world regions. EFs are available for all countries of the world (see WWF et al. 2004 for the latest global data set). The calculation method of the EF is in general not based on actual land use data, but starts from the resource consumption of a specific population in terms of mass units and transforms this mass into land appropriation in a second step. The largest share of the EF is made up by "hypothetical land areas" required to absorb the CO_2 emitted from the combustion of fossil energy carriers (or to produce an energy carrier of the same energy content from renewable resources).

A number of critical points concerning the calculation procedure of EFs have been raised (Ecological Economics 2000; McDonald and Patterson 2004), such as the aggregation of actual appropriated land areas with hypothetical land areas to the total EF, the assumption that current practices of land use (e.g. in agriculture) are sustainable, the focus on those (biotic) products, for which conversion of mass units into land areas is feasible and the inability to relate EFs directly to other economic and social indicators derived from the System of National Accounts.

For all those reasons, in our opinion, a more suitable approach for including land use aspects in physical accounting is to use land use data, available from land use statistics or from Geographical Information Systems (GIS) (for example, EEA 2002). In some European countries (for example, in Germany), land use accounts are compiled according to classifications of economic use (such as transport, housing, agriculture, industrial production, etc., see Statistisches Bundesamt 2002), making them directly connectable to economic accounts and models. By using real land use data and keeping it separate from the material accounts, problems related to the conversion of different categories is avoided, which increases scientific transparency and credibility of the approach.

Extending Monetary IO Models with Physical Accounts

As mentioned above, monetary IO models extended by environmental information in physical units[2] were already applied since the late 1960s, in particular in the areas of energy and pollution studies. The integration of material accounts in physical units into economic input-output models was first explored by Leontief et al. (1982), in order to forecast trends in the use of non-fuel minerals in the US. First studies linking monetary IO models and material flow accounts on the economy-wide level to calculate natural resource productivities of different sectors and to estimate direct and indirect material inputs to satisfy final demand were presented by Behrensmeier and Bringezu (1995) and Femia (1996), using the example of the German economy. Since then, the method to apply IO analysis of material flows was further improved in several steps and applied in various studies using the German case (Bringezu et al. 1998; Hinterberger et al. 1998, 1999; Moll et al. 2002, 2004).

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[2] Other approaches are entirely based on input-output tables in physical units, either in energy or mass units or on hybrid tables, containing both monetary and physical units. These methods are not further described in this paper. For a discussion on similarities and differences of monetary and physical approaches see, for example, Weisz and Duchin (2005), Hubacek and Giljum (2003) and the chapters on physical input-output tables in this handbook.

IO Models and MFA

IO analysis of material flows within a dynamic IO model was performed by Lange (1998), who integrated natural resource accounts in a 30-sector, dynamic input-output model for Indonesia in order to assess possible environmental implications of policy goals stated in Indonesia's national development plan. In the project "Work and Ecology", carried out by three research institutions in Germany (Hans-Böckler-Stiftung 2000), a dynamic input-output model for Germany ("Panta Rhei", see Meyer et al. 1999) was extended by material input data, in order to simulate and evaluate different sustainability scenarios for Germany (Hinterberger et al. 2002; Spangenberg et al. 2002). Bailey and colleagues 2004) perform an analysis of material flows within an ecological input-output framework to analyse material flow paths and cycles in the industrial system of selected production branches (such as the aluminium industry). The first application of IO analysis of material flows using a global IO model system is being realised in the EU-funded project *MOSUS*.[3]

The starting point for an explanation of the basic calculation procedure, which follows the standard procedure for the extension of monetary-input output tables by an additional input vector (see Miller and Blair 1985), is a monetary input-output table (MIOT) (Fig. 8.1).

From the monetary flow table, we derive the general equation for the static input-output model:

$$x = (I - A)^{-1} y \tag{8.1}$$

with x: Total output,

$(I{-}A)^{-1}$: Leontief inverse matrix,
y: Total final demand

The vector with material inputs (r') (in the case of materials in tons) of each sector consists of domestic material extraction in sectors such as agriculture, forestry,

Use / Supply	Sectors *(1,..,n)*	Final demand (y)		Total output
		Domestic	Exports	
Sectors (1,..,n)	**Z**	**Dy**	***de***	**x**
Value Added	**W**			
Imports	**M**			
Total input	**x'**			
Material input (physical units)	**R**			

Fig. 8.1 Simplified Monetary Input-Output Table (MIOT) Extended by a Material Input Vector in Physical Units

[3] Modelling opportunities and limits for restructuring Europe towards sustainability. MOSUS is funded by the fifth Framework Programme of the EU (see www.mosus.net for more information on this project).

mining and quarrying[4] as well as imports of raw materials, semi-manufactured and finished products.[5] Dividing the physical resource input appropriated by each sector (R_j) by the total (monetary) output of each sector (X_j) leads to a vector of sectoral input coefficients (C_i).

$$C = R/X \ \ for\ all_i \tag{8.2}$$

The extended Leontief inverse matrix or multiplier matrix weighted by material input coefficients (M_w) is finally calculated by post-multiplying the diagonal vector of sectoral material input coefficients ($\hat{c}$) with the Leontief inverse matrix.

$$M_W = \hat{c}(I - A)^{-1} \tag{8.3}$$

with M_w: Weighted multiplier matrix,

$\hat{c}$: Diagonal vector of material input coefficients.

The element *ij* of this weighted multiplier matrix illustrates the amount of material input of sector i needed to produce one additional unit of output of sector j. In order to calculate direct and indirect material input required to satisfy the different categories of final demand in different economic sectors, the weighted multiplier is multiplied with final (domestic[6] and foreign) demand.

$$r^d = M_W * d \text{ and } r^e = M_W * e \tag{8.4}$$

With r^d: Vector of direct and indirect material input for domestic consumption

r^e: Vectors of direct and indirect material input for export production
d: (Monetary) vector of domestic consumption
e: (Monetary) vector of exports
and $r^d + r^e = r$

This basic calculation procedure was later specified by Moll et al. (2002, 2004). Their approach on the one hand distinguishes domestic material extraction for intermediate use from domestic material extraction, which directly enters final demand. On the other hand, imports are divided into imports for intermediate use and imports for final demand, respectively. If the used MFA data set allows disaggregation of the mentioned categories, we recommend applying this more elaborated method.

[4] Domestic material extraction can either include only used domestic extraction, or used plus unused (e.g. overburden from mining) domestic extraction.

[5] Foreign material requirements can either comprise only direct imports in physical units, or direct plus up-stream indirect material requirements. In the German studies cited above, both categories were considered in the IO calculation, with indirect material requirements being estimated assuming imports to be produced with domestic technology.

[6] Domestic final demand can be further disaggregated into private consumption, investment, government expenditures, etc., in order to calculate material input requirements for more specific categories.

Material input accounts are generally compiled in a disaggregated way, distinguishing a large number of material flow categories within the three major groups of biomass extraction, extraction of minerals and ores, and extraction of fossil fuels. This detailed information can be used to split up the aggregated material input vector and perform IO analysis for specific material flows (for example, fossil fuels or heavy metals), which are more specifically related to different environmental problems (e.g. climate change; toxic pollutants, etc.) than aggregated material flow-based indicators (for a methodological description see Moll et al. 2004).

IO Models and Land Use Accounting

In the past few years, several studies relating input-output analysis to land use accounting were presented (Bicknell et al. 1998; Eder and Narodoslawsky 1999; Ferng 2001; Hubacek and Giljum 2003; Hubacek and Sun 2001). These approaches proved to be useful for the calculation of directly and indirectly appropriated land areas of production and consumption processes and are discussed as a possible further development of ecological footprint calculations (McDonald and Patterson 2004).

The basic calculation procedure is analogous to the one described for material flows, with the difference that the vector of resource input (l) is expressed in hectares of sectoral land appropriation.[7] Consequently, the land input coefficient, calculated by dividing total land appropriation in each sector by total monetary output, illustrates the appropriated land area necessary to deliver one unit of (monetary) output. Post-multiplying the diagonal vector of land input coefficients with the monetary multiplier delivers the multiplier weighted by land inputs. The element ij of this weighted multiplier matrix illustrates the amount of land input of sector i needed to produce one additional unit of output of sector j.

Direct and indirect land inputs necessary to satisfy final demand in the categories of domestic consumption and exports are finally calculated by multiplying the weighted multiplier with the different final demand categories:

$$l^d = M_W * d \text{ and } l^e = M_W * e \tag{8.5}$$

With l^d: Vector of direct and indirect land input for domestic consumption

l^e: Vectors of direct and indirect land input for export production
d: (Monetary) vector of domestic consumption
e: (Monetary) vector of exports
and $l^d + l^e = 1$

[7] In analogy to material inputs, the vector of land requirements should include both domestic land appropriation by economic sectors and land appropriation necessary abroad for producing imports to the national economy, calculated either assuming domestic technology or (preferably) using multi-country models (see also below). So far, few data on embodied land inputs of traded products are available (Hubacek and Giljum 2003).

In parallel to the category of material flows, the sectoral land input vector should be disaggregated in order to separately reflect different types of land categories (e.g. land for infrastructure, for transport purposes, etc.) appropriated by the respective economic sectors.

Parallel Analysis of Material Flows and Land Use

Material flows (including energy carriers) together with land use are widely regarded as the most important categories of resource inputs for economic activities. In the literature on material flow accounting on the economy-wide level, spatial aspects are in general not addressed. To our knowledge, no empirical study has been published so far addressing questions of the spatial distribution of material flows and the implications of changes in the metabolic profile of countries or regions for land use changes.

On the product (micro) level, the definition of an indicator, which relates the intensity of land use to the service provided, was presented by Schmidt-Bleek (1994). This procedure was intended to follow the "MIPS" (material intensity per service unit) approach developed for the category of material use. However, this approach was not further developed or applied for empirical studies.

The integration of environmental data in physical units (from physical accounts) into monetary IO models allows the parallel analysis of these two categories within a consistent and comprehensive framework. Thereby, parallel analyses of resource intensities and land intensities of different economic sectors can be performed, clarifying correlations and possible trade-offs between material intensity and land intensity can be identified. Finally, land intensity could be one possible criterion to evaluate different types of material flows with regard to negative environmental impacts.

Another possible extension of this analysis is to establish links between resource and land-related indicators to other indicators that can be attributed to the economic sectors under investigation, in order to allow for comprehensive sustainability analyses. These indicators can comprise labor in terms of employed people as well as working time (see Hinterberger et al. 2002) as well the use of capital.[8]

Global Economic Environmental Models

The increasing availability of multi-national economic models opens up new possibilities for performing integrated economic environmental assessments of globalisation processes. This allows analysing economic and environmental implications

[8] In economic terms, capital use would be measured in economic terms of official SNA statistics. Related to sustainable development, the term can also be broadened to include natural, social and human capital (see Spangenberg et al. 2002).

of, for example, international structural change and increasing liberalisation of trade on the global level. This section aims at providing requirements for the construction of global economic environmental models for accounting material flows and land use on the international level and modelling integrated sustainability scenarios, as described below.

Required Model Properties

There are five requirements, which global economic environmental models should fulfil (see Meyer et al. 2003):

1. They have to be *multi-country* global models. The multi-country approach is needed as policy decisions are made in countries and for countries and in general not for whole world regions. Therefore, all countries important from an economic and environmental point of view have to be described explicitly. The model must include a region "Rest of the World" to close the system and to ensure global coverage.
2. *Multi-sector* models are needed. The interrelations between the economy and the environment with its complex structures for the different resources and emissions can only be depicted in a deep sector disaggregation of the economy.
3. From 1 and 2 follows that also *international trade* has to be analysed in a *multi-sector/multi-country* approach. This means that for every product group, which is important to describe the economic–environmental interdependencies, international trade between all important countries has to be depicted bilaterally.
4. The models have to provide an *endogenous explanation of socio-economic development and its linkage with the environment.* This follows from the integrative approach of sustainability.
5. The models must be able to describe concrete and realistic policy alternatives. How will the future be in the business-as-usual case? How can this path be influenced by currently debated policy instruments? A *forecast* model is needed, which is able to reproduce the historical development because of the *statistical significance of its parameters*.

State of the Art

Uno (2002b) found and summarised 34 global simulation models in the literature – most of them focussing on energy issues – that were developed since 1993. In 27 of these models, economic development is *exogenous*. Whether the exogenity of final demand is a useful assumption or not depends on the questions that the models have to answer. Duchin (2005) developed the *World Trade Model*, a linear programming model, which calculates for given and region specific final demand, technologies, factor endowments and factor prices the factor cost minimising production and goods prices for every region. This means, that international trade is the result of a world wide optimal allocation of factors of production including environmental resources. Normative questions like this of course allow that final demand, factor prices and other important economic variables are exogenous.

But if we ask positive questions we expect answers, which explain observable phenomena. Since we are interested in the interdependencies of socio-economic and environmental development from the integrative perspective of sustainability, then exogenity of the economic development is not a promising approach. Another five models endogenise the economy, but do not fulfil other requirements, since they are not deeply disaggregated with regard to countries/world regions and industrial branches.

The fundamental qualities – global coverage, endogenous economy and a deep sector and regional disaggregation – are accomplished by the models of the Global Trade Analysis Project (GTAP) (Hertel 1997), COMPASS (Meyer and Uno 1999; Uno 2002a) and the Global Interindustry Forecasting System (GINFORS) (Meyer et al. 2004). GTAP distinguishes 57 sectors/commodities and 67 countries and regions, COMPASS distinguishes 36 sectors and 53 countries and regions, GINFORS has 41 sectors and 43 countries and two regions. The core of all three models is a multi-sector bilateral trade model.

GTAP is a neoclassical Computable General Equilibrium (CGE) model, whereas COMPASS and GINFORS follow the philosophy of the INFORUM (Interindustry Forecasting at the University of Maryland) group (Almon 1991), which combines the traditional input-output analysis with the econometric modelling approach. Based on the assumption of a long run general competitive equilibrium, the elasticities of the GTAP model are obtained from the literature and all other parameters are calibrated by one data point. The INFORUM approach allows bounded rationality of the agents, which are acting on imperfect markets. The parameters of COMPASS and GINFORS are estimated econometrically based on time series data, information about the statistical significance of the parameters is therefore included.

Global resource use models should consistently link monetary flows in a bilateral trade model to country or regional models on a sector level. In COMPASS and GINFORS, the country models consist of an IO model, a macroeconomic model including the System of National Accounts (SNA) and additional resource modules for energy, material flows, and land use. The trade model is based on trade matrices describing bilateral trade flows at the commodity level. It obtains from each of the countries export prices and import volumes and delivers export volumes and import prices to the country models. The IO models describe the production technology in the countries as reflected in the input structures. It delivers components of primary inputs to the SNA system, where sector information is aggregated. The SNA system describes the redistribution of income between corporations, households, government and the rest of the world. Resource use is linked to production on the sector level in every country or world region represented in the model. The whole system is consistently linked and simultaneously solved on a global level. Behavioural parameters are estimated by econometric techniques to catch country and sector specifics.

The calculation of indirect resource requirements (ecological rucksacks in terms of materials, energy and land use) of all goods – whether imported or domestically produced – and the attribution of primary resource use to final demand of all economic sectors in all countries is then carried out by the model system according to the monetary structure of interindustry relations and international trade flows. This allows a consistent (double counting is obviated) and comprehensive (total world-wide resource extraction and land use is considered) assessment of the overall resource use of final demand for each sector in each of the countries/regions specified in the model.

Data Requirements and Data Sources

Data requirements for constructing a global economy–environment model according to the requirements presented above are enormous. Interindustry relations of monetary IO tables should be available for countries or regions with a global coverage. IO tables are especially important for those countries which host different production stages (i.e. processing of raw materials, manufacturing, etc.) and have significant shares in global final demand. For countries exporting large shares of domestically extracted or harvested raw materials or slightly processed products (such as many OPEC countries), IO tables are not a necessary precondition, as resource use is mainly transmitted via international trade to final consumption in other countries.

International trade flows for all the countries or regions have to be available in the same or a compatible sector classification. Monetary IO tables are produced by national and international statistical offices. As national IO tables often differ in format – commodity-by-commodity versus industry-by-industry, sector and time coverage, and classifications, they have to be harmonised for application in an international framework. Additionally, macroeconomic data has to be integrated, as monetary production and consumption are main drivers for resource use and changes of international trade patterns. If available, (already harmonised) international data sources should be used to provide high transparency of the model.

Box 8.1 summarises most important data sources for the building of global economic environmental models.

Box 8.1 Data Sources for Global Economic Environmental Models

(a) *Economic models*

For the construction of the economic models, the following components are needed: macroeconomic and monetary data, national accounts data, input-output data and data on international trade flows.

International data are provided by UN annual trade yearbooks and OECD trade statistics, IMF and World Bank provide basic macroeconomic and monetary data for almost all countries in the world, and OECD publishes more detailed national account data. Input-output tables are available from several sources. Table 8.1 summarises the availability of input-output tables for European countries and non-European OECD countries.

Table 8.1 Available Input-Output Data for European and OECD Countries

Country	EUROSTAT[a,b,d] 1995/2000	National[a,b] 1995 ff.	OECD[a] 1990	OECD[b] 1995/97	GTAP[b]
EU OECD					
Austria		c			1983
Belgium/Lux	c	c			1995
Denmark	c	c	c	c	1992
Finland	c	c		c	1995
France	c	c	c	c	1992
Germany	c	c	c	c	1995
Greece	c	c		c	
Ireland					1990
Italy	c	c	c	c	1992
The Netherlands	c	c	c	c	1995
Portugal	1999	c			1993
Spain	c	c		c	1984
Sweden	c	c		c	1995
UK	c	c	c	c	1990
Czech Republic		c		c	
Hungary	c	c		c	1991/96
Poland	c	c		c	1997
Slovak Republic		c			
EU non-OECD					
Cyprus					
Estonia	1997	c			
Latvia					
Lithuania		c			
Malta					
Slovenia	1996	c			
non-EU OECD					
Turkey					1990
Iceland					
Norway	c	c		c	
Switzerland					1990
Canada		c	c	c	1990
Mexico					1995
The United States		c	c	c	1992
Japan		c	c	c	1995
Korea		c		c	1995
Australia		c	c	c	1996/97
New Zealand				c	1992/93
non-EU non-OECD					
Bulgaria		c			
Romania		c			

[a] Product-by-product tables.

[b] Industry-by-industry tables.

[c] Input-output data available.

[d] A year indicates the availability for a certain base year different from the other tables.

(continued)

Box 8.1 (continued)

The GTAP database is compiled from several different sources providing IO tables for different base years. The new GTAP 6 database has been released in spring 2005 and contains input-output tables for 87 countries or regions, although most statistical offices have not yet published or even produced input-output tables for this year. The procedure of ad-hoc data harmonisation is therefore not transparent. The most reliable and largest harmonised data set on monetary input-output tables is published by the OECD for 20 countries on an industry by industry format for 42 harmonised sectors. Industry classification makes use of NACE, Rev 1. Time coverage ranges for most countries from 1995 up to 1998. Since spring 2005, EUROSTAT delivers input-output tables for 60 sectors for 17 countries, for 13 of them for the year 2000 or later.

(b) *Material input models*

Concerning material input models, a number of internationally available statistics are used to compile material flow accounts in the different categories. In general, about 200 renewable and non-renewable natural resources are distinguished. Most common data sources are:

- Data on extraction of fossil fuels published by the International Energy Agency, the Industrial Commodity Statistics of the UN and the US Energy Information Administration (the latter providing free download of worldwide energy tables at www.eia.doe.gov).
- Data on extraction of metal ores and industrial and construction minerals published in statistics by the British Geological Survey, in the Industrial Commodity Statistics of the UN and in freely available country and mineral reports from United States Geological Survey (USGS) (www.usgs.gov).
- Biomass extraction data published by the Food and Agricultural Organisation of the United Nations (FAO), which provides an online database for agricultural, forestry and fishery production on the national level (www.fao.org).

(c) *Land use models*

In addition to a number of national studies and statistics on land cover and land use, the online database of the FAO reports data on land used for different purposes (e.g. agricultural areas disaggregated into arable land, permanent crop and permanent pasture areas, forest and wood lands and all other land). Concerning forestry areas, also more detailed studies are available, such as the "Temperate and Boreal Forest Resource Assessment (TBFRA)" reporting country data for 81 countries in North America, Europe, Asia and Oceania. TBFRA data can be downloaded from the website of the UN timber committee (www.unece.org/ trade/timber/fra). Data can also be obtained from a large number of studies using a GIS (Geographical Information System) approach (see the Internet page www.geo.ed.ac.uk/home/giswww for a comprehensive collection of related information sources).

Global Resource Use Accounting and Policy Scenario Modelling

Global multi-country and multi-sector models allow for accounting indirect material flows and land appropriation (ecological rucksacks in material and land units) and thereby provide a comprehensive assessment of *all* direct and indirect material flows (domestically extracted or imported) related to production and consumption activities. The concept is to use the monetary proportions as proxies for the complex physical relations behind indirect resource uses. Information concerning resource use for traded products in physical units is not necessary, as the model uses its inherent bilateral monetary trade flows for allocating physical inputs along international product chains. Resource extraction in a country is thus linked to the final demand of goods and services either in the extracting country or in any other part of the world. Obviously, the sector dimension should be the same in both the monetary IO tables and the international trade models to transmit the resource use correctly from one country to another. The system has to be closed on the world level for consistent modelling.

Accounting Total Resource Use of Final Demand

This procedure for assessing total resource use based on input-output modelling is an alternative to the life-cycle assessment (LCA)-oriented approach for calculating ecological rucksacks, which has been applied in most MFA studies published so far (for a description of this method, see Schmidt-Bleek et al. 1998).[9] Applying the LCA-oriented approach for material flow accounting on the national level is mainly suitable for the calculation of resource requirements associated to biotic and abiotic raw materials and products with a low level of processing. Applying this method to calculate resource use for semi-manufactured and finished products, in particular, if several countries are part of the international production chain, requires the compilation of an enormous amount of material (and land) input data at each stage of production. This is a cost- and time-intensive undertaking and makes the definition of exact system boundaries a difficult task (see also Joshi 2000). One major advantage of the IO approach is therefore that it avoids imprecise definitions of system boundaries, as the entire global economic system is the scope for the analysis. Furthermore, it allows estimating total resource inputs for all types of products with less effort than the LCA-based method, as only material inputs of those economic sectors have to be assessed, which are extracting primary materials (mainly agriculture, forestry and fisheries for biotic materials, and mining and construction for abiotic materials).

[9] Other studies (van der Voet et al. 2003) linked material flow data on the national level with information from LCA databases to provide a ranking of materials according to their different environmental impacts.

Resource Availability in Global Scenario Simulations

In standard IO models, all production activities are assumed to be demand driven and supply is assumed to be perfectly elastic in all sectors. Applying this assumption to the categories of natural resource use would imply that whatever changes in production and consumption levels would be simulated in future scenarios, resource availability would never be a restricting factor. With regard to this issue, a distinction between the categories of material flows on the one hand and land use on the other hand has to be made concerning the future availability of natural resources.

If running models up to the year 2020 or 2030, it can be assumed that there will be no major resource constraints concerning material inputs for economic activities. This assumption is backed by a number of studies and policy documents, which illustrate that at least within the next 20 years, natural resources will in general not become scarce, in particular with regard to non-renewable resources (extraction of minerals and ores), as known reserves for many raw materials are growing faster than production (European Commission 2003). However, if growth in worldwide demand outpaces opening of new resource extraction sites (e.g. oil drillings or mines of metal ores), significant increases in prices for raw materials and fossil energy carriers can be the consequence (as currently being observed due to rapidly growing demand for natural resources in particular in China). Furthermore, for some renewable resources (such as marine fish and timber), scarcity will be an increasingly serious problem to be addressed by policy makers already in the next few decades (EEA 2003).

Land availability obviously is a limiting factor for future global development (Wackernagel and Rees 1996), even within a relatively short time horizon such as up to 2020. Clearly, it cannot be assumed that certain sectors will expand or shrink their land requirements in proportion to changes in demand and output, due to restriction of land availability or land use regulations. Unmodified land multipliers used in the different country models could thus deliver unrealistic results. A much more appropriate assumption is that land use will actually restrict future economic activities. Consequently, land use models used in global economy environment models have to be adapted in order to include supply restrictions, which could be even completely inelastic for some of the economic sectors. Increase in demand will then have to be met by increased output in non-restricted sectors or by imports from other countries. These restrictions are important factors for the evaluation of future scenarios of land use (see Hubacek and Sun 2001 for a land-related IO simulation study on China).

Policy Scenarios Towards a Sustainable Use of Natural Resources

Global integrated sustainability models allow a comprehensive quantification of the use of natural resources (scale) in terms of material flows and land appropriation, including “ecological rucksacks” induced by international trade flows in other regions of the world. Time series of this analysis reveals, whether or not a tendency towards re-location of resource intensive production from rich countries towards the global South can be observed. Thus it can be analysed, whether the process of relative dematerialisation, which can be observed in industrialised countries, is going along with a dematerialisation of imported products or whether Northern dematerialisation is connected to a "re-materialisation" in other world regions, as some empirical studies suggest (Fischer-Kowalski and Amann 2001; Giljum 2004; Schütz et al. 2004). By doing so, comprehensive indicators on resource use can be provided, which extend and update existing indicators of resource use (as published for example for the European Union in Bringezu and Schütz 2001) and add the dimension of land use, for which no comprehensive indicators (including "embodied" land appropriation of traded goods) have been calculated so far.

Second, this research allows accounting for and analysis of the economic sectors (industries) and world regions/countries by which these resource flows are activated. Thus, interlinkage indicators, such as resource productivities and labor intensity of resource use of sectors of economies and their changes over time can be calculated. Furthermore, the role of domestic and total material inputs for growth potentials and job creation can be analysed and economic policy strategies identified, which could facilitate a reduction of resource use in an economically efficient way. Recent studies (see Fischer et al. 2004 for a simulation study with an integrated IO model for Germany) revealed that there exist high potentials for economically profitable resource savings even under current policy regulations and at prevailing price levels.

Third, global resource use models can be applied for analysing different questions regarding the interrelations of technological change, consumption behaviour (lifestyles) and international production and trade patterns. Changing final demand components in a country or a group of countries can help calculating the global resource elasticity of a specific component of final demand. For example, a 10% increase in private car expenditures in the USA has various impacts on the resource extraction in the USA and worldwide. Relations may change over time due to changes in life-style (consumer demand shifts to low weight cars), due to changes in the production process (steel may be substituted by plastics) as relative prices change, due to changes in import shares either in intermediate inputs (steel from Germany instead of Korea) or final demand (Japanese cars instead of US cars) and due to changes in other countries in resource extraction or production of intermediate inputs (adapting US production technologies and reduce resource use). All these possible changes may be driven by technical change, changing consumption patterns or policy measures. These three drivers of potential resource use decrease can be included into global resource use models: Technology transfer may take place between countries due to spill-over effects. Technology transfers can be modelled via changing input structures in an economy that may shift towards the input structures in the technologically leading economies. Changes in consumption patterns may also be influenced by experiences in other countries, which may be a target for policy measures. Changes of relative prices due to policy measures in some or a group of countries may also change trade flows. Of course, leakage effects (such as an increasing substitution of domestic production in polluting sectors by imports) are possible, that could countervail decreasing resource use in a country. Therefore, different policy options have to be tested.

Finally, and most importantly from the policy perspective, global resource use models can be used to simulate and evaluate sustainability scenarios. These scenarios can illustrate potential impacts of key environmental policy measures (e.g. ecological tax reform, reform of the subsidy system, flexible mechanisms within the Kyoto Protocol) for socio-economic indicators as well as for the use of natural resources in different world regions. Scenario evaluation can explore opportunities as well as barriers and limits for restructuring economies towards a more sustainable development path, giving special emphasis on potentials for technological changes for supporting these restructuring processes. In particular, possibilities for de-coupling economic growth from environmental pressures can be identified on a country and sector-specific level. Based on scenario evaluation covering the economic, environmental and social dimension, policy strategies and actions capable for reconciling long-term economic development and competitiveness with social cohesion and environmental protection requirements can be elaborated, in order to suggest formulated and tested best policy tools to realise the implementation of sustainability strategies.

Conclusions

This chapter consisted of three main parts. In the first part, the methodological foundations for extending monetary input-output models with physical accounts with regard to material flows and land appropriation were presented. It was illustrated that extended IO analysis provides a powerful and innovative framework for parallel accounting and analysis of material flows and land use on the level of economic sectors. This allows calculating total (direct and indirect) resource requirements of final demand and addressing important questions such as trade offs between sustainability goals of material dematerialisation and de-intensification of land use. In the second part, we summarised the state of the art and necessary properties of global resource use models and most important data sources for constructing economic IO models as well as material input and land use models in physical units. We argued that proper modelling requires time series of deeply disaggregated economic data with regard to the number of countries, the different industries, and the international trade flows, in order to allow a proper estimation of resource requirements along international production chains. In the final part we discussed empirical policy applications of this integrated modelling approach with regard to sustainability assessments on the global level. Comprehensive economic–environmental IO model systems are in particular suited to perform scenario simulation of the environmental and socio-economic effects of the implementation of environmental policy measures. Thus, policy strategies and instruments can be tested and elaborated, which are capable of best reconciling competing policy goals in economic, social and environmental policies.

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Chapter 9
Constructing Physical Input-Output Tables with Material Flow Analysis (MFA) Data: Bottom-Up Case Studies

Ottilia De Marco, Giovanni Lagioia, Vera Amicarelli, and Antonella Sgaramella

Introduction

In an economic system that aims at sustainable development, material indicators become increasingly more important than monetary indicators, as much of the literature now testifies (Ayres and Ayres 1998). Monetary indicators are often not able to reveal all the implications and interactions between the biosphere and technosphere (Nebbia 2000; De Marco et al. 2001).

The knowledge of these indicators is an essential requisite to evaluate the environmental impacts caused by human activities. The scarcity of information on the amount and the quality of waste flows, from the economic system to the biosphere, makes the evaluation of environmental impacts and the choice of an adequate disposal system both very difficult (Ayres and Ayres 1997; Nakamura and Kondo 2002).

In this context, studies and research regarding, in particular, (a) the description of economic system material bases (MFA) and (b) the material flows between different economic sectors and from these to the biosphere, become more and more important (Kneese et al. 1970; Ayres 1978; Bringezu 1997; Strassert 2001; Brunner and Recheberger 2004).

In the first case (a) the objectives are: to detect the different materials used in different economic activities, to see how they are used and how they are transformed into waste. An analysis of this type, known as Material Flow Analysis (MFA), can be applied to the whole economy of a country, to a single industrial sector or to a single firm.

The second case (b) regards Physical Input-Output Accounting through which it is possible to illustrate intersectoral material and energy exchanges existing within

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different economic sectors and between these sectors and the biosphere. Generally, this analysis refers to an annual base and concerns the whole economy of the country.

Both of the analyses use the very useful tool of material and energy balance which is based on the principle of conservation of matter (materials and energy).

The first attempts to evaluate materials passing or circulating through the economy were made two centuries ago. These attempts were the first steps that eventually led to the Input-Output Analysis (IOA), the father of which was Wassily Leontieff. W. Leontieff was educated in the Soviet Union at a time when decision makers of the socialistic economy were improving tools and methodologies that could identify the materials, goods and energy, as well as their circulation, that were necessary to support that model of economic development (Nebbia 2000; Leontief 1970).

With this aim, the first intersectoral tables of the economy were constructed. However, because of the difficulties encountered, the IO table was based solely on monetary units. The result was an IO table that focused on material flows exclusively associated to the monetary units within the economic system. This type of elaboration implies the loss of certain information, in this case the flows from the technosphere to the biosphere that is essential for a full evaluation of environmental burdens caused by economic systems.

The explosion of concerns regarding the environment that took place after the Second World War led to a new interest about the description of material flows between the economic system and the biosphere. The first examples of the environmental extension of Input-Output Analysis were intersectoral physical input-output schemes later termed PIOT, Physical Input Output Table. Although these examples date back to the 1960s, a lot of methodological problems have yet to be resolved (Kneese et al. 1970; Daly 1968; Nebbia 1975) and this is one reason why the PIOT elaboration in physical units has proceeded with difficulty. However, it is important to underline that there is a renewed interest in studies of this type (Strassert 2000).

In the last few decades complete macroeconomic material flow accounts in the form of input-output tables have been presented by official statistical offices for Germany and Denmark and by researchers for other countries (Italy, Japan, Austria, USA) (Stahmer et al. 1997; Gravgård 1990; Nebbia 2003).

The principal aspect of these studies is the strong relationship between Material Flow Analysis and Input-Output Analysis since MFA is able to present figures needed to illustrate typical inputs and outputs of economic activities, and IOA records them as intersectoral exchange flows. However, one of the principal limits is the approach most used to collect this information, and that is to say top-down one. In this case the intersectoral physical units IO table is constructed starting from statistical information. The data are often incomplete and/or not based on material balance principle. As a consequence, the final result is a table able to give a general outline of a country's macroeconomic situation but not able to give a detailed flows outline regarding an economic sector or a homogenous group of economic activities. Thus, it becomes more difficult to use PIOT as a tool for the making of governmental choices.

In this paper, the approach chosen is the bottom-up approach which records in the intersectoral physical units IO table figures obtained directly from MFA of different industrial sectors. Therefore, in the section on Material Flow Analysis, we analyze two Italian industrial sectors, aluminum and sugar, and, after having applied MFA analysis to them, in the section Plot Construction we will attempt elaborate the PIOT with the bottom-up approach.

Material Flow Analysis

In this section, articulated in two separate sub-sections, we illustrate the MFA results regarding the Italian primary aluminum industry and the Italian sugar industry, with the aim of monitoring the material flows of these productive sectors. Detailed quantitative information concerning the amount of natural resources used and the amount of waste produced by the anthropic system are the basis for the evaluation of different production, consumption and recycling policies and for the construction of specific environmental impact idices. These, indeed, are the figures necessary to construct the PIOT.

The Primary Aluminum Industry

The present world consumption of aluminum is approximately 33 million metric tons (Mt)[1] per year, of which approximately 25 Mt are primary aluminum and 8 Mt are secondary aluminum. The European Union consumes less than 25% of the annual world consumption (8 Mt). Domestic aluminum consumption today totals approximately 1.7 Mt, making Italy one of the largest aluminum consumers in Europe.

As previously mentioned, aluminum is a much used metal in Italy. The domestic primary aluminum industry supplies more than 20% (190,000 t, about 1% of world primary aluminum production) of the Italian primary aluminum consumption, which is approximately 900,000 t per year. In Italy, the primary aluminum industry has just one alumina producing plant[2] and two smelting plants,[3] all owned by the American company Alcoa. Figure 9.1 illustrates the flow chart related to the production of 1,000 t of primary aluminum based on material balance data collected from international literature and companies.[4] Figure 9.1 also includes those activities, mining and transportation, which took place outside of Italy.

[1] All references to ton in this text refer to metric tons and Mt refer to millions of metric tons.

[2] The only alumina plant is located in Sardinia, at the locality of Portovesme. Its annual capacity is approximately 1 Mt per year.

[3] Also in Sardinia, there is one of the two smelting plants. The other one is in Fusina, near Venice.

[4] For a detailed study of MFA of the aluminium industry in Italy see (Lagioia et al. 2005; Amicarelli et al. 2004).

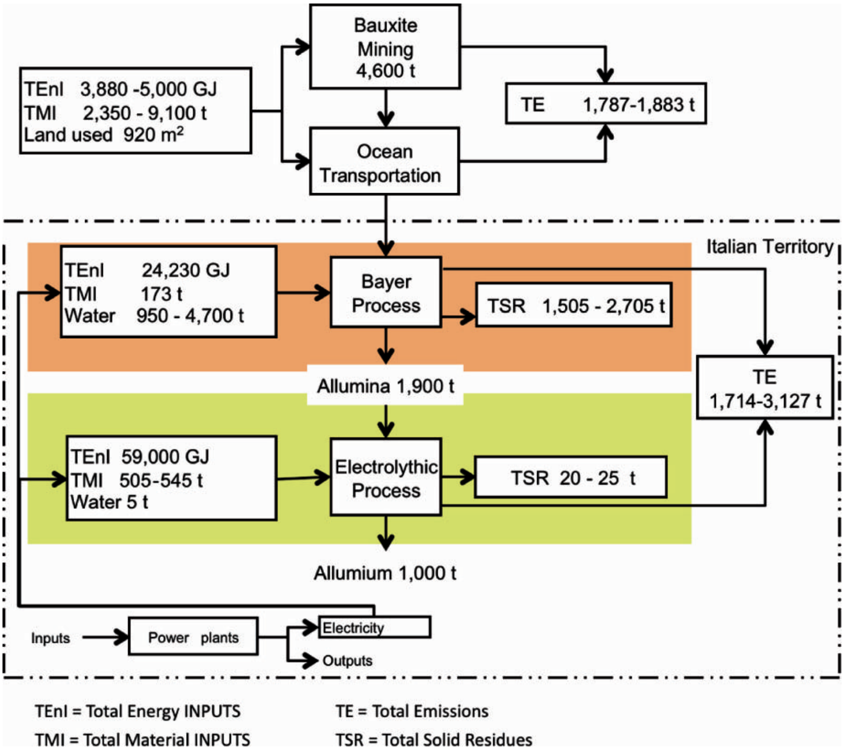

Fig. 9.1 Material Flows of Production of 1,000 t Primary Aluminum (Summary Chart)*

A synthesis regarding the material base of this Italian industrial sector and regarding the flows from and to other industrial activities and/or biosphere has been elaborated and recorded in Fig. 9.2. These quantitative figures allow the construction of the Input/Output table in physical units. The emissions of different phases have been calculated considering the emission factors processed by European and Italian Environmental Agency.

The primary aluminum industry obtains its raw materials from different types of mineral. The principal commercial source is Bauxite ($Al_2O_3 \cdot nH_2O$) the quality of which depends on the amount of alumina (40–45%) and silica (no more than the 5%) it contains.

In the year 2002, Italy imported more than 2.5 Mt[5] of Bauxite (from Australia and Guinea), all of which transformed into alumina. Approximately 37% of the alumina manufactured is destined to primary aluminum production whilst the remaining part is used in other sectors (the chemical industry for instance) or exported. Bauxite quarries cause the alteration of the ecosystems and an environmental impact due to operations such as (a) digging, necessary for the exploitation of opencast mines,

[5] This figure refers to minerals with 12% of humidity.

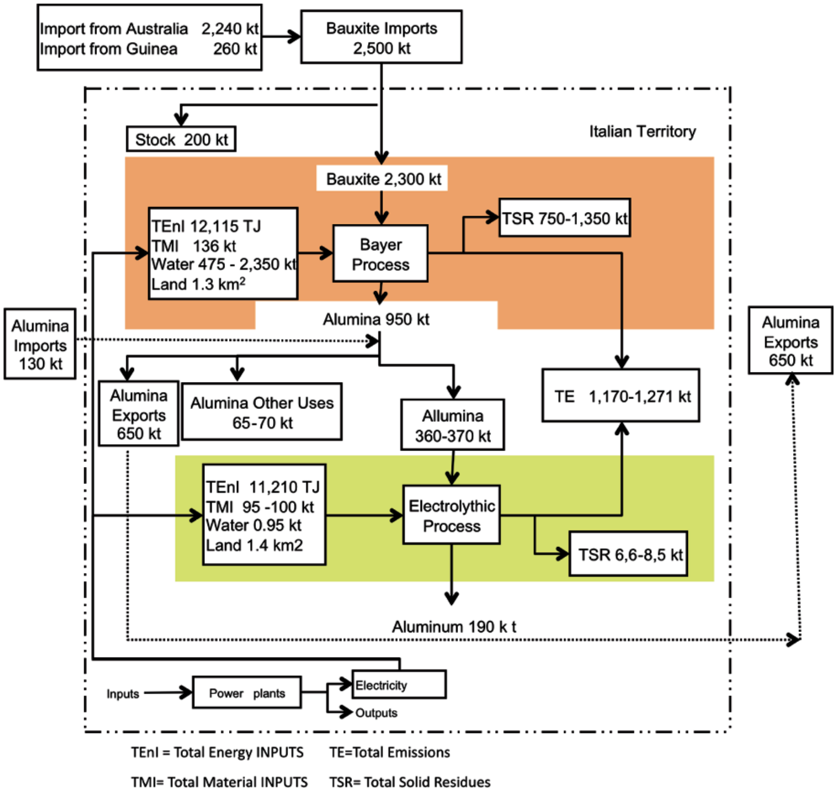

Fig. 9.2 Material Flows of Italian Primary Aluminum Production in the Year 2002 (Summary Chart)*

(b) fossil fuels used for local energy production, (c) water pollution due to waste water produced by washing-ore plants. Regarding this last point, water consumption has been reduced over the last 3 decades or so from 6 to 0.5–2.5 m^3/t thanks to enhanced natural resource saving policies.

Twenty days of navigation and over 40 cargo ships[6] per year are necessary to transport Bauxite to Italy, directly in the Sardinian Portovesme port. The estimated energy cost of this phase ranges from 0.7 to 0.8 GJ/t of transported Bauxite.

Aluminum metallurgy includes two distinct phases: one chemical and one electrolytic. In the first chemical phase, known as the Bayer process, the alumina is extracted from the Bauxite using a solution of caustic soda. To aid alumina extraction, small quantities of lime are often used. It is generally known that alumina production and lime consumption depend on the Bauxite quality. In the year 2002, the Italian aluminum industry used, on average, 2,400 kg of Bauxite, 40–50 kg of caustic soda and 40–50 kg of lime per each ton of alumina produced.

[6] Average cargo ship tonnage is estimated at approximately of 60,000 t.

The estimated fresh water use is approximately 5 m^3/t of alumina produced. Purification water systems reduce water consumption, as happens in the Sardinian Portovesme plant where it ranges from 0.5 to 2.5 m^3/t of alumina produced. Small quantities of flocculants agents (polyacrylate) and sulf acid are also used during the Bayer process.

As regards the energy consumptions of this phase, international values range from 8 to 30 GJ/t of alumina. The European, American and Italian averages are all approximately 13 GJ/t.[7]

The principal waste in the Bayer process is the red mud. Since this is non-toxic waste, it causes quantitative (from 300 to 500 kg/t of alumina produced) rather than qualitative disposal problems. At the Portovesme plant (100,000 m^2) the red mud is disposed of in a basin (1,200,000 m^2), about 3 km from the plant. The total of land used in 2002 covered approximately 1,300,000 m^2. In the near future the disposal area will be extended by 400,000–700,000 m^2.

The following step in the primary aluminum production chain is the electrolytic process known as the Hall–Héroult process, through which elementary aluminum is extracted. The Italian electrolytic covered cells, approximately 400 units, utilize precooked anodes. The cells are loaded with fused alumina and dissolved in a cryolite bath, which is needed to reduce the melting point. The current of electricity passing through the cells decomposes the alumina into aluminum and oxygen. The aluminum deposits on the cathode at the base of the cell and, the oxygen goes towards anodes where, combining with the anode carbon, it leaves the cell as carbon dioxide (CO_2). The fused aluminum, pure to 99.6%, is, periodically, extracted from the electrolytic cells and is used to prepare metal alloys or ingots.

The principal gases produced by electrolytic cells contain carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2) and volatile hydrocarbons and fluorides. Over the last 40 years atmospheric emissions, and particularly those of the dangerous fluorides, have been notably reduced thanks to the use of closed cells and to the introduction of dry gas purification systems. Today, emissions are estimated at 1–2 kg/t of aluminum produced.

Particular attention is required as regards the energetic inputs in the aluminum industry. Primary aluminum is an energy intensive production. The total energetic cost to obtain a ton of this non ferrous metal ranges from 145 to 180 GJ/t. The energy utilized is mainly electricity bought by the aluminum plants from the national electricity grid. This means that the primary energy cost for each kilowatt-hour produced, in terms of primary energy resources consumption and the environmental impacts, differs from country to country, from region to region, and from plant to plant. European and American Associations, analyzing the regional grids of all the aluminum manufacturing areas, have calculated the following conversion factors: respectively 8.3 and 7.6 MJ primary energy for each kilowatt-hour produced. In Italy, if we consider the national electricity grid, the conversion factor is 9 MJ/kWh,

[7] The Bayer process energy cost is 13 GJ of which approximately 2 GJ refers to primary energy used to obtain electricity (287 kWh) and 11 GJ refer to thermal energy directly used and produced in the plant by oil combustion (270 kg/t of alumina produced).

Table 9.1 Energetic Cost of 1 t of Primary Aluminum in Europe, United State and Italy

	Bayer process		Electrolytic Process		Conversion factor	Primary energy cost	Energy cost [a]
	Thermal energy	Electricity	Thermal energy	Electricity			
	(A)	(B)	(C)	(D)	(E)	(F = (B × 1.9 + D) × E)	(G = A × 1.9 + C + F)
	GJ/t Al_2O_3	kWh/t Al_2O_3	GJ/t Al	kWh/t Al	MJ/kWh	GJ	GJ/t Al
US	<11	290	5	15.000	7,6[b]	>118	>144
Europe	<11	290	5	15.000	8,3[b]	>129	>155
Italy	<11	290	5	15.000	9[c]	>140	>165
Italy	<11	290	5	15.000	10[b]	>155	>180

[a] It does not include the energetic cost of Bauxite extraction and transport. For Italian aluminum industry this cost is estimated 5 GJ/t Al.
[b] Conversion factor of the specific regional grid of aluminum manufacturing area.
[c] Average conversion factor of the whole Italian national grid.

but if we refer to the regional situation, the kilowatt-hour primary energy cost increases to 10 MJ for kilowatt-hour produced. In Table 9.1 the different energetic costs necessary to produce a ton of primary aluminum are recorded.

In order to transfer energy figures from MFA analysis to PIOT we used the specific conversion factor for the aluminum manufacturing area. The Italian energy industrial system has "sold", per each ton of aluminum, 55 GJ of electricity (15,287 kWh) and approximately 30 GJ of thermal energy to the primary aluminum industry. This means that the electrical system has bought more than 155 GJ of primary energy resources.

Production Cycle of Beet Sugar

The production cycle of beet sugar, as we know, can be divided into three main phases: sugar beet cultivation, industrial transformation and commercial distribution of beet sugar (the final product). In the sweetener market, sugar is the most used for human nutrition. Sugar (saccharose) is mainly extracted from sugar cane and sugar beet. In the world, the land used for sacchariferous crops is about 27,000 km^2 and this permitted the production, in 2002, of 143 Mt of raw sugar, 30% of which came from sugar beets. In the European Union, Germany, France and Italy are the main sugar beet producers. In 2002, these three countries produced, respectively, 31, 26 and about 12 Mt. In Italy sugar beet cultivation is common throughout most of the country with a total of 2,220 km^2 dedicated to its cultivation. In 2002, 12 Mt of beets were produced and transformed into 1.4 Mt of sugar.

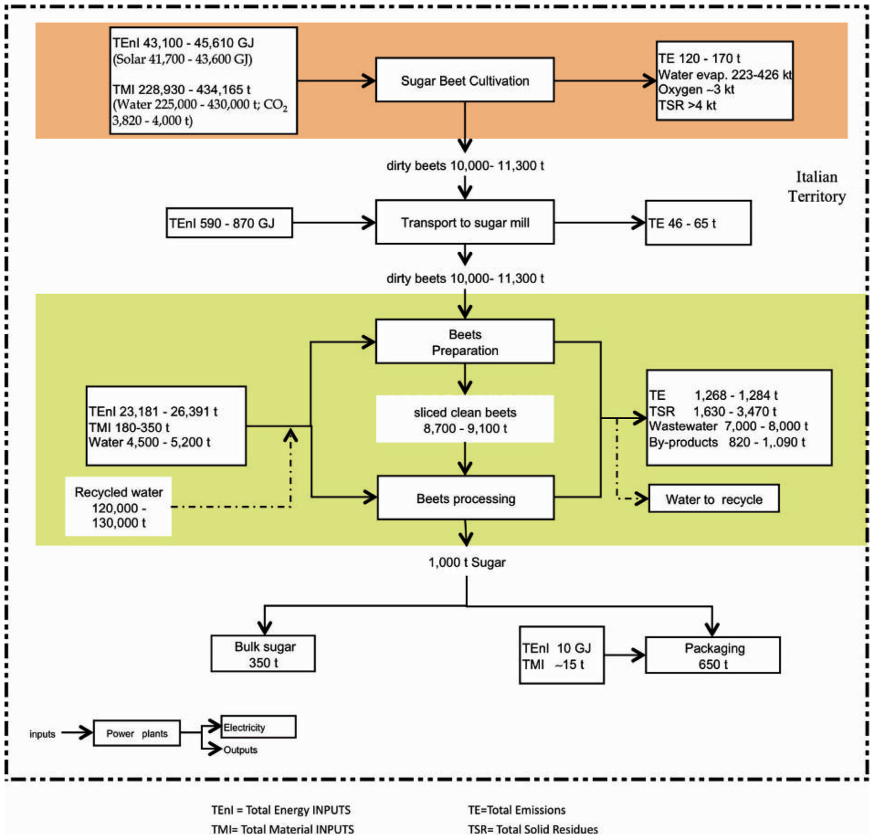

Fig. 9.3 Material Flows of Production of 1,000 t Sugar (Summary Chart)*

On the basis of the information obtained by the material flow analysis of cultivation, production and distribution of sugar in Italy, it has been possible to construct a flow chart for 1,000 t of sugar (Fig. 9.3) and the whole sugar Italian production in the year 2002 (Fig. 9.4).[8] The resulting data of this diagram allows us to retrace the exchange of materials between this sector and other industrial sectors as well as between the environment. This is all necessary to construct the intersectoral table in physical units (PIOT). Also in the case of sugar, emissions have been calculated considering the emission factors processed by the European and Italian Environmental Agencies.

As in the case of aluminum, we should pay particular attention to electricity consumption. The latter is converted into primary energy value (MJ) based on the national conversion factor of 9 MJ/kWh. In the case of sugar production, it is not

[8] For a detailed study of MFA of the sugar industry in Italy see (De Marco et al., 2002, 2003, 2004).

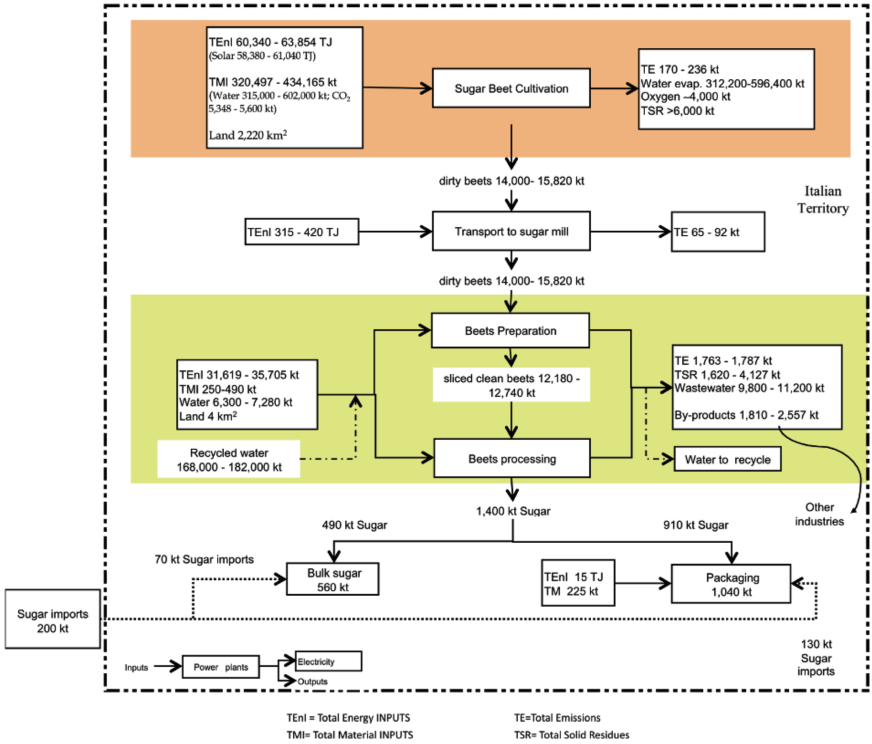

Fig. 9.4 Material Flows of Italian Sugar Production in the Year 2002 (Summary Chart)*

possible to consider specific regional references since sugar production and beet cultivation are so scattered throughout the country.

The sugar beet (*Beta vulgaris*, variety saccharifera L.) belongs to the class of Dycotiledons and to the family of Chenopodiacee. Proper soil preparation, which involves several phases, is required for this crop. The seed used, 25–40 g, is coated with geoinsecticides to protect it and the seedling from attacks of parasites and insects. After sowing, soil fertilization takes place; the dosage of fertilizer depends on the chemical–physical condition of the soil. It has been estimated that 50–60% of the nitrogen used for fertilizing is lost in the environment as nitrogen oxide.

After seed germination, photosynthesis starts and this allows the beet to grow and amass sugar substances in the pulpy root. It has been evaluated that, during the whole cultivation cycle, sugar beet crops absorb about 440 kg of CO_2, 180 kg of water,[9] 4.8 GJ of solar energy and release 320 kg of oxygen, to produce 1 t of roots.

[9] This amount of water refers only to water employed in photosynthesis, based on dry matter produced in the process.

Herbicide, fungicide and insecticide use depends on the presence/absence of serious plant infection. A useful tool to reduce specific plant illnesses could be the utilization of illness-resistant plants. Nevertheless, it has been estimated that the chemical spreading needs 2–13 MJ/t of beet.

Sugar beet cultivation requires a large absorption of irrigation water (25–52 m^3/t of beets) and about 90 MJ/t of energy to start up the irrigation devices (water raising pumps, nozzle movement, etc.).

Seventy days after sowing, sugar beets are harvested by mechanical means which are more efficacious, less expensive and require 28–36 MJ/t of beets. After harvesting, the sugar beets are taken to sugar mills[10] where they are cleaned and washed.

Thanks to water purification systems, the amount of water employed (to wash and to convey) in the whole sugar production cycle is about 0.3–0.4 t/t of roots. In the 1970s this amount was 0.6–0.9 t/t.

Clean beets are sliced into cossettes and sent for extraction. The countercurrent flow extraction takes place inside continuous extractors (drum or tower type) where cossettes and sugary juices move in opposite directions. Continuous extraction and dry transport permit further reductions in water consumption (0.7–0.8 t/t of beets).

Extraction produces exhausted cossettes and raw juice which contains about 13% of saccharose. The exhausted cossettes obtained are pressed, dried, and transformed into pellets and sent to the livestock industry. It has been estimated that in Italy in 2002 most of the sugar industry's by-products were used for animal feed.

Raw juice obtained by extraction is purified and treated with carbon dioxide, calcium oxide and sulfur dioxide. At the end of purification, thin juice, containing 1% of impurity, and filter cakes are produced. These cakes, after washing, can be used as fertilizer and this is another improvement in waste management. The thin juice, meanwhile, is evaporated, concentrated and, after cooling, centrifuged by water-centrifuge extractors to separate sugar crystals which are subsequently washed by water and steam. Centrifugation produces molasses and sugar, which is then dried and cooled. Molasses is used for the chemical industry to produce ethanol or chemicals such as inositol, glutamic acid, succinic acid, or together with dry pulp, to make animal feed. In 2002, 50% of the molasses produced was used for animal feed.

The sugar produced is distributed and sold in Italy as bulk (35%) or packaged (65%) sugar. Sugar is packaged in bulk bags (Big bag), paper shipping sacks, or disposable sugar mini bags. Generally kraft paper is used for paper shipping sacks because it is strong and cheap, and so suitable for a low added value product like sugar. The disposable mini bags are multilayer flexible packaging made of a combination of kraft paper and polyethylene. Big bags are made of plastic material (polypropylene tissue). The main characteristics of sugar distribution and its packaging are shown in Table 9.2.

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[10] It has been calculated an average distance of 8–40 km from beets cultivation to sugar mills.

Table 9.2 The Main Characteristics of Italian Sugar Distribution in 2002

Sector	Package typology	Gross weight	Tare	%[a]
Industrial	Bulk (30 t tank truck)	–	–	50
Industrial	Paper kraft bag	25 kg	90–130 g	30
Industrial	Paper kraft bag	50 kg	165–175 g	15
Industrial	Big bag	500–1,000 kg	800 g	5
Wide consumption	Paper kraft bag	1 kg	7.5 g	96
Wide consumption	Other package	–	–	4
Ho.re.ca.	Multi-layers (Kraft-PE) disposable mini-bag	5–7 g	0.32 g	100

[a] Percentage of sugar used by each single sector per package typology.

PIOT Construction

As previously mentioned, the utility of MFA also provides the quantitative information necessary to construct the PIOT. The PIOT is a Physical Input-Output Accounting tool through which it is possible to measure material and energy flows passing through the economy of a country.

The idea of using a tool of this type is not new and over the years it has taken many paths (Kneese et al. 1970; Strassert 2001; Stahmer 2000). In any case, many studies relative to the construction of an Input-Output model of the economic systems require good knowledge, at the moment lacking, of the material flows of the various economic activities. Nevertheless, the impulse to Physical Input-Output Accounting was given by the introduction of the Material/Energy Balance Principle (Kneese et al. 1970; Strassert 2001; Nebbia 1975; Strassert 2000; and Chapter 4 [Giljum and Hubacek] of this handbook). The link between MFA and IOA, as here proposed, contributes to filling this gap.

In general a PIOT is a tabular scheme in which a certain number of economic activities or sectors are represented by their material input and output. Our PIOT construction is based on the Herman Daly matrix, one of the first examples of this methodology. It can be synthesized in the following table split into four different quadrants:

	Nature (i)	Technosphere (j)
Nature (i)	a_{ii}	A_{ij}
Technosphere (j)	a_{ji}	A_{jj}

where a_{ii} represents material flows within the biosphere, a_{ij} resources "sold" by the biosphere to the technosphere (water used in different processes, for example), a_{ji} material flows from the technosphere to the biosphere (waste disposed or emissions, for example), a_{jj} commodities, semis etc. exchanged between different technosphere sectors (electricity "sold" to the Bayer process, fertilizers used in sugar beet cultivations etc.) (Nebbia 1975, 2000; Daly 1968).

Generally, quadrant a_{ii} is left empty because the description of economic activities does not include the flows within Nature. In several analyses it is omitted (Strassert 2000).

To make the comparison and analysis between PIOT and MIOT (Monetary Input Output Table) easier, the columns and the lines concerning the technosphere are named using the codes utilized by the NACE 1.1 classification of the economic activities which is based on the last revision of the general nomenclature of the economic activities in the European Communities.

The biosphere sectors are given numerical codes, "1" for the air, "2" for the aquatic ecosystem, "3" for soil, and "4" for the natural deposits. Finally, another two sectors have been added: one, called *stock* (code AA), represents the material "contained" in each sector[11] and the other (code AB) represents the flows from and toward other countries. The line AB records importation whilst column AB records the exports.

In our case studies we use Italian aluminum and sugar MFA (Figs. 9.2 and 9.4), in order to individualize and quantify the type of intersectoral exchange and then attribute this exchange to corresponding PIOT box. The transfer of the quantitative information in MFA Figs. 9.2 and 9.4 to the PIOT boxes has been performed with the aid of the electronic spreadsheets.

The result of the transferral of MFA data to the PIOT is that the output produced by each production chain (that is the sum of final products, semis, by-products, waste, emissions and wastewater) is split among various columns, and each column refers to a specific economic sector and/or biosphere sector (soil, for instance). As a consequence, each column represents the figures related to the inputs received by a single sector. In this way the quantitative information relating to each economic sector is visualized in the form of intersectoral exchanges.

In synthesis, the phases of elaboration involve (a) the displaying of the MFA results of the entire industrial sector so that they are ready to be transferred to the PIOT; (b) identification of the NACE codes of the origin and destination sectors of the various material flows reported in Figs. 9.2 and 9.4; (c) construction of the PIOT for each single sector, in this case aluminum and sugar (Figs. 9.5 and 9.6);(d) designing a PIOT that summarizes the results of the case studies (Fig. 9.7). In order to improve PIOT reading the charts have been reorganized representing, whereas there are no exchanges, only the column related to the section.

It should be noted that since the various boxes may contain several material flows the PIOT has an appendix which gives the details of each individual box. This is important especially when the results of the studies of several sectors are grouped together (Fig. 9.7). For example, box "X(D-DJ-27.42.0),(1)" of Fig. 9.7 indicates the total of the emissions (1,170–1,271 kt) generated by the aluminum industry. The details of these emissions would risk being lost if there were no link with the MFA (Fig. 9.2). Only with MFA does it emerge, for example, that the principle flow of emissions is due to the release of 1,130–1,185 kt of CO_2.

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[11] For example this box represents the amount of bauxite ore imports and the amount stored in alumina plants.

Since PIOT concerns only the flows inside the national territory, not all the values of MFA, which focuses on the entire material base, are recorded in the PIOT. For instance, inputs and outputs associated to the Australian Bauxite mining or the energy consumption for its transport are included in MFA analysis but, since they occur outside national territory, the related flows are not included in the PIOT table. In this case only the amount of mineral imported will be recorded in the line AB.

One of the most important aims of analyses of this type is to evidence the amount of waste that the economic activities generate and send into the environment. It is therefore important to observe the way these flows are recorded and this represents one of the main problems in designing a PIOT. In our cases, all the waste was considered as outputs of the various economic activities and is, therefore, split amongst the various columns/sectors of destination in correspondence with the line/sector of origin. As regards this point, there are two possibilities: (a) the waste may flow directly from the economic sector to the biosphere and (b) the waste may pass through "intermediary" economic sectors of treatment, reuse, recycling or disposal and consequently do not flow directly into the biosphere.

In the first case, the waste is easily identifiable as negative pressure indicators of the economic activities since it is recorded in the quadrant a_{ji} which illustrates all the flows of the technosphere towards the natural environment. For example, box "X(D-DJ-27.42.0),(1)" of Fig. 9.5 reports the emissions of CO_2, CO etc. "directly" flowing from the aluminum sector (code D-DJ-27.42.0) to the atmosphere (code 1). It is therefore easy to reconstruct that in Italy the production of 1 t of Al in 2002 generated a flow towards the environment of 6.1–6.7 t of emissions. This can then be easily compared with all the other sources of emissions and to the total amount of emissions. It is possible to see clearly the contribution of the aluminum industry to this total.

In the second case, the negative output (the waste) is not directly disposed of in the environment due to the input of other economic activities (treatment, recycling, etc.). It becomes more difficult, therefore to evidence the amount produced by each single sector. This can be seen, for example, in box "X(D-DA-15.83.0),(O.90.02.0)" of Fig. 9.6, which reports the waste produced by the sugar mills and then passed on to the systems of treatment. Here, however, it appears as an exchange within the economy. The final "sale" of the waste from the technosphere to the biosphere (box "X(O.90.02.0),(3)") would therefore be only indirectly linked to the sector under study. This point is also discussed in another chapter of this handbook (see Chapter 7 by Dietzenbacher et al.) and in the literature (Nakamura and Kondo 2002; Suh 2003; Giljum et al. 2004; Giljum and Hubacek 2004). The building of the intersectoral tables often entails the recording of the various flows in just one box, as in the case of waste which flows from the economic sector to the environment, and this leads to the loss of information of the quality of the materials and of the substances that have been disposed. The integrated reading of the MFA results and the PIOT appendices allow us to understand the nature of these flows and so to express a more complete evaluation, also qualitative, of the environmental problems associated to the sector under consideration. An example of this can bee see in the already mentioned box "X(D-DJ-27.42.0),(1)" of Fig. 9.5.

a

Section (S)				*S*	1 Air	2 Water	3 Soil	4 Natural Stock	A .. C
Subsection (Sb)				*Sb*					....
Division, Group, Class (DGC)				*DGC*					......
Description (Des.)				*Des.*					......
S		*Sb*	*DGC*	*Des.*					
1	Air								
2	Water								
3	Soil								
4	Natural Stock								
A	Agriculture	....	....	.....					
B	Fishing	....	.....	.....					
C	Minerals	....	.....	.....					
D	Manufacturing	DF	23.20.1	Manufacture of refined petroleum products					
		DG	24.13.0	Manufacture of other inorganic basic chemicals					
			24.14.0	Manufacture of other organic basic chemicals					
			24.16.0	Manufacture of plastics in primary forms					
		DI	26.52.0	Lime production					
		DJ	27	Metals products					
			27.42.0	Primary Aluminium industry	X		X		
E	Energy and water		40.11.0	Production of electricity	X	X			
			41.00.2	Collection, purification of water					
F ... Q	....	....	....	.....	X				
AA	Stock	....	....	.....					
AB	Import	....	....	.....					
				Totals (min)	4.669	383.560	759	0	0
				Totals (MAX)	4.770	832.510	1.361	0	0
			Land use (km^2)						

Fig. 9.5 Input-Output Table of Primary Aluminum Industry (Nace Code 27.42.0) in Italy in 2002 (Summary Chart)*

Another important block of information, the recording of which poses particular methodological problems, is the quantity of land used by the different economic sectors. This voice cannot be inserted among the other voices of the PIOT on account

b

D Manufacturing			E Energy and water		F … Q	AA Stock	AB Export		
DG	DJ				……	….	….		
24	27	27.42.0	40.11.0	41.00.2	……	….	….		
Manuf. of chemicals	Metal products	Industry Primary Al	Prod. of electricity	Collection, purification of water	…..	…..	…..	Totals min	Totals MAX
		X	X					2.238	2.322
			X	X				383.580	834.405
								0	0
								0	0
								0	0
								0	0
								0	0
		X	X					1.082	1.082
		X						48	52
		X						22	26
		X						0	0
		X						43	43
								0	0
X	X					X	X	3.034	3.742
		X						387.315	836.265
		X						476	2.351
								0	0
								0	0
		X						2.630	2.630
65	190	4.172	385.727	476	0	200	650	780.468	
70	190	6.139	834.677	2.351	0	200	650		1.682.918
		3							

Fig. 9.5 (continued)

of the different units of measurements used. We have, therefore, as also proposed by others (see Chapter 7 from Dietzenbacher et al. In this handbook; Suh 2003; Giljum et al. 2004), inserted a final line after the totals in order to express in square meter the quantity of land used by each column/sector in such a way as to be able to build the relative indicator of the land used by each sector examined.

a

Legend: Section (S); Subsection (Sb); Division, Group, Class (DGC); Description (Des.)

S					1	2	3	4	A	B	C	D			
					Air	Water	Soil	Natural Stock	Agriculture			Manufacturing			
Sb										....	....	DA	DA	DA	DG
DGC									01.11.3	....	....	15	15.7	15.83.0	24
Des.															
S		Sb	DGC	Des.											
1	Air								X					X	
2	Water								X					X	
3	Soil								X						
4	Natural Stock								X						
A	Agriculture		01.11.3	omissis	X	X	X								
B	Fishing	....	....												
C	Mineral extraction	CB	14.12.2											X	
D	Manufacturing		15												
D	Manufacturing	DA	15.83.0		X	X			X				X		X
D	Manufacturing	DD	20.40.0												
D	Manufacturing	DE	21.21.0												
D	Manufacturing	DF	23.10.1											X	
D	Manufacturing	DF	23.20.1						X						
D	Manufacturing	DG	24.13.0											X	
D	Manufacturing	DG	24.15.0						X						
D	Manufacturing	DG	24.20.0						X						
D	Manufacturing	DH	25.22.0												
D	Manufacturing	DI	26.52.0						X						
E	Electricity, Gas &		40.11.0		X	X								X	
E	Water		40.21.0											X	
F	Costruction	....	....												
G	Wholesale and ...		51,2						X						
H	Hotels and restaurants	....	....												
I	Transport,...		60.24.0		X							X		X	
J	Financial intermediation	....	....												
K	Other....		74.82.1												
L-N	....	....	....												
O	Other community, ...		90.02.0				X								
P	Family														
Q	... service activities	....	....												
AA	Stock														
AB	Import														
			Totals (min)		8.236	393.034	8.014	0	326.404	0	0	560	959	21.307	189
			Totals (MAX)		8.587	784.687	10.740	0	616.277	0	0	560	1.253	24.443	273
			Land use (km^2)						2.220					4	

Fig. 9.6 Input-Output Table of Sugar Beet Cultivation (Nace Code 01.11.3) and Sugar Industry (Nace Code 15.83.0) in Italy in 2002 (Summary Chart)*

Another problem we encountered with the methodology that we adopted is that tables are usually partially incomplete since the material flows of a specific analyzed economic sector do not involve all the sectors present in the technosphere or in the biosphere. This is the reason why often a lot of boxes in the tables are left empty (see Figs. 9.5–9.7). However, it is observed that this is a frequent situation when

b

E	F	G	H	I	J	K	L-N	O	P	Q	AA	AB		
Electricity, …		Trade		Transport, …		Other…		Other …	Family		Stock	Export		
	….		….		….		….			….				
40.11.0	….	51,2	….	60.24.0	….	74.82.1	….	90.02.0		….			Totals	Totals
omissis													min	MAX
X				X									8.335	8.569
X													406.520	799.500
													1.260	3.640
													1.390	1.453
				X									324.359	611.966
													0	0
													252	490
									X				560	560
				X		X		X					16.375	20.770
						X							11	11
						X							10	10
													12	23
X				X									122	156
													1	2
													70	144
													0	2
						X							1	2
													78	83
						X							85.412	190.444
													720	803
													0	0
													0	0
													0	0
													14.625	16.472
													0	0
									X				1.040	1.040
													0	0
													1.924	4.371
													0	0
													0	0
													0	0
				X		X							200	200 -
85.375	0	0	0	14.613	0	1.062	0	1.924	1.600	0	0	0	863.277	
190.400	0	0	0	16.457	0	1.064	0	4.370	1.600	0	0	0		1.660.711
									+		+	+		

Fig. 9.6 (continued)

only one sector is analyzed but, using MFA results it will be possible to compile the whole intersectoral table if studies like the ones we have carried out will be carried out for all the sectors of an economic system.

The approach we used is named 'bottom-up' on account of the fact that we aggregate the details and specific information regarding each economic sector in order

a

Legend

Section (S)
Subsection (Sb)
Division, Group, Class (DGC)
Description (Des.)

S		Sb	DGC	Des.	1 Air	2 Water	3 Soil	4 Natural Stock	A Agriculture	B	C	D Manufacturing							
Sb										....	....	DA	DA	DA	DG	DG	DG	DJ	DJ
DGC									01.11.3	....	....	15	15.7	15.83.0	24	24.15.0	24.20.0	27	27.42.0
Des.									omissis										
1	Air								X					X					X
2	Water								X					X					
3	Soil								X										
4	Natural Stock								X										
A	Agriculture		01.11.3	Omissis	X	X	X												
B	Fishing	....	....																
C	Mineral extraction	CB	14.12.2											X					
D	Manufacturing	DA	15																
		DA	15.7																
		DA	15.83.0		X	X			X				X		X				
		DD	20.40.0																
		DE	21.21.0																
		DF	23.10.1											X					
		DF	23.20.1						X										X
		DG	24.13.0											X					X
		DG	24.14.0																X
		DG	24.15.0						X										
		DG	24.16.0																X
		DG	24.20.0						X										
		DH	25.22.0																
		DI	26.52.0						X										X
		DJ	27.42.0		X		X								X			X	
E	Electricity, Gas & Water		40.11.0		X	X								X					X
			40.21.0											X					
			41.00.2																X
F	Costruction	....	....																
G	Wholesale		51,2						X										
H	Hotels and restaurants	....	....																
I	Transport, storage ..		60.24.0		X							X		X					
J	Financial ...	....	....																
K	Other.....		74.82.1																
L-N	....	....	....																
O	Other		90.02.0				X												
P	Family																		
Q	... service activities	....	....																
AA	Stock																		
AB	Import																		X
			Totals (min)		12.905	776.594	8.773	0	326.403	0	0	560	959	21.308	254	0	0	190	4.172
			Totals (MAX)		13.357	1.617.547	12.102	0	616.278	0	0	560	1.253	24.444	343	0	0	190	6.139
			Land use (km^2)						2.220					4					3

Fig. 9.7 Input-Output Table of Aluminum and Sugar Industry in Italy in 2002 (Summary Chart)*

to have an overall and complete picture of all the exchanges that characterize the economic system. The PIOT of Fig. 9.7 is an example of the a single table for both sectors analyzed and in which it is possible to find the union of flows.

One consequence of this method is that the indirect flows are visualized only when the exchanges of materials of related sectors are inserted. For example, the use of caustic soda in the Bayer process (box(D-DG-24.13.0), (D-DJ-27.42.0) of

b

0		F .. H	I	J	K	L-N	O	P	Q	AA	AB		
Electricity, Gas & Water			Transport …		Other …		Other, etc.	Family		Stock	Export		
		….		….		….			….				
40.11.0	41.00.2	….	60.24.0	….	74.82.1	….	90.02.0		….				
omissis												Totals min	Totals MAX
X			X									10.573	10.892
X	X											790.100	1.633.905
												1.260	3.640
												1.390	1.453
			X									324.359	612.316
												0	0
												252	490
								X				560	560
												0	0
			X		X		X					16.375	20.770
					X							11	11
					X							10	10
												12	23
X			X									1.203	1.238
												49	54
												22	26
												70	144
												0	0
												0	2
					X							1	2
												121	126
										X	X	3.034	3.742
					X							472.729	1.026.710
												720	803
												476	2.351
												0	0
												0	0
												0	0
												14.625	16.472
												0	0
								X				1.040	1.040
												0	0
												1.924	4.371
												0	0
												0	0
												0	0
			X		X							2.830	2.830 -
471.102	476	0	14.614	0	1.062	0	1.924	1.600	0	200	650	1.643.746	
1.025.077	2.350	0	16.457	0	1.064	0	4.370	1.600	0	200	650		3.343.981
								+		+	+		

Fig. 9.7 (continued)

Fig. 9.5) implies that the economic sector is indirectly linked to the flow "X(C-CB-14.40.0), (D-DG-24.13.0)". This box should report the quantity of salt sold by salt mines to the alkaline substances industry (sector "D-DG-24.13.0"). In the present study we have, nevertheless, deemed it opportune not to ignore the principle indirect flows (consumption of primary resources and emissions) associated with the use of electrical energy.

This means that the figures represent not only the quantity of energy that flows from the electricity sector to the examined sectors but also all the primary energy resources used to produce electricity. The fuel sector, for instance, sells to the electricity sector 768–773 ktoe[12] of thermal energy. After the transformation the electricity sector sells to the aluminum and sugar industries, respectively, 257 and 22–24 ktoe of electricity and "offers" to the biosphere 489–492 ktoe of heat losses.

Conclusion

In the present chapter we have analyzed two Italian productive sectors: the aluminum and sugar industries. Utilizing the material balances, the MFA methodology applied has allowed the description of all the phases of these two production chains taking place in or outside the domestic territory (Figs. 9.1–9.4). Then, with the MFA results, the PIOT has been constructed for each of the two sectors. Figures available in literature often have to be confirmed by companies and this makes MFA analysis rather painstaking. In the study cases presented it has been possible to collaborate with Italian aluminum and sugar firms (Comalco Limited 2004, personal communication; Alcoa Portovesme Alumina Plant 2004, personal communication; Sadam Zuccherifici S.p.A. 2004, Jesi Plant, personal communication; S.F.I.R. S.p.A 2004, Foggia Plant, personal communication) and we hope for a greater collaboration between universities and the business world to improve this type of study.

Nevertheless, the MFA results utilized to compile material balances illustrate the degree of efficiency the considered sectors have reached compared to the previous years and to the international situation in general, particularly as regards the use and saving of resources and the reutilization or the disposal of waste produced. It is noted, for example, that energy consumption for each ton of Bauxite quarried is now at the lowest level possible. It is also noted that the Italian Bauxite/alumina ratio is very close to the European and American averages. Also the water consumption in both analyzed industries shows substantial changes due to the reduction in water use and to water recycling. At the same time, modern soil fertilization techniques have reduced the total amount of fertilizers used. Unsolved is still the disposal management of red mud, the principal aluminum industry waste.

Based on figures obtained from the MFA analysis of the aluminum and sugar industries, PIOT tables have been constructed using the bottom-up approach. The

[12] In the elaboration of the data for the construction of the PIOT, the energy consumptions have been converted in toe.

tables illustrate the material flows that took place between these sectors and the others (technosphere and biosphere) in the year 2002 in Italy. Figures 9.5 and 9.6 illustrate, respectively, the two analyzed sectors whilst Fig. 9.7 summarizes the figures related to them. The transposition of the flow figures into the intersectoral PIOT allows us to synthesize direct and indirect input and output associated to the various productive sectors. It is possible, for example, to calculate that, in 2002, the industrial sector (from DA to DJ PIOT sections) sold the aluminum sector approximately 0.9 Mt of direct material Input and the electricity sector approximately 0.3 Mtoe. If we consider also the flows related to the electricity sector (NACE code 41.00.2), it is obvious that the indirect inputs of the aluminum industry are approximately 0.7 Mtoe and 400–820 Mt of cooling water used to produce electricity.

The complete illustration of the total of indirect inputs can be achieved only if all productive sectors are recorded. Although the top-down approach does not have this limitation, it does, however, lack the details regarding a single sector or single commodity.

Based on these coefficients it is possible to construct scenarios which would be useful to individuate the effects caused by shifts in business and/or government policy and to evaluate benefits of technological innovations. If the aluminum plant were located in an area characterized by a better efficiency of the local electricity plant (conversion factor 8.5 MJ/kWh instead of 10 MJ/kWh) it should be possible to reduce energy consumption by approximately 0.1 Mtoe and reduce the related environmental impacts.

The utility of this tool is also to unite the monetary indicators (GDP)[13] and the material indicators (GMP)[14] in order to achieve better planning policies aimed at sustainable development.

Obviously, the environmental extension of Input-Output Analysis (quadrants a_{ij} and a_{ji}) allows us to know also the details regarding waste or emissions associated to each industrial sector.

In this way, it is possible to point out the role of one specific sector compared to the country's total emissions. This detailed information is lacking in the monetary analysis of an economic system.

The direct contribution of the aluminum industry to the total Italian CO_2 emissions, for instance, is approximately 0.13% but if we consider indirect CO_2 emissions (those associated to the electricity sector), the aluminum industry's contribution passes from 0.13% to over 0.8%. Furthermore, the aluminum PIOT shows that, from a quantitative point of view, apart from the wastewater flows, the aluminum industry flow is represented by solid waste (particularly red mud) going into the ground. To evaluate the environmental impacts of these flows it is, nevertheless, necessary to analyze the quality of these flows. Because the PIOT construction entails the summing of materials which are often very heterogeneous, it is difficult

[13] GDP is Gross Domestic Product.

[14] GMP, Gross Material Product is a physical indicator capable of illustrating the whole mass of materials absorbed by the final consumers, services, stocks, and plus exports minus imports (Nebbia 2003).

to illustrate the effects that each flow has on the biosphere (air, water, and ground). MFA results can help overcome this flaw since they can detail what is summarized in the PIOT box.

The principal limitation of the bottom-up approach is that it is laborious and a long time is required to obtain an overall picture of the intersectoral exchanges within the whole economy. Moreover, to achieve the latter, it is necessary to aggregate information of many different MFA analyses and for this, as stated before, a greater collaboration between researchers and the world of business would be necessary (De Marco et al. 2001; Nebbia 2003; ANPA 2001, 2002).

Furthermore, from a methodological point of view, it would be better to follow a standardized scheme to assign material flows to different production branches, or to consumption, or to stocks. In this way it may be possible to obtain a tool that offers more truthful and verifiable results. The MFA studies presented, as shown in Figs. 9.1 and 9.3, allow us to illustrate the coefficients related to the inputs and outputs used. The transparency of the figures could favor comparison with analyses made in other countries. If we had similar analyses from other industrial sectors, it would be possible to obtain detailed data able to illustrate direct and indirect effects of the many changes taking place in the economy. The great benefit of this system is that it would provide the user with a very flexible tool that offers many types of aggregations. If, for example, decision-makers want general information on, let's say, waste disposal in Italy, it is sufficient to refer to the waste disposal section of the PIOT. If, however, they want more detailed information they simply have to enlarge the PIOT to be able to consult the details in the subsections.

In conclusion, we stress the necessity of uniting MFA analysis and IO analysis since a better understanding of the physical flows within an economy (or technosphere) and between the technosphere and the biosphere could illustrate the relationship between economic activities and the environment; and this, as every knows, is at the heart of the environmental problem (De Marco et al. 2001; Kytzia, 2004; Bailey et al. 2004).

End Note

*The complete charts are available from the authors by request. They can also be found at http://www.dgm.uniba.it/Docenti/Lagioia/pubblicazioni.htm

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Appendix 1
Primary Aluminum Industry PIOT (27.42.0 NACE Code)

We supposed that the electricity, used to produce 1 t of primary aluminum, was obtained by thermoelectric plants located close to the domestic primary aluminum industries. Considering that Italian primary aluminum (190,000 t) is produced for 75% in Portoscuso (Sardinia) plant and for the other 25% in Fusina (Venetia) one, we applied the same bipartition to calculate material base (primary energy, emissions, etc.) associated to thermoelectric plants. We did the same hypothesis to calculate the amount of water (cooling and industrial water) used in thermoelectric plants. Thermoelectric production efficiency calculated is more than 35.5% for Sardinia (10.1 MJ/kWh) and more than 36.5% for Venetia (9.8 MJ/kWh).

X (1), (D-DJ-27.42.0) 328–413 kt – Oxygen for fuel combustion in aluminum plant (only Aluminum Oxide plant).
X (1), (E-40.11.0) 1,910 kt–Oxygen for fuel combustion in power plant.
X (2), (E-40.11.0) 383,104–832,054 kt – Cooling water (128–278 L/kWh) and industrial water (0.3 L/kWh) used by power plant.
X (2), (E-41.00.2) 476–2,351 kt – Water pass from natural system to water distribution industry.
X (D-DF-23.20.1), (D-DJ-27.42.0) 369 ktoe – Petroleum coke and fuel oil (thermal energy, as toe) used by aluminum industry.
X (D-DF-23.20.1), (E-40.11.0) 713 ktoe – Fuel used by power industry to manufacture electricity.
X (D-DG-24.13.0), (D-DJ-27.42.0) 48–52 kt – Caustic soda; Acids and fluoride used by aluminum industry.

Table 9.3 Emission Factors of Electricity (g/kWh)

CO_2	889–944
SO_2	1.30–2.40
Particulate	0.04–0.03
NOx	0.75–1.17
CO	0.10

X (D-DG-24.14.0), (D-DJ-27.42.0) 22–26 kt – Pitch and cathodes used by aluminum industry.
X (D-DG-24.16.0), (D-DJ-27.42.0) 0.05 kt – Flocculants used by aluminum industry.
X (D-DI-26.52.0), (D-DJ-27.42.0) 43 kt – Lime used by aluminum industry.
X (D-DJ-27.42.0), (1) 1,170–1,271 kt – Emissions produced by aluminum industry.
X (D-DJ-27.42.0), (3) 759–1,361 kt – Dry red mud, sand, sodium oxalates, spent lining pot, other solid residue produced by aluminum industry.
X (D-DJ-27.42.0), (D-DG-24) 65–70 kt – Alumina sold to chemical sector.
X (D-DJ-27.42.0), (D-DJ) 190 kt – Aluminum sold to metal products industry.
X (D-DJ-27.42.0), (AA) 200–200 kt of Bauxite ore stored.
X (D-DJ-27.42.0), (AB) 650–630 kt of alumina exports.
X (E-40.11.0), (1) 3,499 kt – Air emission from power industry based on factors showed in the following table (Table 9.3). Industrial water (0.3 L/kWh) realized by power industry.
X (E-40.11.0), (2) 383,560–832,510 kt – Heat loss and plant cooling water (128–278 L/kWh) realized by power industry.
X (E-40.11.0), (D-DJ-27.42.0) 256.5 kt – Power used by aluminum industry.
X (E-41.00.2) (D-DJ-27.42.0) 476–2,351 kt – Water from water distribution industry to aluminum industry.
X (AB), (D-DJ-27.42.0) 2,630–2,500 kt of Bauxite ores and 130 kt of alumina imported from aluminum industry.

Appendix 2 Sugar Industry PIOT (01.11.3 and 15.83.0 NACE Code)

X (1), (A-01.11.3) 8,200–8,400 kt – CO_2 for beet production.
X (1), (I-15.83.0), 1 kt – Oxygen for fuel combustion in sugar mill.
X (1), (E-40.11.0) 100–120 kt – Oxygen for fuel combustion in power plant.
X (1), (I-60.24.0) 34–48 kt – Oxygen for fuel combustion in trasportation service.
X (2), (A-01.11.3) 315,000–602,000 kt – Fresh water for sugar beet cultivation.
X (2), (D-DA-15.83.0) 6,300–7,280 kt – Fresh water for sugar mill.
X (2), (E-40.11.0) 85,220–190,220 kt – Cooling and industrial water for power plants.

X (3), (A-01.11.3) 1,260–3,640 kt – Soil stuck to beets.
X (4), (A-01.11.3) 1,390–1,453 ktoe – This figure (as ktoe) is the solar energy used in photosynthesis.
X (A-01.11.3), (1) 6,069–6,326 kt – Oxygen from photosynthesis, atmospheric emissions from agricultural machinery.
X (A-01.11.3), (2) 298,200–583,450 kt – Water released from cultivation for evapotranspiration.
X (A-01.11.3), (3) 6,090–6,370 kt – Leaves and epicotyls.
X (A-01.11.3), (I-60.24.0) 14,000–15,820 kt – Dirty beets.
X (C-CB-14.12.2), (D-DA-15.83.0) 252–490 kt – Limestone.
X (D-DA-15), (P) 560 kt – Sugar contained in food products sold to the family.
X (D-DA-15.83.0), (1) 1,745–1,785 kt – Air emission from sugar mill.
X (D-DA-15.83.0), (2) 9,800–11,200 kt – Wastewater from sugar mill.
X (D-DA-15.83.0), (A-01.11.3) 358–487 kt – Filter cake sold to sugar beet cultivation. It is assumed 35–40% of total filter cake output.
X (D-DA-15.83.0), (D-DA-15.7) 959–1,253 kt – Molasses (270–390 t/1,000 t of sugar) and dry pulp (550–700 t/1,000 t of sugar) used in animal feedstock. It is assumed that 50% of molasses output is sold to this industrial sector.
X (D-DA-15.83.0), (D-DG-24) 189–273 kt – Molasses (270–390 t/1,000 t of sugar) used by chemical industry. It is assumed that 50% of molasses output is sold to this industrial sector.
X (D-DA-15.83.0), (I-60.24.0) 490 kt – Bulk sugar transported to food industry.
X (D-DA-15.83.0), (K-74.82.1) 910 kt – Bulk sugar to food packaging industry.
X (D-DA-15.83.0), (O-90.02.0) 1,924–4,371 kt – Soil and stone (900–2,600 t/1,000 t of sugar) removed in sugar beet preparation phase. Filter cake (730–870 t/1,000 t of sugar). This is the 60–65% of filter cake not re-used in sugar beet cultivation.
X (D-DD-20.40.0), (K-74.82.1) 11.2 kt–Wood pallets.
X (D-DE-21.21.0), (K-74.82.1) 9.6–10.4 kt – Containers of paper (Kraft) and carton board.
X (D-DF-23.10.1), (D-DA-15.83.0) 12–23 ktoe – Carbon coke (as toe) for lime kiln.
X (D-DF-23.20.1), (A-01.11.3) 47–67 ktoe – Diesel fuel for cultivation equipment.
X (D-DF-23.20.1), (E-40.11.0) 55–60 ktoe – Primary energy (as toe) to manufacture electricity used in sugar industry.
X (D-DF-23.20.1), (I-60.24.0) 20–29 ktoe – Diesel fuel for transport (as toe).
X (D-DG-24.13.0), (D-DA-15.83.0) 1–2 kt – Sulfur dioxide for sugar purification phase.
X (D-DG-24.15.0), (A-01.11.3) 70–144 kt – Nitrogen fertilizer (as N), phosphorous fertilizer (as P_2O_5), potassium fertilizer (as K_2O).
X (D-DG-24.20.0), (A-01.11.3) 0.49–2.38 kt – Herbicides, insecticides, fungicides.
X (D-DH-25.22.0), (K-74.82.1) 0.85–1.65 kt – Polyethylene and polypropylene containers.

Table 9.4 Emission Factors of Electricity (g/kWh)

CO_2	550–580
SO_2	0.2–1.9
Particulate	0.01–0.06
NOx	0.4–0.7
CO	0.07

X (D-DI-26.52.0), (A-01.11.3) 78–83 kt – Lime used by sugar cultivation.
X (E-40.11.0) (1) 357–383 kt–Emissions from power plant related to electricity used in sugar industry based on factors showed in the following table (Table 9.4).
X (E-40.11.0) (2) 85,034–190,037 ktoe – Heat loss and plant cooling water (128–278 L/kWh) realized by power industry.
X (E-40.11.0), (D-DA-15.83.0) 21.3–23.3 ktoe – Electricity (as toe) sold to sugar mill.
X (E-40.11.0), (K-74.82.1) 0.4 ktoe – Electricity (as toe) sold to sugar packaging activities.
X (E-40.21.0), (D-DA-15.83.0) 720–803 ktoe – Natural Gas (as toe) to manufacture water vapor and thermal energy in sugar mill.
X (G-51.2), (A-01.11.3) 0.28–0.42 kt – Seeds of beet.
X (I-60.24.0), (1) 65–92 kt – Atmospheric emissions from transport.
X (I-60.24.0), (D-DA-15.83.0) 14,000–11,520 kt – Dirty sugar beet transported to sugar mill.
X (I-60.24.0), (D-DA-15) 560 kt–Bulk sugar for food industry.
X (K-74.82.1) (P) 1,040 kt – Packaged sugar sold to the family.
X (O-90.02.0), (3) 1,924–4,371 kt – Waste disposal to landfill. We consider landfill on the outside of technosphere.
X (AB), (I-60.24.0) 70 kt – Sugar imports.
X (AB), (K-74.82.1) 130 kt – Sugar imports by food packaging activities.

Chapter 10
Analysing the Economic Impacts of a Material Efficiency Strategy

Carsten Nathani

Introduction

One of the fundamental goals of industrial ecology is to change and reduce material and energy flows related to satisfying the needs of human society, so that volume and quality of these flows can be carried by the natural environment without severe disturbances. Among the many redesign strategies proposed in industrial ecology, the strategy of material efficiency improvement mainly targets bulk material flows and aims at producing and using material goods in a more efficient way. Understood in a wider sense, material efficiency improvement also covers material and product substitution which reduces the environmental burden of material goods. As common in the field of industrial ecology, a life cycle view should be chosen to evaluate the efficiency criterion. Thus a higher material efficiency of an alternative design option should be proven over the complete life cycle of a product.

Understood in such a wide sense, options for improving material efficiency can be differentiated into the following main groups[1]:

- Efficient use of materials and material goods in manufacturing and final use
- Materials substitution
- Recycling and reuse of manufacturing wastes, used products and components
- Design of more durable goods and
- Material efficient product substitution, including intensification of product use like in product service systems (Mont 2003)

A characteristic feature of these material efficiency improvement options is that they induce changes not only within certain processes or enterprises, but in various parts of product life cycles and across different economic sectors. If these strategies are

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[1] See Nathani (2003a, b) for further discussion, Worrel et al. (1995) and Gielen (1999) for overviews of the material efficiency concept.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

realized on a large scale they can lead to major changes of societal material flows and shift the division of labor between the sectors of the economy. The relevance of activities such as resource extraction, energy conversion, primary materials manufacturing or waste disposal would probably be diminished. On the other hand waste collection, sorting and processing as well as secondary materials manufacturing would gain in importance. In manufacturing the focus could be shifted from manufacturing new materials to remanufacturing and reuse of products and parts. The need for redistribution logistics as well as accompanying services would probably increase. Changes would also occur in the supply chains of the directly affected enterprises as well as in the industries supplying capital goods. These changes could also affect foreign trade of a country. On balance the realization of a material efficiency strategy could result in a strong impetus on structural change in the economy and further macroeconomic impacts. Therefore it is important for decision makers discussing these options to be informed about their possible economic impacts on an economy-wide scale.

Answering questions with such a level of complexity requires the use of quantitative models. In the field of industrial ecology several tools have been developed that can be used for systems analysis and design or for the evaluation of the environmental consequences of alternative technical and organizational options (e.g. life cycle assessment, substance flow analysis, and material flow analysis [MFA]). These tools are mainly rooted in natural sciences and engineering. Tools for evaluating or integrating economic indicators have recently been developed, e.g. economically extended MFA (Kytzia et al. 2004), but are still only rarely used (for an overview see Kytzia and Nathani 2004). Besides analyzing the microeconomic aspects of industrial ecology strategies it is also important to turn to the meso- and macroeconomic aspects.

Material flow models are usually restricted to a subsystem of the economy, which they cover in great detail. On the other hand they usually lack integration into the overall economic context. They require exogenous assumptions on future product or materials demand or relevant macroeconomic variables. The consequences of changed material flows on economic sectors outside the particular system boundaries and on the economy as a whole are not taken into account.

The integration into the overall economic context can be realized by a hybrid modeling approach, which links a material flow model with a meso- or macro-level economic model. Such an approach is presented in this chapter.

The existing hybrid approaches can be subdivided into two groups. In the first group, the material flow model is linked sequentially to an economic model (mostly an input-output model). Thus there is no feedback from the material flow model to the economic model. In the second group both models are mutually linked and interdependent.

With regard to the first group of models, several approaches have been proposed, which focus on the economy as a driver of materials consumption. Ayres (1995) presented a methodological approach linking a process-based material flow model with an economic input-output model, in which the activities included in the material flow model (such as resource extraction and basic industry processes) are excluded from the IO model. The latter's role is to generate a demand vector for certain goods to be delivered by the materials subsystem, whereas the manufacturing of these goods and the material flows induced (resource consumption, waste, emissions) are calculated in the material flow model. Similar approaches were presented, e.g. by Konijn et al. (1997) and Duchin and Lange (1998), with an application to plastics consumption and recycling.

Concerning the second group of modeling approaches, linking process chain models to economic models, there have been several applications in the field of energy policy modeling (see, e.g. James et al. (1986) for an early example, Zhang and Folmer (1998) for an overview). Applications to industrial ecology issues are not as widespread yet. Kandelaars (1999) linked a substance flow model with an applied general equilibrium (AGE) model. The aim was to simulate the economic consequences of regulatory levies on substances or products containing particular substances. The information from the substance flow model allows to determine the use of substances and the substance-based levy burdens in the economic sectors. With the AGE model the economic impacts of the levies (e.g. on sector output) are calculated, which in turn allows to determine new values for substance flows. Although this approach mutually links the two models, it represents a weak link in the sense that the respective structural model parameters are still independent.

Approaches with stronger links between structural parameters were presented by Mäenpää (1996) and Nathani (2003b). Mäenpää linked satellite material flow models to an econometric inter-industry model in order to evaluate the economic effects of changes in the sub-sectors. Nathani presented an approach for linking a material flow model with an economic input-output model and discussed in-depth the conceptual aspects of linking these two models. In the following the latter modeling system is presented in more detail.

The methodological framework of linking a material flow model with a dynamic input-output model is presented below. For the purpose of illustration, Empirical Application contains the application of this approach to the case of the paper cycle in Germany. Finally the benefits and limitations of the proposed approach are discussed and an outlook to further research is presented in the concluding section.

The Modeling Framework

In the following sections input-output and material flow models are introduced briefly before the linkage method is presented. The introduction is restricted to aspects necessary for understanding the model linkage. For further information the reader is referred to the respective handbook chapters.

Input-Output Models

Among macroeconomic models used for empirical research, input-output models have the highest level of sectoral detail and are thus especially useful for linking with a detailed material flow model. They are based on input-output tables, which disaggregate the (national or regional) economy into a number of economic sectors and describe the flows of goods between these sectors. The inputs and outputs of each sector are recorded in monetary units. The rows of the table display the outputs of each producing sector to other producing sectors and to the sectors of final demand (e.g. households, investment or export). The columns display the inputs of each producing sector, which are either intermediate inputs from producing sectors or primary inputs such as labor, capital depreciation or profits.

Several kinds of input-output models have been designed for different economic questions (see Miller and Blair [1985] for a good overview). This variety of models can be grouped into:

- Open and (partly) closed models
- Quantity and price models and
- Static and dynamic models

The linkage method described in this chapter makes use of two types of models: a dynamic input-output quantity model and a static price model.

Dynamic quantity models also exist in various specifications. In the following the dynamic input-output model MIS (Macroeconomic Information System IKARUS), which was used for the empirical application, is presented briefly. It has been developed as a macroeconomic driver for the German energy flow optimization model IKARUS (Pfaffenberger and Kemfert 1997). MIS is used for projecting future input-output tables of the German economy. In the model version used for the empirical application the base year is 1995 and the projection years 2005 and 2020. Production activities are aggregated to 27 sectors. The final demand sectors include private consumption, government consumption, investments and exports. Except for investment, final demand is projected exogenously. Since investments are calculated endogenously the basic equation for calculating output differs from the standard static IO model.

Sectoral output in the period t_1 is calculated as:

$$x(t_1) = (I - A(t_1))^{-1}(y(t_1) + v(t_1)) \tag{10.1}$$

with $x(t_1)$: vector of sectoral outputs in period t_1

I: identity matrix

$A(t_1)$: matrix of input coefficients in period t_1

$y(t_1)$: vector of exogenous final demand (excluding investment) in period t_1

$v(t_1)$: vector of investment in period t_1 = depreciation + net investment

For the endogenous calculation of investment the sectoral capital stock is integrated into the model. The increase of capital stock is tied to the increase of value added by sectoral capital coefficients.

Model calculations of output $x(t_1)$ in period t_1 are run iteratively, starting with preliminary values for investment. From the output values sectoral value added and the required capital stock are derived. Capital coefficients remain exogenous, but can change in time. Net investment is calculated with the assumption of linear growth of capital stock between the two time periods t_0 and t_1. Investment for capital

Table 10.1 Scheme of a Material Flow Table

Inputs	Outputs	Economic System				Natural system	
		Processes and activities within system boundaries	Exogenous use				
Economic system	Process products	Material and energy flows within system boundaries Other inputs from processes within the economic system	Intermediate use	Final use	Total product output	– Air emissions – Water emissions – Solid wastes – Excess heat	Total material output
Natural system		Material inputs from the natural system – Soil – Water – Air					
		Total material inputs					

replacement is derived from capital depreciation. With the new calculated values for investment, a new calculation of $x(t_1)$ is started. The iterative calculation procedure stops when the deviation of results between two calculations is sufficiently small.

In the model MIS energy efficient technological change is integrated through factors for autonomous energy efficiency improvement and price dependencies of the energy input coefficients in the transaction matrix as well as through links with technology-based submodels.

The static open price model of input-output analysis is used to calculate the effects of primary input value changes on sectoral prices (Miller and Blair 1985). It is based on the identity that the price of a good is equal to the costs of the necessary intermediate goods plus the primary input values. Price effects can be calculated by assuming that cost changes are completely passed on as price changes and that demand functions are perfectly inelastic. Since in most cases these assumptions are not very realistic, the calculated price effects have to be understood as crude estimations.

Material Flow Models

Material flow (MF) analysis[2] can be seen as the analysis of a system of processes and activities interconnected by material and energy flows within defined system boundaries. The choice of the system and the definition of system boundaries depend on the objective of the analysis.[3] In the context of this research work the aim is:

- To analyze the upstream and downstream material and energy flows connected to a selected product or product group
- To study the effects of production alternatives or different concepts of delivering a product service on material and energy flows in a consistent manner, i.e. by including all the relevant interactions

Therefore in a cradle-to-grave approach the analyzed system covers all important processes including extraction of resources, various manufacturing steps for turning the resource inputs into final products, product use, waste disposal and recycling. In principal all processes and materials relevant to the objective of the analysis should be covered. Alternative production and disposal routes, including those that might be realized in the future, should be included too. Often time restrictions and data limitations will pose a limit on the complexity of the analyzed system. Therefore the transparent definition of system boundaries is of great importance. Furthermore if the analysis of material flows is restricted to a certain region, appropriate regional boundaries have to be defined.

[2] The term material is used with a very broad meaning covering resource inputs, goods of different processing stages as well as wastes and emissions. To improve readability the term material flows is also used when material and energy flows are meant.

[3] For an overview of methods and applications see, e.g. Bringezu et al. (1997), ***cross reference to chapter on industrial ecology***.

Material flow models can be constructed as simulation or optimization models, as static or dynamic models. Here we will look at a static simulation model, since in the hybrid model system the dynamics will be provided by the input-output model. A simulation model was chosen so that soft factors such as institutional and regulatory developments or changes of consumer behavior could be taken into account.

In a material flow model each process or activity[4] is characterized by its inputs, outputs and a transfer function, which links inputs and outputs and can be linear or non-linear. In case of linear transfer functions the transfer coefficients, which are calculated for each input as input divided by total output, become important model parameters. Technical change of a process, e.g. improved energy efficiency or increased use of recycled materials can be described through changes of the transfer coefficients.

For the purpose of linking the material flow model with an input-output model it is convenient to represent the material flows of a time period in an input-output table. Following Baccini and Bader (1996) the table columns contain the process inputs and the rows show the process outputs. The table consists of three sub-matrices with the central transformation matrix containing material flows between the processes included in the system, a matrix on the right of the central matrix containing flows leaving the system boundaries and a matrix below the central matrix containing the input flows into the system. This description of a material flow system also bears similarities with the economic–ecologic models of Victor (1972) or Isard et al. (1968) as described in Miller and Blair (1985) and formulations of a physical input-output table (e.g. Stahmer et al. 1998).

Regarding the linkage with an input-output model the structure of the material flow table can be differentiated as follows (see Table 10.1):

- Processes are assumed to have one specific product or homogenous group of products as main output. In case of co-production it is assumed that a process can be split with an appropriate allocation of inputs and outputs. The aggregation level of processes or activities can be freely chosen according to the aim and aggregation level of the analysis.
- Process inputs are further subdivided into
  - Inputs from other processes within the system boundaries
  - Inputs from processes outside system boundaries, but within the economic system and
  - Non processed inputs from the natural system, e.g. natural resource inputs
- The following outputs are distinguished:
  - Outputs to processes within system boundaries
  - Outputs to economic sectors outside system boundaries (exogenous use), which should correspond as far as possible with the sectoral classification of the input-output table. These outputs can be further classified as outputs

[4] These two terms are used as synonyms in the following text.

for use in sectors of intermediate and of final demand (including exports, but excluding consumption processes within system boundaries)
– Outputs to the natural system, esp. air and water emissions, solid wastes or excess heat

For each process as well as the system as a whole the mass balance principle applies, which states that total material input must equal total material output plus net stock change. Even though in practice it often proves difficult to collect all input and output data because of data restrictions, this principle can still be used as a consistency criterion and for the estimation of missing data.[5] This description of a material flow table is incomplete as it only considers material and energy flows, but no stocks. This poses a drawback especially for investment and consumption of durable goods, where after a certain lifetime these goods will enter the material system again as waste.

The Hybrid Model

In this section the hybrid model, which links a dynamic IO model with a static material flow model, is presented. First some conceptual aspects of model linkage and the steps necessary for linking the two models are highlighted. Finally the use of the linked model system is described.[6]

Linking an IO Model with a Material Flow Model

The basic idea of the approach presented in the following is to create a mutually linked modeling system consisting of a dynamic input-output model and a static bottom-up material flow model, which is set up as a satellite model to the IO model. The latter covers in detail a subsystem of the economy (e.g. the iron/steel or the paper cycle) as a network of connected processes. The models are connected by soft links in order to account for their conceptual and structural differences. The dynamics of the modeling system is provided by the input-output model, which supplies exogenous demand information for future projection periods to the material flow model. In the latter several scenarios for meeting this demand can be simulated (e.g. a business-as-usual scenario and one or several material efficiency improvement scenarios), integrating assumptions about technological development, behavioral patterns or regulatory measures. The results show the new material flows in the subsystem for these scenarios. In order to calculate the economic impacts

[5] In this description of a material flow system it is possible that a row comprises values in different units. Since the table is not used for calculation, but only for the link to the IO model, this does not pose a problem.

[6] This section focuses on the main aspects. For details, e.g. equations, see Nathani (2003b).

on sectors outside the subsystem, the simulation results of the material flow model are fed back to the input output model and lead to the adjustment of selected variables and parameters, which reflects the changes in the subsystem. For each scenario the adjusted IO model is run. The structural and other economic effects related to the material efficiency strategies are indicated by comparing the different scenario results.

The modeling concept includes a mutual link between the two interdependent models. Accordingly two interfaces need to be defined. From the perspective of the material flow model the input interface contains the variables and parameters which for future projection periods are influenced by values of the IO model (e.g. exogenous demand for the ‘core’ products or materials driving the considered material flow system). The output interface contains variables and parameters of the material flow model which influence their associated values in the IO model. The data flow is established for each time period, for which the IO model generates an IO table (1995, 2005, 2020 in the model version used). The feedback of the material flow model results to the IO model technically is done as follows. The IO model MIS generates IO tables for each considered time period. Since the material flow model only partly covers the sectoral transactions in the IO model, the values of these tables are partly adjusted on the basis of the material flow model simulation results, and partly left unchanged. The models are calibrated for the base year 1995 to determine for each value of the IO table, to which share it is not influenced by the results of the material flow model and thus left unchanged in the projection.

For the calibration of the models as well as for the feedback of MF model results to the IO model certain conceptual differences between the two models have to be taken into account:

- First, the accounting units are different. The material flow model is set up in physical units, whereas the IO model transactions are recorded in monetary units.
- An important difference concerns the activity concepts. Whereas a MF model can cover production, consumption and waste management processes alike, the latter two are only partly considered in the IO model. In a material flow model any technically or otherwise definable unit process can be represented separately. By contrast an IO model usually is restricted to production processes with market(-able) outputs, which are recorded in the underlying statistical sources. Therefore production processes included in a material flow model are not necessarily part of a producing sector in an IO model (e.g. recycled pulp as an input for recycled paper manufacturing). These aspects are important for associating processes in the material flow model with economic sectors in the IO model.
- Another aspect of model compatibility concerns the description of activities, which differs too. In both models activities are described with their respective inputs and outputs, though on different levels of aggregation. In material flow models process inputs and outputs are recorded in physical units. An important requirement is to fulfill the material balance condition. Thus in most cases the range of inputs and outputs included is restricted to material and energy inputs, whereas service inputs are usually excluded (with the possible exception of transport services). In an input-output model the sectoral inputs and outputs are

recorded in monetary units. Here it is necessary that a similar 'monetary balance principle' is followed, which requires the sum of inputs and outputs in monetary units to be equal. Compared to a material flow model, the scope of inputs and outputs is wider since also services are included. It is narrower since only goods with a market value are considered.

- Furthermore in the input-output model MIS the capital requirements of each sector are also recorded. This is also outside the scope of the material flow model.

These conceptual differences make several steps necessary in order to transform the results of the material flow model and make them compatible with the IO model concept.

In a first step the material flows recorded in physical values need to be converted into monetary values. This requires multiplying the physical values with base year prices. Depending on the material and the underlying activity these prices can be positive (in the case of traded/marketed process outputs), zero (in the case of consumption activities or non-priced materials e.g. material outputs to the ecosphere) or negative (in the case of most waste materials delivered to waste management). Waste outputs with a negative value are reallocated as inputs to waste management services (with a positive value). The result of these calculations is a material flow table in monetary values. It still may contain rows and columns belonging to activities yielding non-marketable outputs, which have no equivalent in the IO table. Therefore the inputs and outputs of these processes have to be reallocated to processes with market outputs in an appropriate way (e.g. inputs and outputs of recycled pulp processing to paper manufacturing). Finally inputs, which have not been considered in the material flow model (e.g. services), value added components and capital requirements need to be added for each market oriented process. The resulting extended monetary material flow table – including an additional row with the capital requirements of processes – is shown in Table 10.2. Finally this table is transformed into a table with the – usually more aggregated – sectoral classification of the IO model. The transformation steps mentioned above can be performed by a series of matrix operations which are described in detail in Nathani (2003b).

Table 10.2 Scheme of an Extended Monetary Material Flow Table

	Production	Use	Waste management	External demand	Exports	Natural system outputs
Production	x	x	0	x	x	0
Use	0	0	0	0	0	0
Waste management	x	x	x	x	x	0
External inputs	x	x	x			
Other economic inputs	x		x			
Value added	x	0	x		0	
Primary natural system inputs	0	0	0			
Similar imports	x	0	x			
Capital requirements	x	0	x			

Calculation Steps with the Linked Modeling System

The aim of the model is to determine the economic impacts of a material efficiency strategy (or more generally of changed material flows) in a subsystem of the economy. In most cases this will make a comparison necessary between a reference scenario and one or several 'material efficiency' scenarios. For each scenario the calculation with the linked modeling system consists of the following major steps:

- A first run with the isolated, i.e. unlinked input-output model
- Determining the exogenous demand for the material flow model
- Simulations with the material flow model
- A feedback of the simulation results to the IO model by adjusting selected IO model variables and parameters and finally
- A new run with the adjusted IO model

These steps are presented in more detail in the following (see also Fig. 10.1).[7]

1. A first calculation with the unlinked IO model for the projection year is started. In the case of MIS the main exogenous inputs, which have to be specified, include growth rates of exogenous final demand by supply sector (excluding investment) between the base year and the projection year, import shares for each of the sector outputs in the projection year, the capital coefficients and the composition of sectoral capital stocks by supply sector.
2. Based on this calculation, the values of the IO variables controlling the input interface variables are used for deriving exogenous demand as an input to the material flow model. Since the IO data is usually more aggregated than the MF data, further specific information or assumptions (e.g. regarding product mix or efficiency of materials consumption) should be used to determine the exogenous demand. For the conversion of IO monetary units into physical units constant base year prices at the product level are used.
3. Exogenous demand is taken as a starting point for simulation runs with the material flow model. Scenario assumptions regarding technology diffusion, development of consumer behavior, product-mix, environmental regulation and adoption of various material efficiency strategies and their effects on the material and energy flows in the system can be consistently simulated in the framework of the material flow model.
4. After the model simulations a new material flow table for the projection year is available for each scenario. This is transformed into a new extended monetary MF table and aggregated to the IO sector classification for feedback to the IO model.
5. The IO table of the projection year is adjusted on the basis of the MF model results. Each IO value at least partly associated with the MF model output interface is calculated as a sum of two components. The part not covered remains

[7] For further details, e.g. equations see Nathani (2003b).

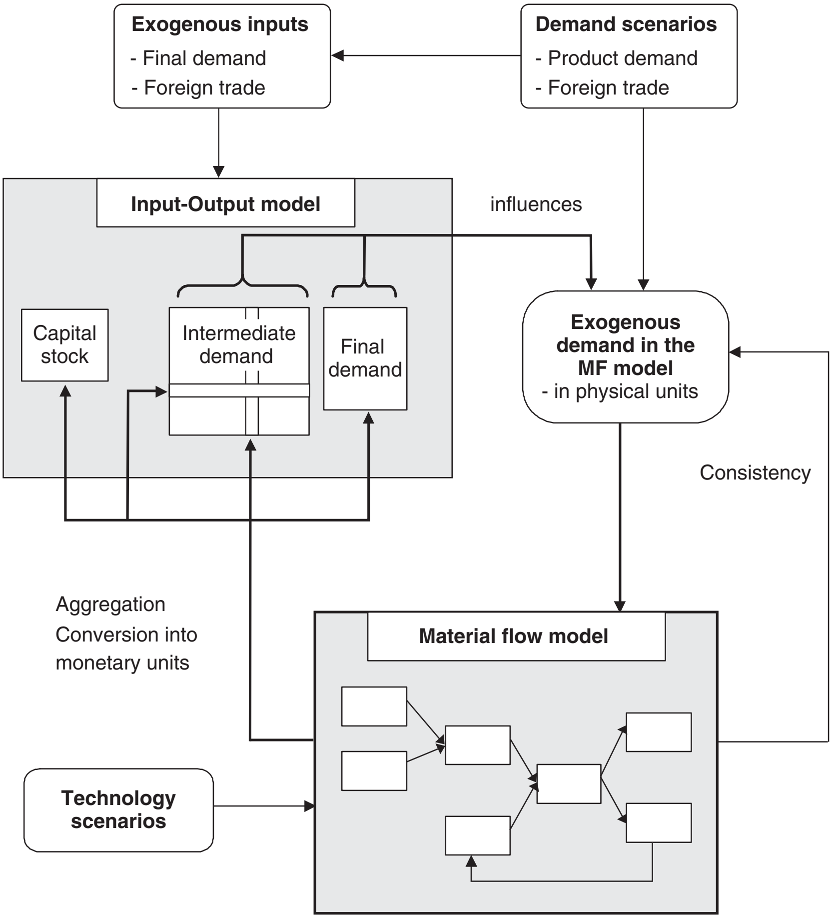

Fig. 10.1 Scheme of the Hybrid Model Link

unchanged, the covered part is replaced by the sum of the projected monetary values of the associated MF variables. Further adjustments reflecting sectoral shifts might be necessary in the IO model.

6. After adjustment the IO model is run again. The new results can influence the values of the input interface variables and thus the exogenous demand in the material flow model. This feedback effect has to be solved by iterative runs of the two models until changes of input interface values are smaller than a chosen threshold value.
7. The economic impacts (esp. on sectoral structure) of a material efficiency strategy are indicated by the differences between the results of the reference scenario and any other material efficiency scenario. Other aspects (e.g. employment) can also be taken into account in such an analysis by integrating the respective sectoral indicators.

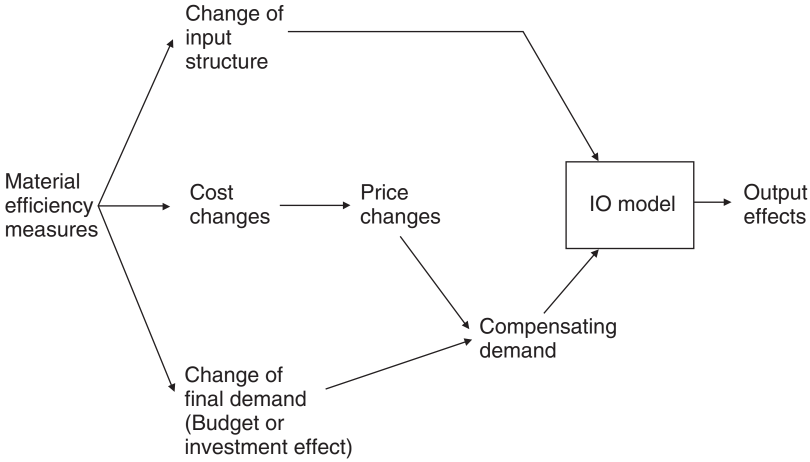

Fig. 10.2 Procedure for Estimating the Economic Effects of Material Efficiency Measures

Altogether the considered material efficiency measures can trigger four kinds of effects, which have to be captured in the input-output model (Fig. 10.2):

- Changes of input structure (first order structural effect)
- Changes of overall costs for the producing sectors
- Change of final demand expenditures, which can be termed as budget effects and
- Change of sectoral capital stock, which affects investment and thus final demand

These changes lead to further economic reactions, which can only partly be analyzed endogenously in an input-output framework. Especially cost changes and changes in final demand budget can have a variety of economic consequences, depending on market conditions, price elasticities, consumption priorities, etc. In this modeling framework they are estimated with subsequent simulations, after calculating the first order structural effects. Concerning the cost changes of the producing sectors, it is assumed that these generally are passed on as price changes throughout the economy, ultimately leading to price changes for final demand. This results in a changed purchasing power of the final demand sectors, which is assumed to lead to additional or less expenditures in these sectors. The price changes are calculated with the open static price model. Changed final demand expenditures are also assumed to result from budget or investment effects.

Regarding the commodities to which these compensating expenditures are directed, two different 'compensation' cases are distinguished to capture the spectrum of possible reactions. If we for example assume decreasing prices, then in the first case (named 'price driven compensation') savings from decreasing prices of a commodity are directed to the same commodity, implying a price elasticity of demand of approximately minus one. In the second case (named 'demand structure compensation') it is assumed that additional demand follows the average final demand structure of the particular projection year. With regard to price or budget effects in foreign countries and their possible flowback to the domestic economy these two cases also contain different assumptions, with the second case leading to a lower boundary for compensating demand. Thus the two cases differ regarding both extent as well as structure of compensating demand.

For the calculation of the cost and budget effects the additional demand estimated for the two compensation cases is added to final demand. Then a new calculation with the adjusted IO model provides the connected output effects.

Empirical Application

The empirical application of the linkage concept is presented with a case study of the German paper cycle as an energy and resource intensive material system. Paper is a material which still shows high growth rates. In Germany paper consumption in the last 30 years has grown stronger than the GDP. Even though paper recycling has reached a relatively high level, there still is a large potential for further improving material efficiency in the paper cycle. In order to analyze the economic effects of realizing these potentials, a material flow model of the paper cycle in Germany was set up with 1995 as base year. Projection years for calculations with the linked model system were 2005 and 2020.

Set Up of the Linked Model

Figure 10.3 contains a rough sketch of the paper cycle covering processes from forestry and industrial wood supply to production of pulp, of paper and paper products, consumption of paper products to their disposal resp. collection and processing of waste paper to recycled pulp. The implemented model has a higher level of detail. Six different paper grades and their flows to ten processes for use or further processing are differentiated, since the respective material efficiency improvement options and their realization potentials differ strongly. Stocks of long-living paper products have not been considered in the model due to their low relevance (7% of total paper consumption in 1995).

For each process the main inputs and outputs were included. Beside the main wood-based materials these are energy inputs, auxiliaries like process chemicals, fillers and pigments and transport services. Because of time restrictions and data limitations the scope of coverage had to be restricted. Special attention was paid to the processes of the paper industry since these dominate environmental pressure from the paper cycle. Since the main focus was placed on resource and energy use, the water use and water emission side was not included. Wastes were considered in so far as they can be used for recycling within the system or for energy recovery. Similar to the input-output model the analyzed system covers material and energy

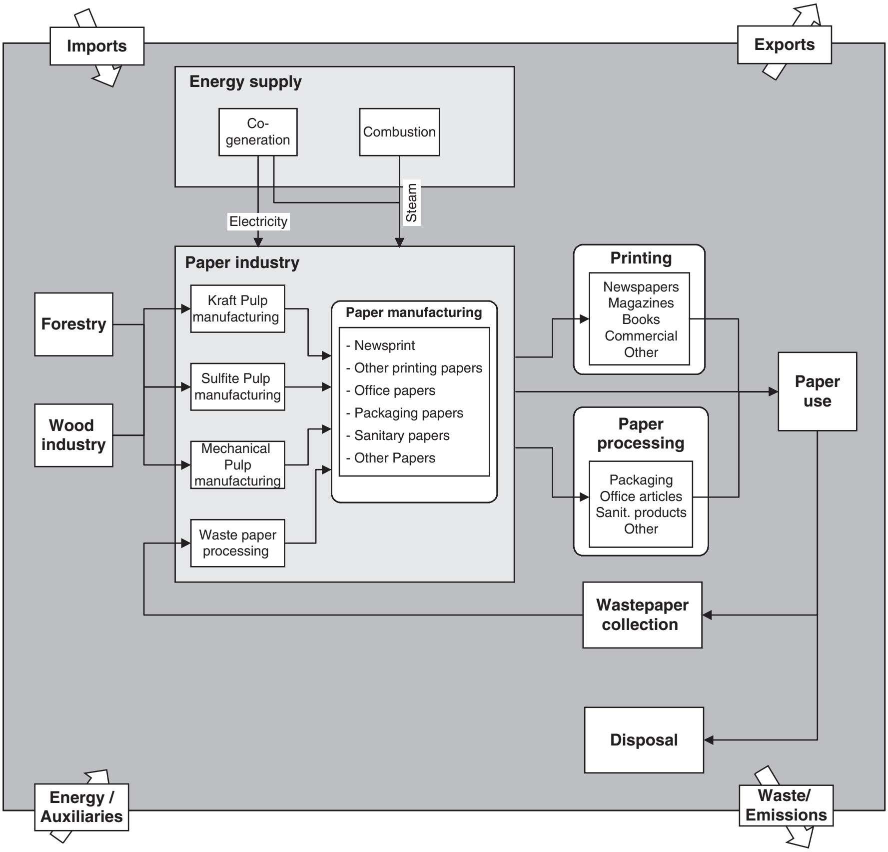

Fig. 10.3 Overview of the Paper Cycle as Represented in the Material Flow Model

flows within the national boundaries of Germany. However, on a product level imports and exports were taken into account.

The material flow model was implemented with the software ‘Umberto’, a professional software developed for material flow analysis (see Schmidt and Schorb (1995) for further information).

The main data sources for production, foreign trade, consumption and waste paper collection were official and industry statistics. Specific data concerning process inputs and outputs ware based on technology-specific data sources like process descriptions, life cycle inventories, material flow analyses of the paper chain or interviews with paper technology experts. Price information was mainly derived from production and foreign trade statistics, which record both mass and monetary units, and industry sources. In some cases export or import prices were used as estimates for domestic prices. In a last step monetary product values were calculated and aggregated to the IO sector level and finally harmonized with the corresponding values of the base year IO table.

In order to link the material flow model with the input-output model the following steps described in the Modeling Framework Section were carried out:

- Setting up a material flow table for the base year.
- Creating a price matrix and a monetary material flow table. The process inputs not covered in the material flow model (e.g. services; value added) were allocated according to the average ratio of the corresponding IO sector. The processes' capital stock data was estimated by using literature data.
- Defining the input and output interfaces. The six paper grades were chosen as core products and their domestic consumption as the characteristic demand driving the material flow system.
- Calibrating the models for the base year.

Table 10.3 contains an overview of the IO sectors partly or completely covered by the material flow model. The main focus lies on the inputs and outputs of the paper industry. In total, 80% of the intermediate inputs into paper industry in monetary terms are covered by the material flow model. The electricity and heat sector is covered partly, with regard to electricity and steam production in the paper industry. Waste paper collection as part of the service sector is also included. Paper products are not used to directly adjust IO data but only in the context of the material flow model.

Scenarios of the Future Development of the Paper Cycle in Germany

Several strategies for reducing environmental impacts from activities in the paper cycle were considered. Apart from pure material efficiency measures, options for improving energy efficiency were also taken into account in order to calculate the energy saving potential of a material efficiency strategy. The considered measures are:

- Increasing waste paper recycling and use of recycled pulp in paper manufacturing
- Increasing the efficiency of paper use in the areas of packaging design, office and home uses
- Reducing specific paper weight in selected paper products, e.g. printing paper
- Realizing potentials of information and communication technology (ICT) for substituting paper products, e.g. e-mail, dissemination of information via internet, CD-ROMs, etc.
- Improving energy efficiency of pulp and paper manufacturing and
- Improving energy supply in the paper industry by expanding use of combined heat and power plants and by substitution of energy carriers

Regarding the development of the paper cycle to the year 2020, one business-as-usual (BAU) scenario and two material efficiency scenarios were generated, reflecting different combinations of the above mentioned measures and different levels

Table 10.3 Overview of the IO Values Covered by the Material Flow Model

to From	Electricity/heat	Paper industry	Paper process	Printing sector	Waste-paper trade	Other intermed. demand	Final demand
Agriculture/forestry		(x)					
Electricity/heat	(x)	x					
Colar sector	(x)						
Natural gas supply	(x)	x					
Chemical industry		(x)					
Refineries	(x)	x					
Nonmetallic minerals		x					
Paper industry	x	x	x	x		x	x
Other industry		(x)					
Waste paper trade		x					x
Services		(x)					(x)
Transport		(x)					
Gross value added	(x)	x			x		
Similar imports		x			x		
Gross output	(x)	x			x		

x: IO value completely covered by MF model.
(x): IO value partly covered by MF model.

of realization. This chapter will focus on the BAU scenario and the second, more ambitious material efficiency scenario.

Furthermore for the unlinked model run a baseline scenario was defined, specifying assumptions for the exogenous variables of the IO model such as the development of exogenous final demand (excluding investment) as well as of foreign trade. For the projection of final demand for wood pulp, paper and paper products micro-level information such as existing projections or market research analyses was used. Technological change resulting in a changed input matrix was not considered. The possibilities of MIS to consider autonomous and price-induced change of energy input coefficients were inactivated just as in all other scenario calculations in order to isolate the effects of the analyzed material efficiency improvement measures.

The business-as-usual (BAU) scenario accounts for developments, which are likely to happen without any further political interventions. Assumptions were made regarding process improvement and diffusion of new technologies, changes of product-mix, trends in energy demand and energy supply and the level of paper recycling. The output level of the paper industry as a whole was taken from the baseline calculation and cross-checked with specific projections by paper industry experts, which also provided the breakdown by paper grade in the future periods. The effects of these changes on the paper cycle were simulated with the material flow model. The BAU case thus was the first case calculated by linking the IO model and the material flow model.

The scenario "sustainable paper cycle (SPC)" assumes a high realization of material efficiency potential. This involves all measures described above, for which improvement ratios were assumed, based on existing bottom-up information (for further details see Nathani [2003a]). In comparison with the BAU scenario, these measures altogether lead to a decline of paper consumption by approximately 20% in 2020, depending on the respective paper grades. The basis for this estimation were several studies analyzing possibilities for reducing paper consumption and the potential of IC technologies for substituting paper products (Abramowitz and Mattoon 1999; BCG 1999; Hekkert et al. 2002; Hoppe and Baumgarten 1997; IIED 1995; Obersteiner and Nilsson 2000; Robins and Roberts 1996; Romm 1999). Yet the estimation is subject to rather high uncertainties. It was further assumed that similar reductions would be realized in other industrialized countries.

As a result of the baseline scenario assumptions MIS calculated a growth rate for German GDP of 2.0% p.a. between 1995 and 2005 and 1.8% p.a. between 2005 and 2020. The aggregated exogenous demand for paper is assumed to grow in line with GDP, though with different growth rates for the different paper grades. Import quotas on the product level were assumed to remain constant throughout the projection period.

Figure 10.4 shows the development of paper production and consumption in Germany in the business-as-usual scenario and in the scenario "sustainable paper cycle". In the BAU case paper consumption increases from 18 million tons in 2000 to 25 million tons in 2020. In the SPC-scenario consumption lies approximately 20% below that value at around 20 million tons. Since production is assumed to increase faster than consumption, in both scenarios Germany would turn from a net importer of paper to a net exporter between 2005 and 2010.

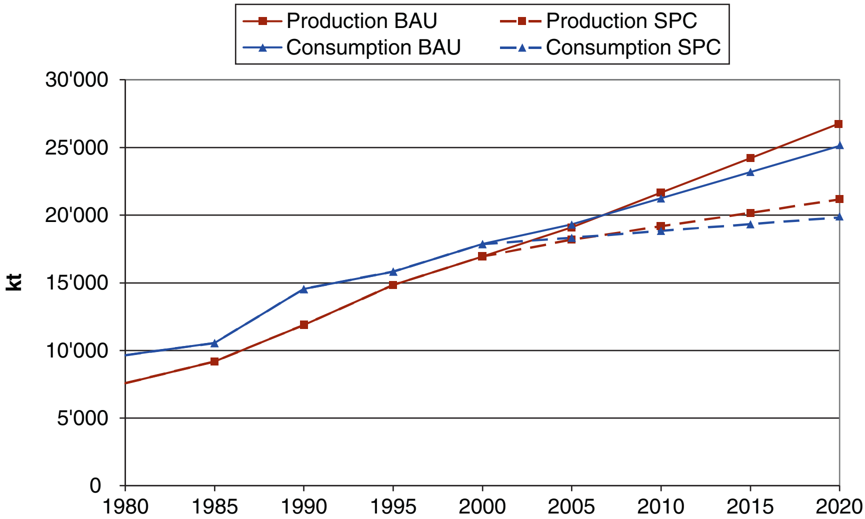

Fig. 10.4 Development of Paper Production and Consumption in Germany Between 1980 and 2020 (VdP, 2001; own assumptions)

Results of the Model Calculations

The discussion of the simulation results will concentrate on the differences between the BAU and the SPC projection for the year 2020. For each scenario the results can be subdivided into three parts:

- The results of the simulation with the material flow model, confined to the subsystem of the paper cycle
- The adjustment of the affected variables and parameters of the IO model and
- The final results of the calculations with the IO model

Regarding the first part, the results shall be only summarized briefly. The scenario assumptions lead to various changes of material and energy flows in the paper cycle. They affect the output and mix of paper grades, fiber and other input demand for paper production, energy consumption and transport service demand, waste paper collection and waste management. By assumption the demand for paper products is also reduced significantly. The results show that a stagnation or slight reduction of resource and energy use in the paper cycle can only be achieved if growth of paper consumption can be restricted to the level of the SPC scenario.

These results directly affect three sectors in the IO model, the paper industry, the electricity sector and the services sector, which comprises waste paper collection and trade. The latter two sectors experience minor changes. With regard to the paper industry domestic output and thus supplies to the other sectors of the economy are considerably lower in the SPC scenario. Monetary output declines from about €21.3 billion in the BAU scenario to €16.9 billion in the SPC scenario. Imports of

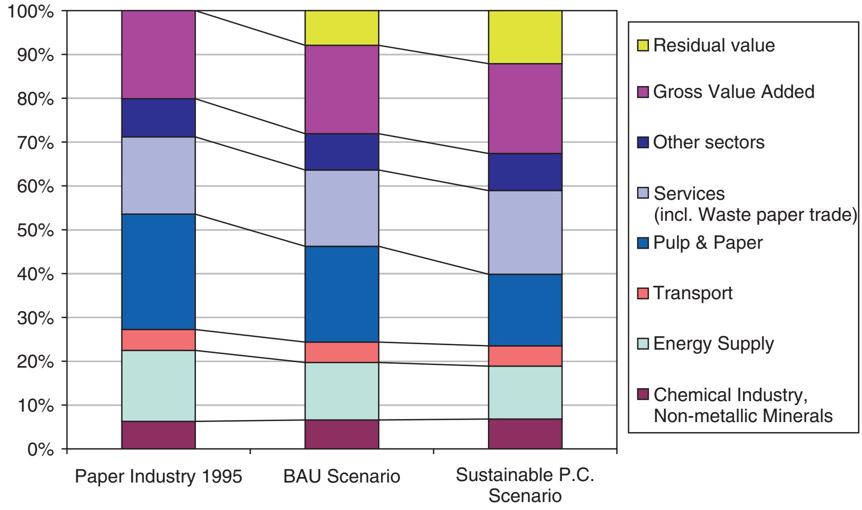

Fig. 10.5 Input Structure of the Paper Industry in 2020 Compared to 1995

pulp and paper also decrease from €12.7 to €9.1 billion. The input structure of the paper industry also changes considerably, reflecting lower energy consumption and slightly lower transport services demand and especially the shift from wood and imported kraft pulp to waste paper (Fig. 10.5). The latter shift can be seen as a decrease of pulp inputs and an increase of service inputs (waste paper collection). Since the use of waste paper is cheaper, the overall costs of the paper industry decrease. Compared to the baseline scenario, in the SPC scenario specific manufacturing costs are approximately 12% lower. The gap between output and inputs is depicted as "residual value" in Fig. 10.5. To a certain extent this can be interpreted as cost savings, although the cost structure for the two scenarios are not completely comparable, since product mix and quality are different. Paper with a higher content of recycled pulp has a different quality than paper with a higher content of fresh pulp.

The reduced consumption of paper and paper products as well as the increasing demand for ICT products and services have various consequences for other sectors, which are directly implemented in the adapted IO model (see Table 10.4). The outputs of the paper processing and especially the printing sector decrease. This decrease is translated into a decreasing supply of these sectors to the other sectors of the economy. The declining demand for printing products is assumed to be offset by an increasing demand for ICT products and especially ICT and media services. Because of lacking data it was not possible to perform an in-depth analysis regarding cost and details of this substitution process and the resulting new demand. Based on the idea, that in order to be accepted by the customers, the new products and services would have to be cost-competitive with paper products, it was assumed that their total costs equal the total costs of the substituted paper products including transport and retail margins. On balance the material efficiency strategy leads to substantial cost reductions for the producing sectors and the households and to reduced exports.

Table 10.4 Change of Supplies to Intermediate Demand (Without Paper Industry) and to Exogenous Final Demand Sectors (Difference Between SPC and BAU Scenario)

Supplying sector	Intermediate demand (w/o paper industry) (Mio. €)	Households (Mio. €)	Exports (Mio. €)
Paper industry	−1,950	−69	−2,593
Paper processing	−635	−341	−399
Printing sector	−11,325	−52	−535
Transport sectors	−479	−368	
Wholesale (services)	−412		−464
Other sectors	−100	343	
(ICT) services	12,079		
Cost balance	−2,822		
Final demand balance		−487	−3,992

The impact on capital stock and thus on investments are negligible. The cost savings lead to price reductions, which are fully compensated by additional demand, just as are the savings in households. The reduced exports are only partly compensated, depending on the compensation case. In the case ‘price driven compensation’ a higher share of export decline is compensated by additional demand than in the case “demand structure compensation”.

Regarding the results of the calculations with the adjusted IO-model, these are depicted as differences between the “sustainable paper cycle” scenario and the business-as-usual scenario in order to highlight the economic effects of the material efficiency measures taken additionally in the SPC scenario.

Figure 10.6 shows the impact on sectoral output resp. imports without considering the compensation mechanisms (first order structural effect). Domestic output of the printing sector and the paper industry as well as pulp and paper imports decrease considerably. On the other hand the services sector, including the ICT services, is the only gaining sector. The other sectors are also affected negatively. Overall domestic output decreases by nearly €13 billion, whereas imports decrease by about €5 billion.

The compensation mechanisms partly offset the overall negative output effects (domestic output and imports, see Fig. 10.7). Yet, in both compensation cases the paper oriented sectors stay negatively affected, though less in the second case. A multitude of sectors gains from a higher final demand, especially the service sectors.

Despite compensation the total impact is still surprisingly negative, with a loss of output between €6.5 and €11 billion. Domestic output decreases between approximately €3.5 and €7 billion, whereas imports are reduced by between €3.5 and €4.3 billion.

This negative overall effect is due to the situation of Germany as a net exporter of paper in 2020. One important scenario assumption was that a material efficiency strategy would also be followed in the other industrialized countries. Since this

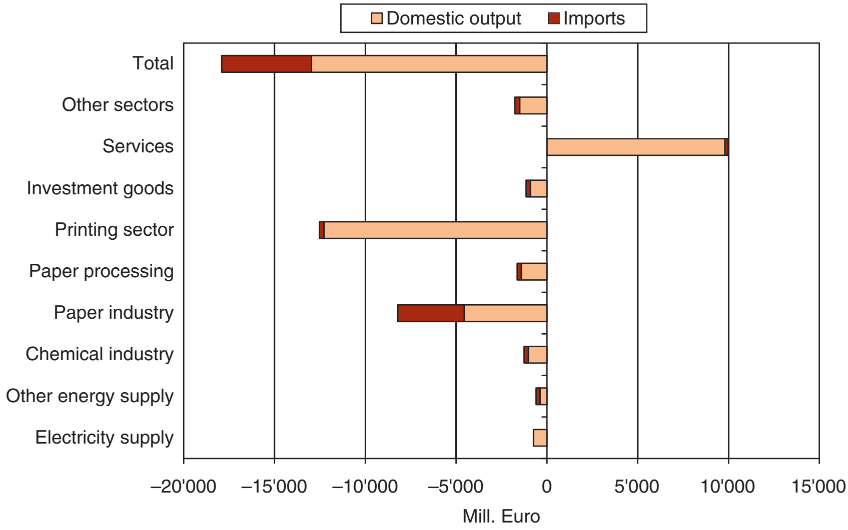

Fig. 10.6 Change of Domestic Output and Imports in the SPC Scenario in 2020

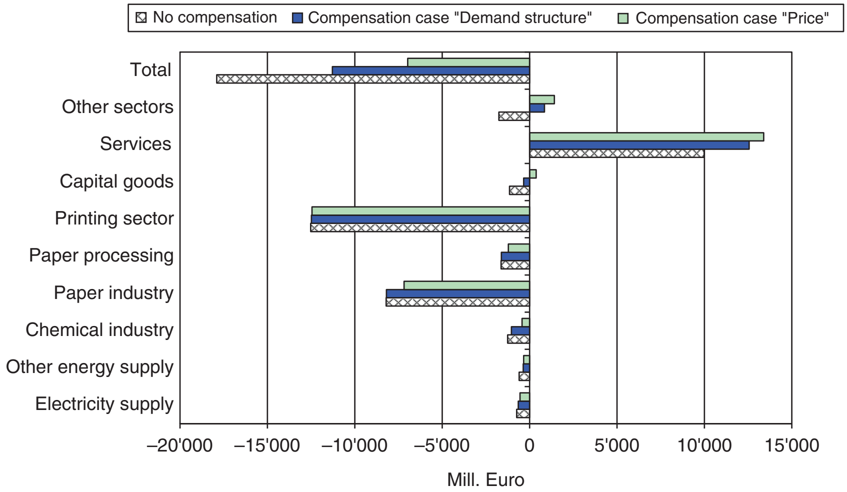

Fig. 10.7 Output Effects in the SPC Scenario in 2020 Including Compensating Effects

strategy on balance causes a shift from paper based products to services, which are assumed to be mainly provided by domestic suppliers, the German economy loses with its net paper exports, whereas the compensation for this decline mainly takes place in the foreign countries. This results in an overall negative output effect for the German economy.

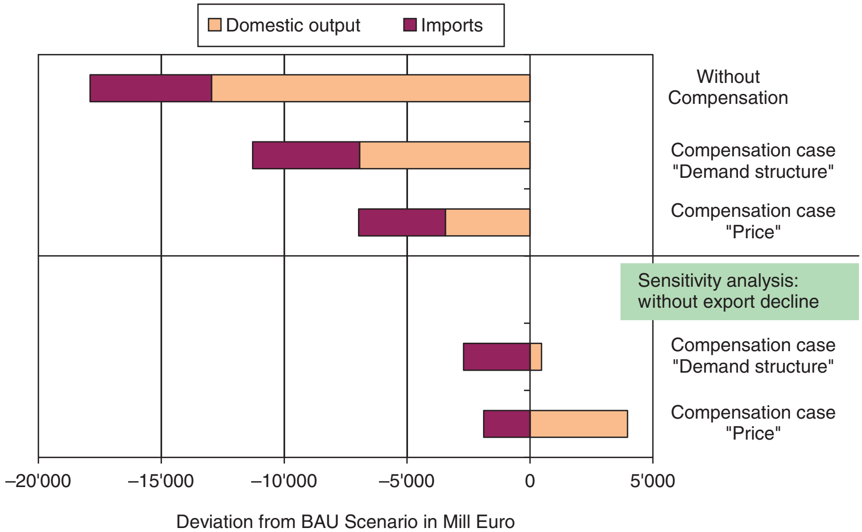

Fig. 10.8 Output Effects in a Sensitivity Analysis Assuming Unchanged Exports of Paper Based Products

This effect can be clarified by a sensitivity analysis, in which the exports of the three paper based sectors remain unchanged at the level of the business-as-usual scenario. In this case final demand in 2020 would increase by about €3.5 billion. The total output effect would lie between a decrease by €2.2 billion and an increase by €2 billion, compared to the BAU scenario and depending on the compensation case. Yet in both cases domestic output increases, whereas only the imports are negatively affected (Fig. 10.8).

A similar analysis was performed for employment, assuming a linear relationship between sectoral output and employment, though with higher sectoral labor productivities in 2020. The results show a significant job loss of about 44,000 employees as the first order structural effect, whereas compensation results in a minor job decrease of about 2,000 employees resp. a moderate job gain of about 17,000 employees depending on the compensation case (Fig. 10.9). Assuming unchanged paper exports the job effect is reversed to a significant positive effect of between 37,000 and 58,000 employees. These results show that the labor intensity is higher in the winning sectors than in the losing sectors.

This kind of analysis was also extended to energy demand as an environmental indicator, again by assuming a linear relationship between sectoral output and energy demand, though with lower energy intensities for 2020. The results show a significant reduction of energy demand by about 70–80 PJ already in the business-as-usual scenario (compared to the baseline), mainly due to increased energy efficiency in the pulp and paper industry. In the 'sustainable paper cycle' scenario the energy demand gap is further reduced to between 90 and 110 PJ, mainly caused by lower output of paper and paper products.

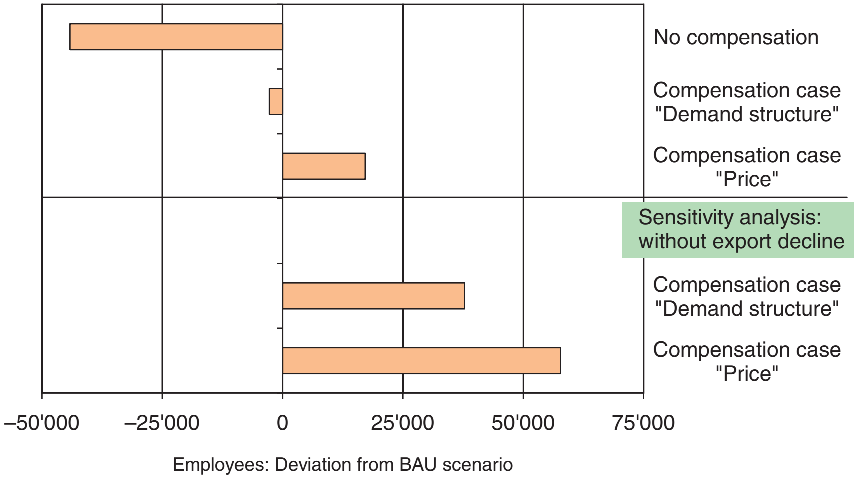

Fig. 10.9 Employment Effects in the SPC Scenario in 2020

Discussion and Outlook

Since material efficiency strategies aim at a redesign of complete process chains or networks it can be assumed that a realization on a large scale will have an impact on the economy as a whole, especially on sectoral structural change. Therefore decision making with regard to these strategies should – apart from the environmental impacts – also take the possible economic impacts into account. In this chapter a methodological approach for analyzing these economic impacts was presented. It was empirically applied to a case study of the German paper cycle.

This so-called hybrid approach implies linking a dynamic economic input-output model with a static technology-based material flow model. The two models are mutually linked and influence each other. Thus the material flow model, which describes a subsystem of the economy with high technological detail, can consistently be embedded into the overall economic context. On one hand its exogenous demand is influenced by the development of the economy, on the other hand changes within the subsystem are fed back to the input-output model.

The hybrid approach combines the advantages of the two isolated models and offsets some of their limitations. The advantages of the presented linkage can be summarized as follows:

- The material flow model allows to catch the complexity of a process network integrating production, consumption and waste management (life cycle approach) and offers a consistent framework for scenario generation with respect to material efficiency measures. Thus the specificity of material and product systems regarding improvement options and realization potentials can be represented in an adequate way. Aspects of technical change or changing consumption patterns can be considered.

- Compared to the usual restriction of material flow models to physical units, the consideration of monetary values allows to show the economic consequences of measures for the involved actors. Apart from direct structural effects, cost and budget effects can also be identified by subsequent simulations with the IO model.
- Technical and intrasectoral structural change, which is a weakness of the IO model, can be represented in the material flow model subsystem by using scenario techniques.

Yet, outside the boundaries of the material flow model this weakness persists. Furthermore the applied input-output model MIS is limited in its representation of some macroeconomic interactions (e.g. explaining the relation between value added and final demand or trade relations). Partly these limitations can be offset by subsequent simulations as proposed in Modeling Framework. In most IO models as in the model MIS, representation of waste management activities is rather inadequate, mainly owing to lack of data for these sectors. For the analysis of economic–ecological interdependencies with the linked model system, the use of extended IO models, which take resource inputs and waste management into account, would be beneficial.

Regarding possible further research steps, other material and product systems could be studied, allowing for the bottom-up analysis of interactions between different subsystems (e.g. competition between different materials). With more complex products (e.g. cars), high-level recycling strategies like product remanufacturing or strategies for intensifying product use could be considered. The analysis of long-living products would also require further methodological developments of the hybrid approach by introducing a dynamic material flow model. Especially establishing consistency between a dynamic economic model and a dynamic material flow model would be challenging. Linking material flow models with other types of economic models (e.g. computable general equilibrium models) might also produce interesting insights.

In the empirical application employment as a social indicator was introduced additionally to economic indicators. This could be extended by indicators describing the quality of work (qualification aspects, extent of shift or weekend work etc.) and by environmental indicators, thus allowing to evaluate the sustainability of a material efficiency strategy – or of industrial ecology related strategies in general – with a methodologically consistent tool. Altogether the empirical application to other material and product systems as well as the further methodological development should enhance our understanding of the impacts of strategies that lead to a more material efficient economy.

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Part III
Life Cycle Assessment

Chapter 11
A Comparison Between Conventional LCA and Hybrid EIO-LCA: Analyzing Crystal Giftware Contribution to Global Warming Potential

Paulo Ferrão and Jorge Nhambiu

Introduction

The growing concern of European citizens with environmental quality and the European Commission's determination to develop stronger environmental policies has contributed to the development and optimization of environmental management tools to support decision-makers in industry and government. These tools help to pro-actively identify sustainable options, optimized according to environmental, social, and economic criteria.

In line with recent European Commission initiatives, an Integrated Product Policy (IPP) approach is to be considered in any economic sector. IPP addresses the whole life cycle of a product, and seeks to avoid shifting environmental problems from one phase of the product life cycle to another.

This vision has emphasized the role of Life Cycle Assessment (LCA) methods, (see, for example, Guinée et al. 2002), which are frequently used with the purpose of accounting for environmental impacts of products and services. These methods show practical limitations, considering that each industry is dependent, directly or indirectly, on all other industries. Consequently, this approach is expensive and time-consuming because resource input and environmental discharge data have to be estimated for each of the modeled processes of the life cycle of a product or service.

The LCA based model has the following advantages: it is accurate within a defined system boundary; it is independent from price fluctuation, and it facilitates unit process level analysis. The disadvantages of this model are related with its high cost for complex product systems, and inherently, it provides incomplete system

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

boundary, as the process inventory associated to the life cycle analysis has to be broken at a given point, there are no infinite boundaries.

An alternative macroeconomic approach, considering the inter-industry effects of product/process decisions for a diverse set of commodities, makes use of the economic input-output tables and environmental information. This approach is known as Economic Input-Output Life Cycle Assessment (EIO-LCA) analysis, (Hendrickson et al. 1998).

This methodology allows for the use of standard data sources, such as the national sector-based economic input-output tables. The method constitutes a coherent approach to environmental accounting, provided that information on emissions and use of natural resources is added. The use of input-output models is advantageous since they take into account the entire supply chain for a product (including indirect suppliers), allowing for tracing of the full range of inputs to a process, and consequently providing a complete system boundary.

The main limitations associated with this methodology are the poor level of disaggregation of the economy, the linearity of the model, its dependence on cost information, the fact that the result omits environmental intervention associated with capital goods, and the temporal difference may cause additional error. For example, the Portuguese economy characterization within the European System of National and Regional Accounts (ESA 79) is based on a national economic input output table, which includes data from 49 sectors, while the USA economy is divided in 500 commodity or service sectors. Additionally, inherently in EIO-LCA lies the assumption that within one production sector, environmental effects are proportional to the price of the product.

Both LCA and EIO-LCA provide interesting characteristics and complementary advantages. The important question is how can one take the most benefit from the two and reduce both truncation and aggregation errors. An answer that has been confirmed by input-output energy analysts is the hybrid approach, as discussed by Suh and Huppes (2005). This new technique, the HEIO-LCA, (hybrid EIO-LCA), is a process-based methodology analysis that replaces the price-proportionality assumption with an assumption of proportionality according to physical units.

The three methodologies, LCA, EIO-LCA, and HEIO-LCA, are discussed and assessed making use of a case study on the production of crystal giftware. The analysis is focused on the greenhouse gas emissions in the context of the Portuguese economy and, in particular, considering the economic sectors environmental performance. This analysis is used to assess the role of these methodologies to promote sustainable policy making in the context of the Kyoto protocol.

Background of EIO-LCA

Environmental Input-Output (EIO) analysis is based in the work of Leontief ([1985] 1986), and was developed for the US economy at Carnegie Mellon University's Green Design Initiative by Hendrickson et al. (1998), in that they have created a web site where the method is made available: www.eiolca.net.

Economic IO analysis describes the interdependence among sectors of a given economy by "a set of linear equations expressing the balances between the total input and the aggregate output of each commodity and service produced and used in the course of one or several periods of time", Leontief ([1985] 1986).

Considering that the relationship between a sector's output and its inputs, are represented in a matrix constituted by technical coefficients, A. The output required from each sector, X, to satisfy an increase in demand, Y, is quantified by: $X = (I-A)^{-1}\,Y$, where, $(I-A)^{-1}$, is commonly referred to as the Leontief Inverse and, I, is the identity matrix. Details of the matrix mathematics can be found in appendix.

The EIO-LCA methodology complements the economic input-output analysis by linking economic data with resource use (such as energy, ore, and fertilizer consumption) and/or environmental impact categories (such as greenhouse gases emissions). At a European level, environmental data is available from the National Accounts Matrix including Environmental Accounts (NAMEA), which accounts for the GHG emissions in the form of a matrix (***b***) of gaseous emissions per economic sector.

Considering that **B** represents the vector of different GHG emissions (CO_2, CH_4...), b is a matrix of GHG emissions per monetary unit of each sector's output, environmental impacts can be estimated by:

$$B = b \cdot X = b \cdot (I - A)^{-1} \cdot Y \tag{11.1}$$

Hybrid EIO-LCA Model

The Hybrid model is based on process-based LCA and economic input-output analysis-based LCA, and its motivation is that process-based hybrid analysis replaces the price-proportionality assumption with an assumption of proportionality according to physical units.

As discussed by Suh and Huppes (2005), a few different types of attempts to integrate benefits of process based analysis and input-output model were performed including addition of input-output based results upon process based models and disaggregation of monetary input-output tables, as in Bullard and Pilati (1976) or Wilting (1996). A hybrid model that allows for full interaction between a process based LCA model and an input-output model was suggested by Suh and Huppes (2005), and constituted the basis for the model presented here, that was extended to develop a computer model for the Portuguese economy, which is run to support the analysis performed in the present paper.

In the hybrid method, a new algebraic formulation is adopted that includes in the same matrix the background processes associated with EIO data, and the foreground processes that are specific of the system to be analyzed and provide greater disaggregation to the analysis. These processes are modeled including material inputs, emission outputs, and their interaction with economic activity (the background system). The representation of the foreground and background systems in the new

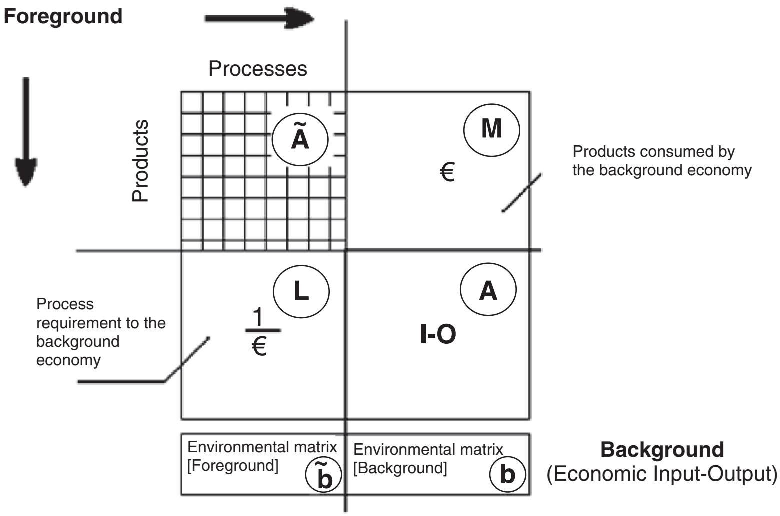

Fig. 11.1 Schematic Representation of the Hybrid EIO-LCA Algebraic Formulation

matrix is represented in Fig. 11.1. Here, the foreground processes are those characteristic of the product life cycle under investigation, and the background correspond to the economic sectors activity, as represented in the national accounting systems.

The integration of the two models has to be done carefully because on one side the foreground and background matrix have different units, and, on the other, it is necessary to avoid duplication of material/processes accounting.

The algebraic formulation of this model is as follows. In the foreground system, let the external demand of process output i be given as $\boldsymbol{k}$, where the use of tilde denotes any activity in the foreground system. If the technical coefficients of the foreground system quantify the products/commodities required in each process, for accomplishing one unit activity level, t, the technical coefficients are denoted by, $\widetilde{\mathbf{A}}$ and:

$$\widetilde{\mathbf{A}} \cdot \mathbf{t} = \mathbf{k} \tag{11.2}$$

This equation can be solved for t (unit activity level required by each process) by inverting the technology matrix $\widetilde{\mathbf{A}}$ and multiplying it with the vector of external demand of process output $\mathbf{k}$.

$$\mathbf{t} = \widetilde{\mathbf{A}}^{-1} \cdot \mathbf{k} \tag{11.3}$$

Considering that the environmental burdens associated with the processes in the foreground system are expressed by $\widetilde{\mathrm{b}}$, as represented in Fig. 11.1, the environmental considerations are expressed in the foreground process as:

$$\mathbf{B} = \tilde{\mathbf{b}} \cdot \widetilde{\mathbf{A}}^{-1} \cdot \mathbf{k} \tag{11.4}$$

The matrix $\tilde{\mathbf{b}}$ is the *intervention matrix*, since its coefficients represent interventions of the different economic processes in the environment: inputs (mainly extractions of resources) and outputs (mainly emissions of chemicals).

If we consider the formulation of the emissions for the foreground system (11.4) with the one for Input-Output (11.1), the Hybrid method can be represented by the following general expression:

$$\mathbf{B} = \left[\tilde{\mathbf{b}} \middle| \mathbf{b}\right] \cdot \left[\begin{array}{c|c} \widetilde{\mathbf{A}} & \mathbf{M} \\ \hline \mathbf{L} & \mathbf{I}-\mathbf{A} \end{array}\right]^{-1} \cdot \mathbf{k} \tag{11.5}$$

According to (Suh and Huppes 2005) the methodology used to create the matrix of coefficients and to normalize the foreground and background units of the process, can be calculated by the expressions (11.6) and (11.7). **L** and **M** denotes inputs from background and foreground systems to one another, respectively. In linking the foreground and background matrix the dimension of elements for **L** and **M** matrices should meet with corresponding rows and columns. **L** shows monetary input to each sector per given operation time, while **M** shows total physical output per total production in monetary term.

$$\mathrm{l_{pq}} = \mathrm{q_{pq}} \times \mathrm{p_p} \tag{11.6}$$

$$\mathrm{m_{pq}} = \frac{-\mathrm{a_{pq}}}{\mathrm{p_p}} \tag{11.7}$$

where:

$\mathrm{q_{pq}}$ = input of sector p in each unit process q,
$\mathrm{p_p}$ = unit price of product from sector p,
$\mathrm{a_{pq}}$ = technical coefficient from economic matrix.

Description of the Case Study – Lead Crystal Giftware Manufacturing

The three environmental analysis tools, LCA, EIO-LCA and HEIO-LCA, were assessed making use of a case study that considers manufacturing 1 kg of crystal giftware, in a notorious Portuguese manufacturer. The environmental burden considered in this analysis was the global warming potential-GWP.

This case study was selected mainly because it includes a complex process, lead crystal manufacturing that is characterized by process specific CO_2 emissions, resulting for chemical reactions characteristic of crystal melting.

The manufacturing processes analysis derived from a detail energy and environmental audit to a Portuguese manufacturer, and a summary of the results obtained are illustrated in Fig. 11.2, where the main production steps are represented together with the respective material and energy flows.

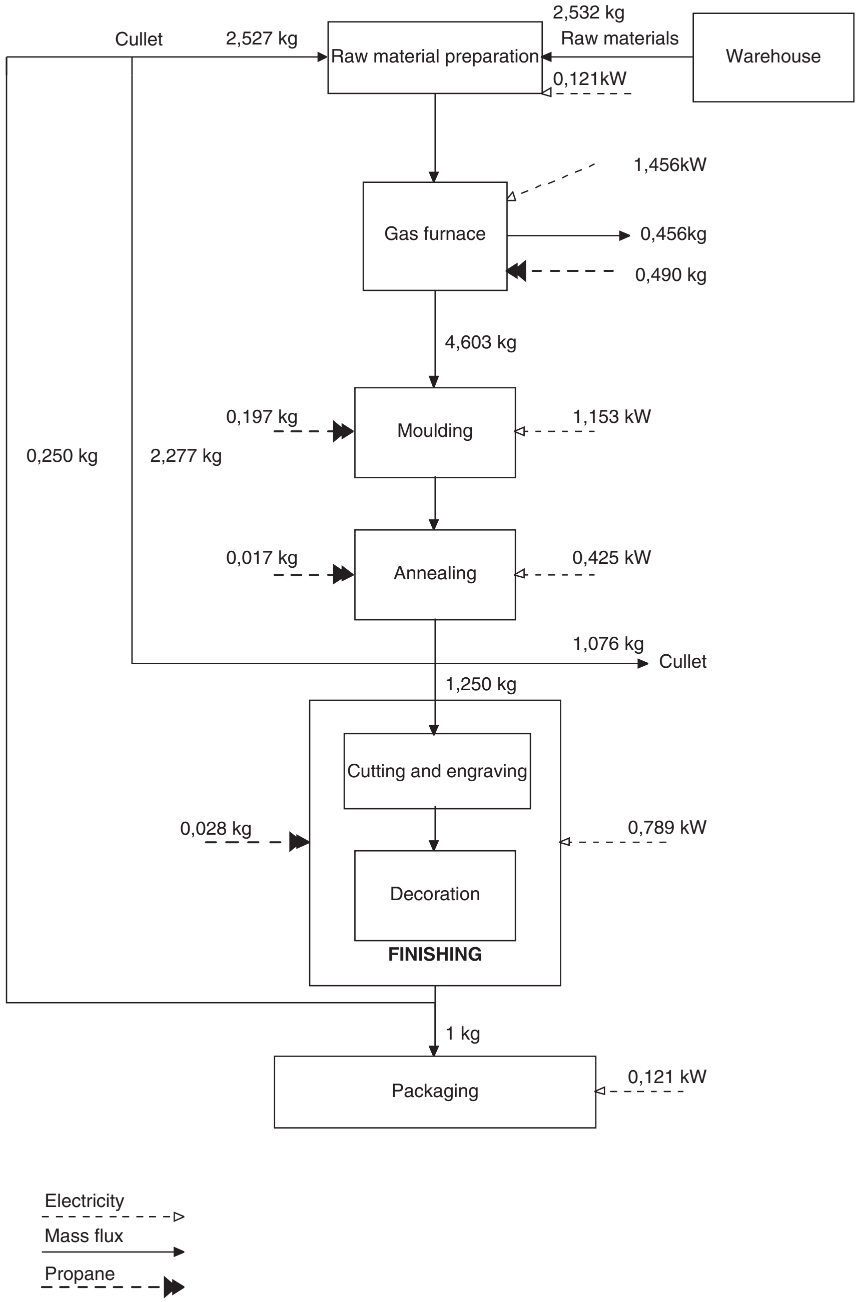

Fig. 11.2 Crystal Manufacturing Flowchart

Full lead crystal is made from a mixture of silica (sand), potash and lead oxide. To be considered "full lead crystal," the content of lead oxide must be at least 24%. After melting in the glass furnace, each piece, created by hand, is worked on by up to 12 craftspeople. First, a "gather" of molten crystal is taken from the furnace by dipping the blowing iron into the molten metal and twisting the iron. The gather is then rotated in a wooden forming block to give it uniformity of shape being produced. The glass is blown to form a bubble. The bubble is then shaped to the basic form by swinging the blowing iron or flattened by spinning. While the crystal is hot, it may be combined with other crystal elements such as handles and stems. After a piece of crystal has been shaped in the blowing room, it must go through a controlled cooling process known as "annealing." This is necessary to prevent internal strains from being set up within the crystal. It is affected by placing the object in a specially constructed oven, known as a "lehr," where it is carried on an endless belt through a series of slowly decreasing temperatures. The annealing of vases or table glass takes 5 to 8 h. Decorating Crystal can consist of hand cutting or engraving with specific designs. By holding the crystal against an abrasive, rotating stone wheel, the crystal can be cut. After decoration, the crystal products are washed and packed.

The GWP resulting from the life cycle (focused on the production phase) of the crystal products analyzed was evaluated using Simapro, an LCA evaluation tool, where specific Portuguese data was built-in. It should be mentioned that detailed manufacturing process was modeled in the LCA software, Simapro, where specific Portuguese energy source data was introduced. However, the boundary established does not include detailed data on the production of the different raw materials required to manufacture the crystal.

In a second step, the EIO-LCA tool was used, considering official data provided by the Portuguese statistical office, in order to enable the analysis of the environmental performance of specific processes and products.

The use of the EIO-LCA tool required the conversion of all the material and energy input along the manufacturing process to be converted in monetary terms, which, in Portugal, was the Portuguese Escudo – PTE, and to be allocated to the economic sector which provided the selected materials. The demand vector which resulted from this exercise is represented in Table 11.1.

The formulation of the hybrid methodology has been implemented in dedicated software developed at IST, (2004). This software enables the user to select

Table 11.1 Demand Vector Corresponding to the Production of 1 kg of Lead Crystal Products. (Only Sectors for Which Demand is Non-zero Are Represented)

Economic sectors	10^6 PTE
Coal	3.80×10^{-5}
Oil	2.74×10^{-4}
Electricity	5.38×10^{-4}
Non metallic minerals	6.90×10^{-6}
Chemical products	1.20×10^{-4}

the products/raw materials/energy sources requested, from a database where more than 12,000 items are available from the Portuguese economy characterization. This data includes the products/raw materials/energy designation, quantities consumed/produced per sector and its average price, information that is crucial to model the purchases of the foreground processes in the background economy.

When the program is run, the following steps have to be followed:

Characterization of the foreground processes, making use of the following information:

Process Available Products – where the available products, raw materials or energy to be consumed in the process are displayed.

Demand – amount of products, raw material or energy chosen to be consumed in the process.

Activity level – amount of the process unit activity used in the functional unit.

Identification of the Input-Output sectors used in the Process: Here the sectors of the input-output matrix that are part of the foreground processes are identified, and the amount used is quantified.

Characterization of the environmental burdens associated with the foreground process.

Once identified the foreground processes and the respective commodities consumed, the program automatically fulfills matrix M in Equation (11.7). These calculations are based on each commodity price, provided by national statistics, which is available in the program databases, and on the technical coefficients in the background system, for the economic sector in which the commodity is classified.

The formulation of the hybrid model has considered nine processes in the foreground system, which interacts with the background economy as represented in Table 11.2, where matrices $\tilde{A}$ and sample rows of matrix L are represented.

In the representation of the foreground processes associated with the bottle production (matrix $\tilde{A}$), each column shows inputs and outputs of each process for a given unit function. Outputs have positive sign while inputs have a negative one. For example, delivering 1 kg of crystal products requires inputs (negative sign) of 2.532 kg of raw materials and 2.527 kg of cullet. The analysis of the furnace shows that the input of 5.059 kg of materials generates 0.456 kg of gaseous emission, and 4.603 kg of melted glass.

Inputs from the background system to the foreground processes show monetary input to each sector, and are represented in the last nine rows of the matrix represented in Table 11.2, which are sample rows from the national EIO Table. For example, obtaining the raw materials required to manufacture the crystal, requires purchases of 3.8×10^{-2} kPTE (1,000 Portuguese escudos) to the coal sector, 2.5×10^{-2} kPTE to the electricity sector, 6.9×10^{-3} kPTE to the non metallic minerals sector and 1.2×10^{-1} kPTE to the chemical products sector.

The results obtained using the three methods, LCA, EIO-LCA and HEIO-LCA, are represented in Fig. 11.3, in terms of each process contribution to the global warming potential.

The results presented in Fig. 11.3 show that process based LCA is limited by the boundary truncations associated to neglecting the raw materials production, the

Table 11.2 Formulation of the Hybrid EIO-LCA Model

	Products	Demand	Foreground processes								
			Warehouse	Raw material preparation	Gas furnace	Moulding	Annealing	Finishing	Packaging	Gas treatment	Landfill
FOREGROUND (kg)	Raw materials	0	2,532	−2,532	0	0	0	0	0	0	0
	Cullet	0	0	−2,527	0	0	3,353	0.250	0	0	−1,076
	Furnace input	0	0	5,059	−5,059	0	0	0	0	0	0
	Melted crystal	0	0	0	4,603	−4,603	0	0	0	0	0
	Raw crystal product	0	0	0	0	4.603	−4,603	0	0	0	0
	Annealed glass	0	0	0	0	0	1,250	−1,250	0	0	0
	Final product	0	0	0	0	0	0	1,000	−1,000	0	0
	Packed Product	−1,000	0	0	0	0	0	0	1,000	0	0
	Gaseous emissions	0	0	0	0.456	0	0	0	0	−0.456	0
BACKGROUND (10^6 PTE)	Raw materials	0	0	3.80E-05	0	0	0	0	0	0	0
	Cullet	0	0	0	−1.40E-04	−1.10E-04	−9.6E-6	−4.3E-6	0	0	0
	Furnace input	0	0	−2.5E-5	−1.5E-4	−2.3E-4	−8.5E−5	−4.3E−5	−4.9E−6	0	0
	Melted crystal	0	0	0	0	0	0	0	0	0	0
	Raw crystal product	0	0	−6.9E-6	0	0	0	0	0	0	0
	Annealed glass	0	0	0	0	0	0	0	0	0	0
	Final product	0	0	0	0	0	0	0	0	0	0
	Packed Product	−1,000	0	0	0	0	0	0	0	0	0
	Gaseous emissions	0	0	−1.2E−4	0	0	0	0	0	0	0

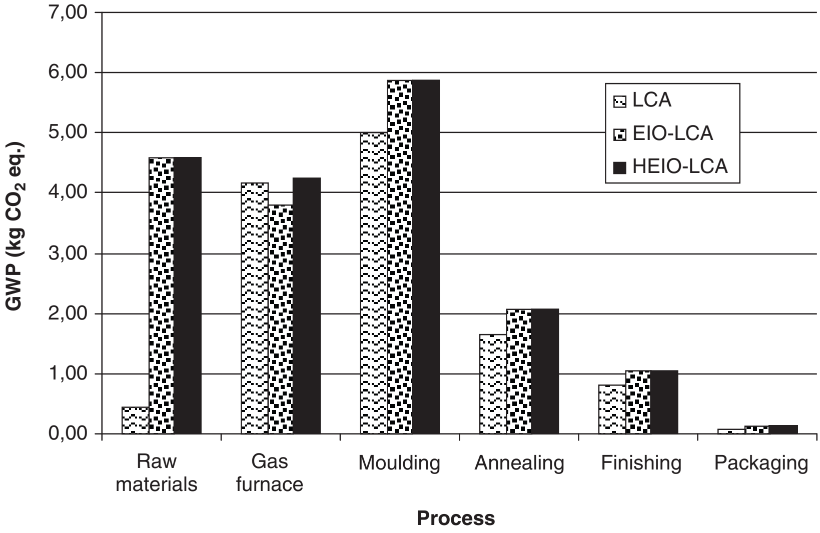

Fig. 11.3 GWP as Evaluated by LCA, EIO-LCA and HEIO-LCA

lubricants consumption in the moulding processes and the cleaning products in the finishing. This is particularly relevant in the raw materials production, as expected, as the process-based LCA clearly under estimate the GWP caused by raw materials production.

The results obtained do also show that EIO-LCA under estimate CO_2 emissions when compared to the HEIO-LCA method. This is because in the last method, the crystal melting process is specifically modeled and considers the emissions of CO_2 that result from the chemical reactions within the raw materials. In the EIO-LCA, this is obviously not modeled, as only the average emissions of the glass and glass products production sector emissions are evaluated. It is clear that the specific nature of the glass-melting process, that has particular CO_2 emissions, cannot be accurately represented by this aggregated analysis. As a consequence, this constitutes a typical situation where the Hybrid methodology may be used with advantage. The remaining sector's environmental burdens were not specifically modeled in the HEIO-LCA analysis and therefore the results obtained coincide with those evaluated in the EIO-LCA model.

These results show that the HEIO-LCA methodology is able to overcome the limitations of the EIO-LCA. Another particularly relevant conclusion is that the results obtained by the HEIO-LCA can contribute to avoid arbitrary boundary analysis decisions in the LCA process analysis and, consequently, avoids truncation that may occur in LCA modeling, when their full range of processes and materials are not properly modeled.

In general, it can be concluded that HEIO-LCA, allowing for process-specific, foreground system models to be inter-linked with national economic system using information on cut-offs, constitute an excellent tool to use when LCA accurate information is required within limited budgets and time scales.

Conclusions

A hybrid model that allows for full interaction between a process-based LCA model and an input-output model is discussed, and a computer model for the Portuguese economy was developed and is run to support the analysis of a case study that compares three environmental analysis tools, namely LCA, EIO-LCA and HEIO-LCA.

Detailed process analyses for the product system of Portuguese lead crystal giftware manufacturer were performed and a process-specific database was created. Compiled process-specific, foreground system is inter-linked with Portuguese national economic data in order to promote the interdependence between the detailed product system and the national industrial system.

The relative merits of LCA, EIO-LCA and HEIO-LCA were discussed considering GHG's emissions in the Portuguese economy making use of the case study. The results obtained show that the HEIO-LCA methodology clearly overcomes the limitations of the EIO-LCA, due to the aggregated nature of EIO data. The analysis of the case study did also show that the HEIO-LCA methodology is able to compensate truncation associated with arbitrary boundary analysis decisions, which may occur in an incomplete LCA analysis. As a consequence, it can be concluded that the HEIO-LCA methodology has provided excellent results, particularly when LCA accurate information is required within limited budgets and time scales.

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Appendix: EIO Matrix Mathematics

Considering the economy divided into n sectors of activity, and if we denote by $\boldsymbol{X}_i$ the total output (production) of sector i and by $\boldsymbol{Y}_i$ the final demand for sector i's product, we have:

$$X_i = z_{i1} + z_{i2} + \ldots + z_{ij} + \ldots + z_{in} + Y_i \tag{A.1}$$

for $i = 1$ to n, and, $j = 1$ to n. The z terms on the right-hand side represent the inter-industry sales by sector i to sector j. Thus, the entire right-hand side represents the inter-industry sales, $\boldsymbol{z}_{ij}$, and, $\boldsymbol{Y}_i$, the demand of sector $\boldsymbol{i}$. Hence, the sum over j represents the total output of sector i.

A fundamental assumption is that the inter-industry flows from i to j depend entirely on the total output of sector j, Leontief ([1985] 1986), which is quantified by a technical coefficient, $\boldsymbol{a}_{ij}$:

$$a_{ij} = \frac{z_{ij}}{X_j} \tag{A.2}$$

The $\boldsymbol{a}_{ij}$'s are fixed relationships between a sector's output and its inputs, and constitute the technical coefficients matrix, A ($\boldsymbol{A}_{ij}$). There is an explicit definition of a linear relationship between input and output. Equation (A.1) can thus be rewritten as:

$$X_i = A_{ij} X_j + Y_i \tag{A.3}$$

The output required from each sector to satisfy an increase in demand $\boldsymbol{Y}$, is quantified by:

$$X = (I\text{–}A)^{-1}.Y \tag{A.4}$$

where $(I\text{–}A)^{-1}$ is commonly referred to as the Leontief Inverse. A detailed derivation of the input-output methodology is provided by Miller and Blair (1976) and Leontief ([1985] 1986). Equation (A.4) can be reformulated as:

$$X = (I\text{–}A)^{-1}.Y = Y + AY + A^2Y + A^3Y + \ldots + A^{\infty}y \tag{A.5}$$

where the component associated with the direct contributions from the different sectors to fulfill the demand, Y, are:

$$X_{Direct} = Y + A\,Y \tag{A.6}$$

and the indirect contributions, i.e. second order are:

$$X_{Indirect} = A^2Y + A^3Y + \ldots + A^{\infty}y \tag{A.7}$$

The indirect contribution accounts for second and higher orders and corresponds to the upstream processes of the inventory associated to a product or service life cycle, inherent to the LCA methodology.

Chapter 12
Application of the Sequential Interindustry Model (SIM) to Life Cycle Assessment

Stephen H. Levine, Thomas P. Gloria, and Eliahu Romanoff

Introduction: LCA in Industrial Ecology

As an emerging science, industrial ecology needs to identify and develop appropriate quantitative methods (Koenig and Cantlon 1998, 2000; Seager and Theis 2002). One of these primary tools has been Life-Cycle Assessment (LCA). LCA is used for assessing the impacts of products, processes, services, or projects on the environment (Graedel and Allenby 2003). The expression life-cycle indicates a "cradle-to-grave" approach, beginning with a product's conception and continuing through to its ultimate recycling or disposal. Thus, a product's or process' lifetime includes (1) a raw materials acquisition phase, (2) a manufacturing, processing and formulation (3) a distribution and transportation phase (4) a use/re-use/maintenance phase (5) a recycling phase (6) and waste management (end-of-life) phase. LCA traditionally consists of four stages, (1) goal and scope (2) inventory analysis, (3) impact assessment, and (4) improvement analysis. In particular, Life Cycle Inventory (LCI) analysis describes those resources required and pollutants produced over the product's lifetime (Fava et al. 1991). Major benefits of LCA include: a systematic method to evaluate the overall material and energy efficiency of a system; the ability to identify pollution shifts between operations or media as well as other trade-offs in materials, energy, and releases; and a means to benchmark and measure true system improvements and reductions in releases (Owens 1997).

Two main methods exist for performing the life cycle inventory stage of an LCA study – Process LCA (PLCA) and Economic Input-Output LCA (EIO-LCA), each

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with its relative advantages and disadvantages (Hendrickson et al. 1997; Matthews and Small 2001). The recent development of hybrid models is aimed at gaining the advantages of both (Suh 2004). Another distinction among LCAs is classifying them as either attributional or consequential. An attributional LCA approach is what one thinks of as the traditional LCA – capturing the environmental properties over the life cycle of a product, process or project. In contrast, a consequential LCA approach describes the changes within the life cycle. Although IO models are considered intrinsically attributional based on the nature of the average industry data that typically supports them, the approach here is more akin to consequential LCA (Ekvall 2002; Ekvall and Weidema 2004).

Leontief Input-Output Models are the basis of EIO-LCA (Hendrickson et al. 1998; Joshi 2000; Matthews and Small 2001). The static Leontief model (Leontief 1966) can provide a useful tool in extending the boundaries of LCA, and defining them in a non-subjective way, by accounting for industrial activities indirectly as well as directly required in the production of goods. The result is a more comprehensive coverage of potential human health and environmental impacts that result from those activities (Duchin 1992; Lave et al. 1995; Hendrickson et al. 1998; Joshi 2000; Matthews and Small 2001). By using an EIO-LCA approach, the problem of subjective boundary definition is addressed by including industrial activities throughout the whole industrial system (Joshi 2000). The focus of an assessment shifts from a boundary issue to one that describes how a particular product being assessed is linked into the economy as a whole.

This chapter will focus on what we presently see as two limitations to EIO-LCA. First, neither traditional LCA nor the static Leontief IO model contains explicit temporal information, that is, describes in any detail how production activities associated directly or indirectly with a product, and its related impacts, economic or environmental, are distributed over time. For some products and processes, and certainly for many long-term capital projects, these activities and impacts, such as the ecological toxicity effects of persistent chemicals of concern, though transient, may be distributed over considerable periods of time. Moreover, the specific pattern of the distribution may be critical to evaluating its impact. Furthermore, EIO-LCA, by extending the boundaries within the industrial system, also extends the temporal boundaries of the analysis. Production activities indirectly related to a product may be carried out a considerable time before the product is completed (e.g., the production activities of mining iron ore that ultimately ends up in an automobile). Thus, temporal information is more important in EIO-LCA than in PLCA.

Second, traditional input-output models are interindustry *production* models. This provides little basis for describing impacts due to a product's subsequent use and retirement phases (Joshi 2000), either of which may generate the greater part of the product's lifetime environmental impact. For example, consider the gasoline, oil, tires and batteries that are consumed by an automobile during its use phase. EIO-LCA models provide a cradle-to-output gate analysis, when in fact a cradle-to-grave analysis is called for. Joshi (2000) has outlined a way in which the input-output model could be readily extended to account for the use phase and we will consider this issue in this chapter (see also Gloria 2000). We should note that with the extension of the IO model to the use and retirement phases the need for temporal-based information becomes even more pronounced.

The approach presented, utilizing the Sequential Interindustry Model (SIM) (Romanoff and Levine 1981), is intended to address a class of problems where the activities within and outside the life cycle are affected by a change within the life cycle of the product under investigation. It is structured around causal relationships, represented by a sequence of events originating from a decision at hand. SIM was originally developed to investigate the impact of transient economic events, such as a construction project (Levine and Romanoff 1989), the "hollowing out of a regional economy" (Hewings et al., 1998, 2001), or an earthquake (Okuyama et al. 2004). The life-cycle of a product, process, or project is such a transient event, possibly managed by formal planning techniques and tools such as the critical path method (CPM). This suggests that SIM might provide a useful extension of the EIO-LCA methodology.

While based on the static Leontief model, SIM is a dynamic system model that describes how the various indirect as well as direct inputs, outputs, and associated impacts of such events are distributed in time – information that the static Leontief model does not provide. SIM is mathematically formulated such that in the absence of temporal change (i.e., in steady state) it reduces to the static IO model, the important emergent dynamic properties that sculpt the framework of SIM disappear in the absence of temporal concerns.

The Importance of Temporal Information in EIO-LCA

In general, if we seek to justify employing a more sophisticated model, in this case a dynamic rather than static model, we must ensure that this additional effort makes a difference to the solutions we discover. How important is temporal information in LCA? As summarized by Udo de Haes et al. (1999a, b): "LCA essentially integrates over time. This implies that all impacts, irrespective of the moment that they occur, are equally included." However, in practice LCA tools provide essentially a static description of the impacts of an existing product or process – a "snapshot" of environmental impact, where the snapshot is based on all that occurred over the time interval of the snapshot. (The same can be said for the static input-output model; it provides a "snapshot" of the economy.) The reason is primarily limitations of available data. Although by definition, the *Goal and Scope* stage of an LCA study determines the boundary of analysis, in practice, it is the Life-cycle Inventory (LCI) that ultimately determines the actual extent of the research. Although there may be temporal information available in some data, it is not true for all data. Historically, the immense task of collecting data to conduct a comprehensive LCA at best, defaults to a static analysis.

Yet, relying on the static model may not be enough to support the decision-making process to know that industry A on average annually emits B pounds of substance C to the environment per dollar of industry A's total output. The rate of production by industry A may vary considerably over the course of the year. The emission does not occur all at once at the completion of the production process. Rather, the emission rate of substance C may vary considerably over the production process. The environment may react in a decidedly non-linear way to increased concentrations of substance C. For instance, there may be a threshold concentration level below which substance C is harmless but above which it becomes a health problem. The concentration of substance C will be determined by its history of emission. This is further complicated if substance C itself may decompose at different rates as a function of average air temperature, or be dissipated at different rates at different times during the year due to wind speed or wind direction.

For these and other reasons, the rate and the specific time at which emissions and other disturbances are produced, and not simply their quantity, may be critical to evaluating their impact on the environment (Field et al. 2000); the loss of temporal information in the inventory phase of an LCA may limit the accuracy of the impact assessment and at a minimum long-term emissions should be inventoried separately from short-term emissions (Owens 1997; Hellweg and Frischknecht 2004). An input-output model dealing with time in an explicit manner could under these circumstances greatly enhance the role of input-output analysis in LCA.

When we move beyond the production phase alone to consider the whole life-cycle of a product, the need for temporal information is, if anything, even greater. Products and projects continue to demand resources and produce impacts during their use phases and in their retirement phases as well. These resources and impacts may be of a very different nature than those occurring during the production phase. They may vary seasonally, or be influenced by the age of the product or project. An input-output model dealing with time in an explicit manner could under these circumstances greatly enhance the role of input-output analysis in LCA.

Static and Dynamic Systems

Both static and dynamic IO models are concerned fundamentally with the structure of the interrelationships or interdependencies among variables and data of models of the system of concern. They differ, of course, in their treatment of time.

> A static model is one whose structural relationships do not contain time in any analytically meaningful way. By contrast, dynamic systems are those which do contain time-relationships among the relations of the variables in meaningful ways, i.e., in ways which could not be eliminated without affecting the solution to the system or eliminating the possibility of the solution (Kuenne 1963, p. 457).

The distinction between static and dynamic models is not simply the existence of time in a dynamic system and its absence in a static model. The use of a static model must still involve the interpretation of its solution "against time as a backdrop" (Kuenne 1963, p.15). That is, although typically not explicitly recognized or even ignored, time is a factor when implementing a static model. Comparative statics (Duchin 1998, p.123), as an example, involves what may be considered a sequence of 'snapshots" of successive equilibria. However, a fundamental difference between the two approaches is that a specific solution to a static system yields a single solution vector, whereas a specific solution to a dynamic system is "a set of such vectors linked in a path through time" (Kuenne 1963, p. 14), that is, a trajectory. A dynamic model, therefore, may have *more than one path* converging to the same (or different) equilibrium.

A static system can yield theorems about "the values of the variables only in a state of rest, or theorems about changes in the values of the variables only between two states of rest." In contrast, incorporating the notion of inter-period relationships, "a dynamic model contains the potential for the derivation of theorems concerning the values of the variables, or changes in those values, before the position of rest, or equilibrium has been attained" (Kuenne 1963, p. 14).

Dynamic LCA to assess long-term environmental impacts was first introduced by Moll (1993). In Moll (1993) static LCA approaches were found to be appropriate to compare and evaluate products under three conditions. First, the products should have relatively short life cycles, on the order of period of less than 5 years. In this case, the context that surrounds the product can be assumed as non-changing. Second, products should have stabilized consumption levels. Here, average values can be used to accurately describe input and output requirements. And third, products should remain static with regard to technologic or social changes in the life cycles considered. Essentially, the static life-cycle is relevant as a method of analysis for a context where the system is in steady-state.

Conversely, Moll (1993) concluded that the dynamic LCA approach is appropriate to compare and evaluate policy options that in essence the criteria are the antithesis of relatively short term product issues examined by static LCA. That is, dynamic LCA is appropriate to assess products with long life cycles (greater than 5 years), that involve substantial changes of consumption levels, and undergo changes in the applied technologies. Here the system context is not in steady-state and is possibly far out of equilibrium. The timing and changes in the use of materials and energy and their subsequent environmental repercussions are significant. The significance of the timing and rate of changes are important for assessing long-term results that ultimately influence policy options.

Moreover, Moll (1993) concluded that the static LCA methodology and the dynamic methodology did not change the rank order of design criteria of the products analyzed. However, additional insights gained by conducting dynamic LCAs of product alternatives that lead to policy options include:

The relevant choice of the integration period, that is, the rate the new technology be phased in and an old technology be retired.

The period required for environmental improvements. For example, the amount of time the policy option is to be implemented to achieve its reparation objectives.

The calibration of the trends in the absolute magnitude of relevant parameters to the environmental policy. That is, a context is established with outside forces, such as trends in national economic conditions or trends in larger sources that affect the dynamics of the policy examined.

The duration of the period to reach steady-state – how long will the policy option induce change, and what will the final state of that change.

Post the seminal contribution to the science of LCA by Moll (1993), Gloria (2000) applied aspects of temporal consideration put forth by Moll (1993). Inspired by the structural economics work by Duchin (1998) and interindustry models that incorporate the details of production sequences (Romanoff and Levine 1981; Levine and Romanoff 1989), Gloria (2000) presents a formulation of Sequential Interindustry Model (SIM) in an LCA context. Examining a case study of market penetration of an emerging technology, fuel cell electric vehicles (FCEVs), and its effects on the reduction of greenhouse gas emissions in the U.S. National Economy, Gloria (2000) presented a structured approach to examine the repercussions of the integration period. That is, an investigation was made of the rate the new technology, FCEVs, were to be phased in and for the old technology, internal combustion engine vehicles (ICEVs) to be retired. Other notable use of dynamics and LCA applied to the pulp and paper industry can be found in Ruth and Harrington (1997).

Sequential Interindustry Model (SIM)

Interindustry models describe the flows of goods (and services) in industrial systems. The traditional Leontief static input-output model represents the total output of an industrial system as

$$g = w + f \tag{12.1}$$

where:

g = total output vector,
w = intermediate output vector, and
f = final output vector.

The assumption of a linear production function leads to

$$g = Ag + f \tag{12.2}$$

where:

A = technical matrix.

While suppressed, time is implicit in the static input-output model. We treat time as a sequence of discrete intervals of finite length. The periodic economic input-output tables published by different countries fit this model, each new table being the next entry in a sequence. Thus, the values of **g**, **f**, **w** and **A** are based on measuring economic activity over some discrete interval of time, such as a year, and can change from one interval to the next. Equation (12.1) can be rewritten making this time dependence explicit,

$$g(t) = w(t) + f(t) = A(t)g(t) + f(t) \tag{12.3}$$

where t is an index of discrete time intervals. Equations of this type are referred to as comparative static models, producing what we will call a static temporal sequence. They provide, as noted, a sequence of ‘snapshots’ of the economy.

Equation (12.3), like Equation (12.2), provides an accounting of output; total output in interval t consists of intermediate output in interval t plus final output in interval t. It is a purely descriptive model of existing economic activity. However, in many applications we are interested in prescribing the specific total output **x** required to produce an arbitrarily specified quantity of final output **y** (Suh 2004, Ch. 3). It is this ability of the input-output model to account for all the linkages, and thus all the sources of environmental impact linked to a final output **y**, that makes it a valuable tool in LCA. Making the assumption that **A**, the technical matrix, is independent of scale, we rearrange Equation (12.2) and replace data-based outputs **g** and **f** by the application-specific outputs **x** and **y,** to obtain the Leontief inverse equation,

$$x = (I - A)^{-1} y = By. \tag{12.4}$$

Again, time is implicit. However, as noted, this is no longer a descriptive statement of ‘annual’ accounting. It is instead a prescriptive model, telling us what total output **x** must be produced in order to achieve the desired final output **y**. Making Equation (12.4) temporally explicit by writing

$$x(t) = B(t)y(t) \tag{12.5}$$

reveals its essentially static nature. **x**(t) is fully determined by **B**(t) and **y**(t); it is independent of **y** or **B** in any interval other than t. Thus, successive values of **x** are independent of each other. Similarly, there is no ‘rule’ relating the value of **B** (and thus of **A**) in interval t to its value in other intervals. Moreover, Equation (12.5) is correct only if it is true that the total output **x** required to provide for interval t’s final output **y(**t) is itself entirely produced in interval t, though it will be numerically correct if the system is in steady-state. In general neither one of these conditions will be true, and the first condition is especially unlikely if the time interval under consideration is short compared to the times required by the various production activities. (It is precisely these relatively short time intervals that are needed, as described earlier, to evaluate environmental impacts.)

In fact, production requires time, and thus some of the intermediate output that ultimately is imbedded in one interval’s final output will likely occur in previous time intervals. Put another way, total output in interval t is determined not only by final output for interval t but by future final output as well. An appropriate formulation must recognize that we are describing a dynamic system in which total output levels in different intervals are dependent on each other. To be consistent with Life Cycle Inventory (LCI) approaches (Suh 2004), while maintaining an explicit representation of time, a more accurate formulation of time dependence will be required.

In order to account for the time required by production activities the coefficients of the **A** matrix must describe not only what inputs are required by a producing sector but when those inputs are required in the production process. For simplicity, and because of its importance in modern day industrial systems, we will assume just-in-time (JIT) production modes. In just-in-time production, with no inventories and assuming no transportation delays, output from a supplying industry occurs in the same interval as it is required by the demanding industry. Duchin, (1998, p. 46) has noted the importance of adding engineering information to economic information in the development of structural economics (the field that includes input-output economics). SIM is an example of just this principle. We might describe this addition of production lead times as moving from a list of ingredients to a recipe, or as supplementing accounting information regarding what is needed to make the product with engineering information on the production process itself.

Again, we will make the assumption that **A** is scale independent. Utilizing the engineering information, the technical coefficient $a_{ij}(t)$ is partitioned into $a_{ij}(t, \tau)$, $\tau = 0, 1, 2, 3, \ldots$, where τ measures in intervals the production lead time, and where $\Sigma_\tau\, a_{ij}(t, \tau) = a_{ij}(t)$. Intermediate production then becomes

$$w(t) = \sum_{\tau=0}^{\infty} A(t, \tau)x(t + \tau), \tag{12.6}$$

and is determined by requirements of future output. In this article we will assume that the **A** matrix does not change over time (i.e., it is time invariant) so that $\mathbf{A}(t, \tau) = \mathbf{A}(\tau)$, and Equation (12.3) becomes

$$x(t) = \sum_{\tau=0}^{\infty} A(\tau)x(t + \tau) + y(t). \tag{12.7}$$

In contrast to the comparative static system description of Equation (12.3), Equation (12.7) represents the production dynamics of the industrial system being modeled. It produces what we will call a dynamic temporal sequence. The model displays one of the characteristics of a dynamic system, its 'memory'; output at one interval is linked to output at other intervals. The apparent non-causal structure of this model is explained by recognizing that in practice these future requirements would be either established future orders or estimates of future demand.

We can put Equation (12.7) into a more computationally convenient form through use of Z transform techniques (DeRusso et al. 1998). For discrete time sequences such as $\mathbf{y}(t)$,

$$y(z) = Z\{y(t)\} = \sum_{t=-\infty}^{\infty} y(t)z^{-t} \tag{12.8}$$

Taking the Z transform of Equation (12.7), we obtain

$$x(z) = A(z)x(z) + y(z), \tag{12.9}$$

with the corresponding inverse equation,

$$x(z) = (I - A(z))^{-1}y(z) = B(z)y(z) \tag{12.10}$$

Inverse Z transform techniques can then be used to determine the time sequence

$$x(t) = Z^{-1}\{B(z)y(z)\} = \sum_{\tau=0}^{\infty} B(\tau)y(t+\tau). \tag{12.11}$$

Thus, the total output at interval t is determined by the future as well as the present final output. Again, the future final product would in general be either orders or estimates.

SIM and Environmental Burden

Joshi (2000) has suggested a method for extending the static input-output model to account for environmental impacts associated with a total output vector through the use of environmental burden coefficients. For this purpose Joshi (2000) introduced the normalized environmental burden matrix **R,** with r_{kj} the kth environmental burden (e.g., carbon monoxide release, toxic chemical release, etc.) generated per dollar output of sector j, and the total environmental burden vector **e**, with e_k the kth environmental burden, where $\mathbf{e} = \mathbf{Rx} = \mathbf{RBy}$.

In the context of SIM, environmental burden is a dynamic concept. The emissions associated with the production of output in interval t occur over a number of preceding intervals, in a similar fashion to the inputs. ε(t), the emissions in interval t, can be expressed as:

$$\varepsilon(t) = \sum_{\eta=0}^{\infty} P(\eta)x(t+\eta), \tag{12.12}$$

where $\mathbf{P}(\eta)$ weighs the contribution of future output to present emissions.

Environmental burden in interval t, **e**(t), is in turn dependent on the accumulation of previous emissions, where physical phenomena such as dispersal and disintegration of emitted materials in the air, water, or land are accounted for by appropriately weighting the past. The environmental burden in interval t is

$$e(t) = \sum_{s=0}^{\infty} W(s)\varepsilon(t-s) = \sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} W(s)P(\eta)x(t-s+\eta) \tag{12.13}$$

where **W**(s) is a diagonal matrix of weighting values. To put this in the form of the Joshi model we let $\mathbf{R}(\mathrm{s}, \eta) = \mathbf{W}(\mathrm{s})\mathbf{P}(\eta)$, and

$$e(t) = \sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} R(s,\eta)x(t-s+\eta) = \sum_{\tau=0}^{\infty}\sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} R(s,\eta)B(\tau)y(t-s+\eta+\tau) \tag{12.14}$$

Applying SIM to LCA: Theory

We now consider the application of SIM to LCA. Up to now our development of SIM has focused, as with the EIO, on the production phase of a product's life. However, we have already noted that operation and maintenance of a product, as well as its retirement, require resources. Gasoline consumption by automobiles, electricity use by factory equipment, and periodic painting of bridges are but three examples of resources required during the use phase of products. All of these contribute to environmental burden. Furthermore, the problem of attributing environmental burden to either production or use phase is complicated because with the exception of final product, the use phase of one product is part of the production phase of another. The two burdens are not independent.

Equation (12.14), similar to the Joshi model, attributes all burden to the production phase. In dealing with vectors of total product this is necessary. If we account for the environmental impact due to the burning of oil in electricity production as part of the environmental burden of the electric power industry, we cannot include this oil usage as part of the environmental burden of the petroleum industry without double counting burdens. However, this presents difficulty if we wish to develop the LCA of a specific product and include its use phase. To overcome this difficulty we will follow a suggestion of Joshi (2000), and deal with the use phase of the product by treating it as a hypothetical industry sector producing a final product. The output of this sector is a used product. This allows us to frame the use phase of a product as if it were part of the production phase of a used product. The inputs required to produce a used product are the product when it was new plus all the resources it required during its use phase. For example, the "production" of a 10-year old car requires as its inputs a new car, 10 years prior to the outputting of the used car, plus 10 years of gasoline, oil, tires, batteries, etc.

We will therefore consider the environmental burden generated by all direct and indirect production activities associated with one unit of final output from hypothetical sector n in interval t_0 after a use phase of σ intervals. Thus, our final output is

$$y^*(t) = 1_n\delta(t - t_0), \tag{12.15}$$

where $\mathbf{1}_n$ is a vector of all 0s except for a 1 as element n, and $\delta(t - t_0) = 1$ when $t = t_0$, and equals 0 otherwise. The total output attributable to this one unit of final output is

$$x^*(t) = \sum_{\tau=-\infty}^{\infty} B(\tau)y^*(t + \tau) = B(t_0 - t)1_n \tag{12.16}$$

with resulting environmental burden

$$e^*(t) = \sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} R(s, \eta)x^*(t - s + \eta) \tag{12.17}$$

Applying SIM to LCA: Computer Results

In order to demonstrate the effect of temporal variation on the environmental burden generated by a product over its production and use phases we have carried out three numerical examples using SIM. All of these examples correspond to an identical five sector static model. This was done to highlight the additional information that is provided by a dynamic model. The first three sectors of the model describe the entire economy with the exception of the industry whose product we wish to assess. The fourth sector describes the industry whose product we wish to assess while a fifth sector represents the "production" of a used product of that type. Our model included two different environmental burdens.

All our examples correspond to the same static model with the following **A** and **R** matrices describing the five sectors and two burdens.

A Matrix

0.24	0.18	0.12	0.24	300.00
0.24	0.30	0.12	0.30	250.00
0.30	0.24	0.18	0.12	200.00
0.06	0.06	0.06	0.00	1,000.00
0.00	0.00	0.00	0.00	0.00

R Matrix

27.74	31.21	24.27	31.21	8,718.83
16.76	25.14	27.93	22.35	10,535.44

The resulting environmental burden vector, $\mathbf{e}^*$, corresponding to the production and use of one unit of the product being assessed is

$\mathbf{e}^*$ Vector

172,302.32
142,818.51

In our SIM versions we will assume the product is produced in interval 0 and retired after ten intervals of use. Given values of $\mathbf{y}^*$(t), $\mathbf{A}(\tau)$, $\mathbf{P}(\eta)$ and $\mathbf{W}$(s), chosen so as to be consistent with the static model, we will then compute $\mathbf{e}^*$(t), the environmental burden history corresponding to the production and use of that one unit. In order to do this we needed to calculate $\mathbf{B}(\tau)$. This was done by utilizing the power series form of the Leontief inverse, that is

$$B(z) = (I - A(z))^{-1} = \sum_{k=0}^{\infty}(A(z))^k \tag{12.18}$$

and truncating the summation at some appropriate value of k. A comparison to $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ in the examples we ran indicated that our approximations captured on the order of 97% of the total production.

We will vary two things in our three examples, the duration of the production processes and the rate at which the emissions degrade. Again, this will be done in such a way as to not create any change in the static IO model. Thus changes in $\mathbf{W}(s)$, accounting for degradation rates, will require compensatory changes in $\mathbf{P}(\eta)$ in order that the resulting $\mathbf{R}$ matrix in the static model is unaffected.

Example 1. Long Production Phase, Slow Emissions Degrading

In this example the first four sectors have production processes requiring six intervals. Sector 5 has a "production" process of ten intervals, corresponding to the use phase of the product being assessed. The emissions producing the two burdens degrade at rates of 20% and 25% per interval respectively. Figure 12.1 shows the history of the emissions burdens for this example.

Example 2. Short Production Phase, Slow Emissions Degrading

This example differs from Example 1 by having production processes that require only two intervals. Everything else is identical to Example 1. Figure 12.2 shows the history of the emissions burden for this example.

Example 3. Short Production Phase, Quick Emissions Degrading

This example differs from Example 2 by having emissions that degrade at rates of 60% and 62.5% per interval respectively. $\mathbf{P}(\eta)$ is modified accordingly. Everything else is identical to Example 2. Figure 12.3 shows the history of the emissions burden for this example.

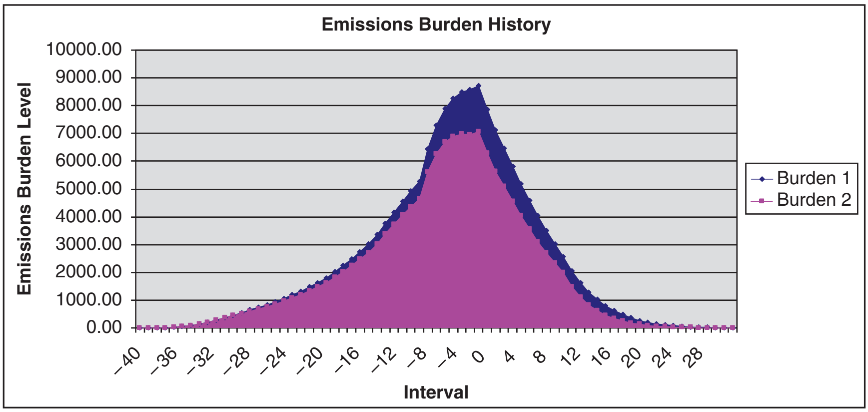

Fig. 12.1 Emissions Burden History for Long Production Phase, Slow Emission Degradation Case

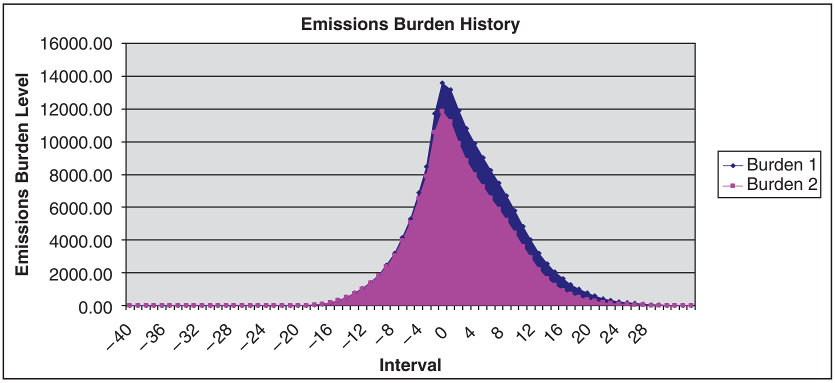

Fig. 12.2 Emissions Burden History for Short Production Phase, Slow Emissions Degradation Case

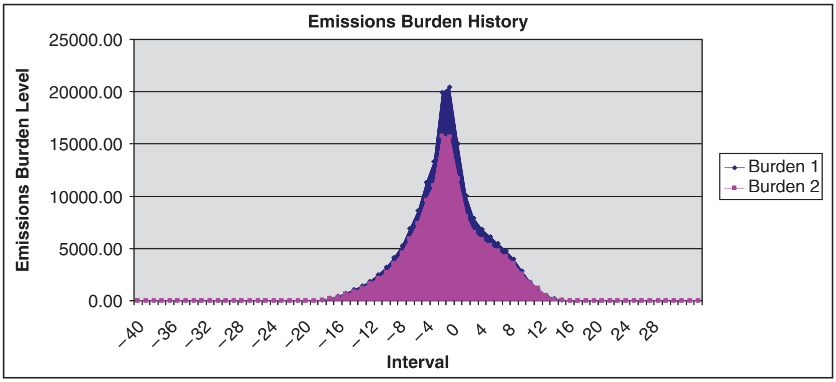

Fig. 12.3 Emissions Burden History for Short Production Phase, Quick Emissions Degradation Case

Udo de Haes et al. (1999a) notes that LCA, as presently practiced, essentially integrates over time. The use of static models is one aspect of this integration procedure. As noted, all three of our dynamic examples correspond to the identical static case, that is, in all the examples the areas under the curves are identical. However, if our concern with environmental burden includes concern for peak values or if the impact assessment phase of LCA recognizes the existence of threshold values, the three examples are dramatically different.

Discussion

Input-output models are likely to play an increasingly larger role as a tool in future LCA applications – both disciplines are grounded in the pursuit of understanding the intricacies of the industrial complex. Input-output approaches have to a fair extent ameliorated LCA issues of truncated boundaries and greatly assisted in the task of identifying the interconnections of the multitude of indirection that are present in the global economy, if not a mere appreciation and awareness of the task. Thus use of input-output provides a large existing database for LCA practitioners. However, LCA has been traditionally applied to products, revealing the limitations of the coarseness of the IO datasets that support the models. The level of aggregation in input-output models limits the ability to compare products within the same sector of the economy. This is a data limitation issue (Lave et al. 1995; Joshi 2000), one that we have not addressed in this chapter. (SIM is, if anything, even more demanding of data.) Moreover, traditionally IO models are cradle-to-output gate models, unable to assess downstream effects. Suh (2004) and others have addressed this issue through hybrid approaches.

Despite these shortcomings the application of the static IO model in LCA continues. However, neither traditional LCA nor the static Leontief IO model contain explicit temporal information, that is, describe in any detail how the production activity associated directly or indirectly with a product, and its related impacts, economic or environmental, is distributed over time.

In this chapter we introduce SIM in order to broaden the discussion of what IO models are, and how they can be applied in an LCA context. The relevance of SIM in this context is multi-fold: it is based on the fundamentals of the static IO model that capture the interdependencies of complex system; as a dynamic model it can express the intricacies of the order of occurrence of events in this broad structure; and it can be easily reduced back to the static model to examine whether a dynamic implementation brings value to understanding the system of concern. Two major additions have been made to the SIM to enhance its contribution to LCA. First, we have expanded the SIM model beyond a cradle-to-gate implementation typical of the static IO model. And second, static IO approaches are solutions to life cycle inventory issues related to LCA under the premise of integrating economic activity and human health and environmental repercussions over an infinite time horizon. Here, a more explicit relationship to such repercussions is made, specifically issues related to rates of production and emissions relative to persistence in the environment.

The IO model developed was applied to a simple five-sector production economy. The scenarios revealed that a potentially significant perspective can be gained by the addition of temporal information. Specifically, this is an understanding not only of the totality of emissions, but also indicators such as when the emissions will occur, peak values of the resulting emission burdens, and length of time thresholds are exceeded. This provides a more accurate assessment of the accumulative characteristics and associated impact profiles (e.g., exposure and dose characteristics that would describe human health repercussions). To fully examine and assess environmental and human health repercussions, the associated impact assessment models will need to be able incorporate this new temporal information.

Life cycle thinking and the associated tools of PLCA and EIO-LCA provide a necessary component for comprehensive assessment. However, post assessment, temporal information required for implementation strategies is the essential for planners. By adding temporal information, issues of the following can be examined more thoroughly: the appropriate integration period for replacement technologies; the amount of time the policy option is to be implemented to achieve its objectives; how long will the policy option induce change, and what will the final state of that change. The snapshot perspective provided by static LCA is one step in selecting preferred options. By providing temporal information, the solution set is more thoroughly understood by introducing the influences of the constraints of real world conditions. Additionally, of course, LCI information that contains spatial characteristics will also greatly enhance the analysis. In the real world, it is not just a matter of getting from point A to B, it also matters when and how you get there – when and where materials are procured and delivered, finances are secured and committed, and people employed and compensated, and practical technological solutions solved and proven practical, and as important, the ramifications of garnering these resources in time and space as they affect the environmental as well as, economic and political that they are interdependent upon.

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Chapter 13
Life-Cycle Assessment (LCA) as a Management Tool: An Emphasis on Electricity Generation, Global Climate Change, and Sustainability

Sergio Pacca

Introduction

The International Organization for Standardization (ISO) recommends the use of life-cycle assessment (LCA) to better comprehend and reduce environmental impacts related to manufactured products and services offered to our society. The principles of LCA are presented in the international standard ISO 14040; however, the implementation of the standard is not simple, and a couple of studies have addressed the existing limitations (Khan et al. 2002; Ross and Evans 2002).

One fundamental question is how to characterize a given environmental insult and how to select an appropriate metric to evaluate and minimize their impacts. This problem stem from the multiplicity of environmental insults caused by human activities, which are difficult to compare using a single approach. Moreover, most environmental problems have an intrinsic temporal dimension since environmental impacts persist in the environment for years and in some cases for generations. This yields sustainability concerns, which demand frameworks that allow the comparison of outcomes over time.

One problem that is still unresolved is the sustainability of our global climate, which requires the stabilization of the carbon dioxide (CO_2) concentration at an acceptable level. Climate change mitigation is challenging, and at the same time fascinating because it involves compromises between different nations and evokes a global decision making perspective, which at the same time affects local decisions and actions.

This chapter presents a decision-making framework for climate change based on the yardstick of the global carbon cycle. The cycle governs the accumulation of

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CO_2, which is the most abundant greenhouse gas (GHG) in the atmosphere .after water vapor, and a product of anthropogenic activities such as the burning of fossil fuels and deforestation. The buildup of CO_2 and other GHGs in the atmosphere increases the odds of extreme climate events, and justify GHG emission reductions now!

Environmental Decision Making Frameworks

Traditionally environmental decision-making has been focused on three classes of approaches (Portney and Stavins 2000):

1. Zero risk approach
2. Balancing approach
3. Technology based approach

The goal of the zero risk approach is to avoid the occurrence of any adverse health/environmental effect. While such an approach is the most desirable one, science and economics defy its practical application. Say we want to apply this principle to global climate change impacts of electricity generation. First, it is difficult to specify GHG emission thresholds, and second, comprehensive environmental assessments show that no electricity generation option is free of greenhouse gas (GHG) emissions (Pacca and Horvath 2002; Gagnon et al. 2002; ORNL/RFF 1995).

The balancing approach weighs competing outcomes and recommends regulatory action based on particular results. Usually this approach involves the use of cost benefit analysis (CBA), which requires the translation of all environmental values into economic values. The problem is that economics is ill-prepared to convert a wide range of non-market values into dollars, and in the case of climate change long time horizons intrinsic to the problem and disputes related to the valuation of local/regional costs complicate the task (Tol 2003; O'Neill 1993).

Finally, the technology-based approach characterizes the maximum attainable pollution level based on the adoption of the best available technology (BAT). A problem with this approach is that it is difficult to define the "best technology" because emissions can often be further reduced at higher costs, and technologies are constantly changing.

This chapter presents a LCA that moves the valuation of environmental sustainable technologies away from economic values and incorporates physical units and simple scientific models. The approach seeks the continuous improvement of technologies and encourages industry to perfect its current practices (Nash and Ehrenfeld 1996). The global warming effect (GWE) framework proposed herein is an objective method to guide industry towards sustainability based on the perils of climate change.

Method

The GWE method combines two well established methods: LCA and global warming potential (GWP).

Life-cycle assessment (LCA) is a method that captures resource consumption, pollution and solid waste production during every life cycle phase of a product or process leading to the production of a service.

Analytical steps in a LCA involve:

1. Compilation of material and energy inputs and outputs in a product/system
2. Evaluation of impacts associated with inputs and outputs
3. Interpretation of results

One of the challenges of LCA is the selection of the indicators used to evaluate the performance of a product or process. This is sometimes classified as a boundary problem, which means that the analyst selects a set of relevant indicators, while others are left aside. In any case, normative choices related to the selection of indicators are value laden and need to be explicit in the LCA (Hertwich et al. 2000). Usually, the choice of indicators to characterize the performance of a product or service is dynamic and its selection is shaped throughout the LCA by means of learning by doing type feedbacks. In the case of electricity generation technologies each technology class presents specific impacts. Nevertheless, the contribution of electricity generation to the emission of GHGs is notable, and justifies the use of a method to compare the performance of alternatives based on their impact on global climate change.

The GWE method seeks the stabilization of the GHG concentration in the atmosphere and the minimization of the potential climate change impacts. The use of the method reflects a concern with sustainability under a broader global standpoint, and its LCA facet adds comprehensiveness.

Accordingly, the LCA of greenhouse gas (GHG) emissions of a power plant takes into account emissions during the extraction of the resources, the manufacturing of the components, the construction of the power plant, its installation, its operation, its maintenance, and finally its decommissioning. In addition, the transport of materials, components, and fuels, which is part of almost all phases, is also considered an emission source (see Fig. 13.1).

LCA can be used in the assessment of various environmental problems; however, depending on the ultimate environmental/health implications the results of the

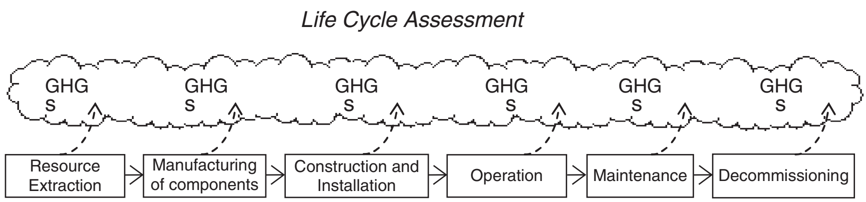

Fig. 13.1 Life Cycle Phases of a Power Plant

assessment are meaningless. For example, emissions of carbon monoxide kill people inside a garage but are harmless in the outdoor environment.[1] That is, most of the time, the location of air releases affects their environmental/health impacts. However, in the case of GHG emissions and their consequences, the spatial distribution is less critical, and the use of LCA renders a robust analytical outcome due to the inclusion of all emissions associated with the various products and services that are consumed to generate electricity.

The use of input output based LCA (IOLCA) is especially desirable since IOLCA tends to be more inclusive than process based LCA in capturing inputs to sustain a given process. An analysis based on a published literature review done by Lenzen and Munksgaard (2002) shows that the average of all IOLCA energy input to output ratio of wind farms is 2.7 times greater than the average of all process based LCA energy input to output ratios. That indicates that IOLCA usually account for more energy inputs than process based LCA.

The effect of GHG emissions is global and the timing of the releases or the way the analysis aggregates emissions that occur at different periods is more important than the spatial distribution of the emissions. The spatial distribution of emissions is not an issue because CO_2 and other GHGs are well mixed in the atmosphere, and the effects of climate change impact the whole world. In contrast, the temporal component of emissions impacts their potential effects. For example, the same amount of GHG released during the construction of a hydroelectric dam 50 years ago poses less potential effects when compared to the potential effects of GHG released from the construction and operation of a new natural gas power plant. That happens because each GHG has a characteristic residence time and eventually leaves the atmosphere and migrates to other pools.

Thus, in order to compare the potential effect of GHG releases at different moments, it is necessary to know their characteristic residence time to estimate how much of the gas is still in the atmosphere in the future. The problem is that the concentration of CO_2, which is a major GHG, is controlled by a myriad of processes and the representation of its persistency in the atmosphere through a single residence time is not accurate. At the same time, because of the importance of CO_2 due to its abundance in the atmosphere it is convenient to compare the effects of other GHGs to the effect of CO_2, by means of global warming potentials (GWP).

The persistence of CO_2 in the atmosphere is controlled by the carbon cycle, which may be represented by a parameterized pulse response function (PRF), as a function of time. One example of PRF is the one used in the GWP calculations by de IPCC, which is derived from a simple global carbon model known as the Bern model. The GWPs are used to normalize the effect of 1 kg of a specific GHG to the effect of 1 kg of CO_2. That is, both the chemical characteristics of different GHGs and the time they are released affect their impacts (Houghton et al. 2001).

The PRF function allows one to calculate the contribution of a stream of carbon emissions over time to the future atmospheric concentration. The idea parallels the present worth (PW) calculation of an income stream ($S_{(t)}$) (Formula 13.1). However,

[1] Eventually, CO is oxidized into CO_2 and contributes to climate change.

in the case of GHGs the monetary discount rate (r) is replaced by the inverse of the residence time (τ) of the greenhouse gas,[2] whereas in the case of carbon dioxide, the exponential decay function is replaced by a parameterized function that represents the fraction of carbon in the atmosphere as a function of time.

$$PW = \int_0^t S_{(t)} e^{-rt} \tag{13.1}$$

The parameterized function is the output of the Bern model cycle assuming a given pulse emission into the atmosphere (10 Gt of carbon in 1995) and a constant background concentration (353.57 ppm) (Enting et al. 1994). Therefore, to determine the amount of CO_2 emitted that remains in the atmosphere after a certain time it is necessary to replace e^{-rt} by $F[CO_2(t)]$ (Formula 13.2) and integrate the function over the desired time interval (t). If the stream of CO_2 emissions are constant over time they can be taken out of the integral and multiplied by the integral of Formula 13.2 to determine the CO_2 remaining in the atmosphere.

$$\begin{aligned} F[CO_2(t)] = {} & 0.175602 + 0.137467e^{-t/421.093} + 0.185762e^{-t/70.5965} \\ & + 0.242302e^{-t/21.42165} + 0.258868e^{-t/3.41537} \end{aligned} \tag{13.2}$$

One advantage of using the function derived from the carbon cycle is that it offers a better evaluation of the cumulative effect of carbon emissions than an economic assessment based on market discount rates or discount rates usually applied to public investments. Figure 13.2 compares $F[CO_2(t)]$ versus a 3.2% annual discount rate, which is suggested by the Office of Management and Budget of the White House to evaluate the feasibility of public projects in the US (OMB 2003). It shows that the future concentration of CO_2 after 50 years is twice as much the economic value ascribed to CO_2 over the same period discounted at a 3.2% discount rate. The use of

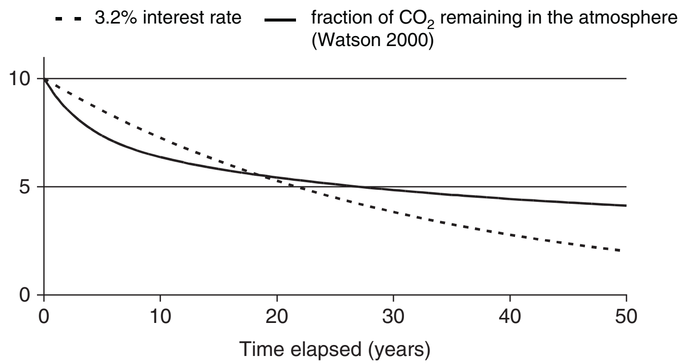

Fig. 13.2 Comparison of $F[CO_2(t)]$ Versus a 3.2% Annual Discount Rate

[2] Residence time for various GHG can be obtained from Chapter 6 of the Working Group 1, Science volume, of the Third Assessment Report of the IPCC, 2001 (Houghton, 2001).

economic assessments in less developed countries is even of bigger concern because higher changes in the consumer price index compared to more developed countries reflect a more abrupt loss of monetary value (UNDP 2004).

The point is not only to be more precise about the future relevance of a given GHG release but also to draw attention to the factors that affect the global carbon cycle and the human impacts related to such factors. That is, anthropogenic disruptions of the carbon cycle are relevant in the assessment of technologies and their global climate change impacts.

Actually, the PRF implicitly embeds a set of assumptions that affects the shape of the function. The PRF it is the output of a box model that represents the global carbon cycle, which is affected by various anthropogenic activities. One contentious issue in the model is the treatment of flows of carbon between the atmosphere and the terrestrial ecosystem. The science in this area is progressing rapidly, and new knowledge may be incorporated in the models in the future. Another important assumption is the background CO_2 concentration in the atmosphere over the period of analysis, which usually demands the construction of scenarios based on various assumptions about the future. Scenarios are affected by many other parameters such as economic growth, technology change, population, land use change, and energy policy (Fig. 13.3).

The PRF plotted on Fig. 13.3 assumes a fixed CO_2 background concentration of 353.57 ppm of CO_2 from 1990 onwards; however, the current concentration is 376 ppm (Keeling and Whorf 2003). If the model runs with the current concentration instead of the 353.57 ppm concentration the future concentration of CO_2 is going

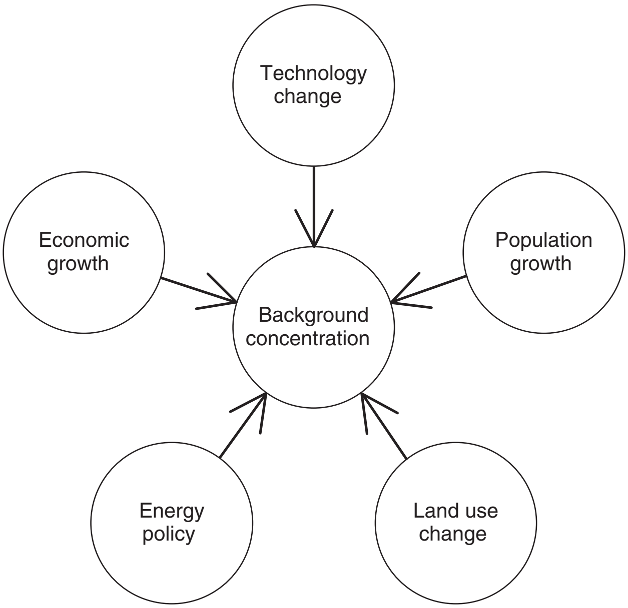

Fig. 13.3 Parameters Affecting CO_2 Background Concentration

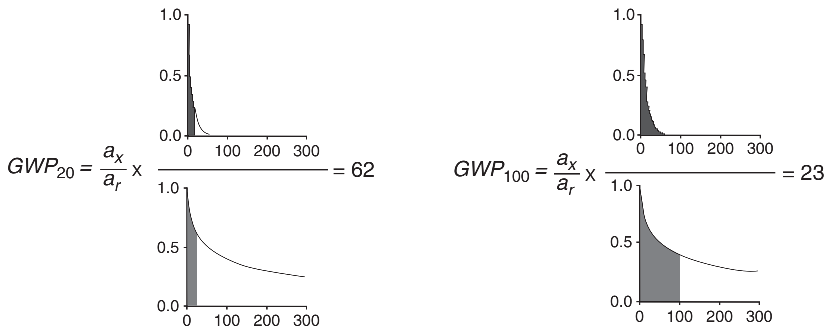

Fig. 13.4 Graphical Representation of GWPs Calculation over 20 and 100 Years

to be even higher. The assumption that the background concentration is fixed is not realistic, and a more realistic figure would incorporate to the calculations an increasing CO_2 profile as the background concentration and would result in even higher future concentrations given the parameterized model.

Nonetheless, the PRF described in Formula 13.2 is used by the latest IPCC report to calculate the GWPs. The GWPs were proposed to compare the potency of 1 kg of any GHGs to the potency of 1 kg of CO_2 over discrete time periods (20, 100, and 500 years). The GWP was not proposed as a proxy for impacts because it only compares the potency of a GHG to the potency of CO_2. For example, the GWP calculated by the IPCC for methane is a function of the analytical period, the ratio between the radiative efficiencies of methane and CO_2 and the residence time of methane and CO_2 in the atmosphere (Fig. 13.4). In contrast, this paper proposes the GWE as a proxy for global climate change impacts. The GWE inherits from the GWP the ability to aggregate and compare effects arising from emissions of different GHGs, and uses LCA to captured emissions associated with a given technology.

In summary, the GWE is a novel method that combines a life-cycle assessment (LCA) approach with a method inspired in the global warming potentials (GWP) method. The GWE compares and aggregates life-cycle emissions of power plants over flexible analytical periods, and intends to reconcile local decisions with global climate decision-making. The GWE can be applied to various technologies. As an example, the use of GWE to compare electricity generation options is presented.

Example: Application to Electricity Generation Sources

The use of GWE to select amongst different electricity generation sources results in significant GHG emission reduction (Pacca and Horvath 2002). Currently Anthropogenic releases of greenhouse gases (GHGs) in the biosphere are the major cause for climate change, and electricity generation accounts for 2.1 Gt year^{-1} (Giga Mg of carbon per year) or 37.5% of total global carbon emissions (Metz et al. 2001).

No electricity generation system is free of greenhouse gas (GHG) emissions through their entire life cycle, despite some being GHG-free in the operation phase. A comparative assessment of different sources available to power industrial activities contributes to the sustainability of a sector that relies on electricity as part of the inputs of its manufacturing chain.

The effects of different electricity generation options on climate change are determined using the GWE, which is the sum of the product of instantaneous GHG emissions (M) and their specific time-dependent GWP. The GWE is the sum of all GHG emissions of a power plant over a given analytical period. Therefore, the global warming effect in mega grams of CO_2 equivalent ($MgCO_2Eq$) is:

$$GWE = \sum M_j \,.\, GWP_{j,TH} \tag{13.3}$$

where:

M_j is the mass (in Mg) of the instantaneous emission of each GHG "j", and
$GWP_{j,TH}$ is the global warming potential for each GHG "j" calculated over the time horizon "*TH*" using Equation (13.2).

Instantaneous emission values *Mj* could be obtained from different LCA libraries, which compile emission factors for various materials and processes; however, this analysis is based on information from the economic input-output matrix (www.eiolca.net).

For example, the GWE of CH_4 emissions over 20 years corresponds to the quantities emitted in years 1, 2, 3, ... 20 multiplied by methane's GWPs when the *TH* is 20, 19, 18, ... 1 years, and then added. In the case of an emission that is constant every year there is no need for the calculation of periodical GWPs. In this case, the calculation of GWP involves multiplying the GWP calculated for the total time period by the constant annual emission rate to give the radiative forcing produced by the annual release of the GHG. If emissions vary from year to year then the calculation of specific GWPs is necessary.

The GWP for a GHG and a given time horizon is (Houghton et al. 2001):

$$\mathrm{GWP} = \frac{\int_0^{\mathrm{TH}} \mathrm{a_x} \cdot \left[\mathrm{x}_{(\mathrm{t})}\right] \mathrm{dt}}{\int_0^{\mathrm{TH}} \mathrm{a_r} \cdot \left[\mathrm{r}_{(\mathrm{t})}\right] \mathrm{dt}} \tag{13.4}$$

where:

a_x is the radiative efficiency of a given GHG. The radiative efficiency represents the radiative forcing divided by the change in its atmospheric concentration prior to the industrial revolution up to 1998 (the base year of the EIO-LCA data is 1997). The Radiative forcing measures the magnitude of a potential climate change mechanism. It represents the perturbation to the energy balance of the atmosphere following a change in the concentration of GHGs.

a_r is the radiative efficiency of CO_2, which is assumed to be equal to 1 because all other GHGs are compared to CO_2.

$x_{(t)}$ in the numerator is the predicted airborne fraction of GHG, which is represented by an exponential decay function using a GHG-specific atmospheric lifetime.

$r_{(t)}$ in the denominator represents the CO_2 response function used in the latest IPCC reports to calculate GWPs, which appears in a footnote of IPCC Special Report on Land Use, Land-Use Change and Forestry (Watson 2000).

$_{TH}$ is the time horizon between the instantaneous release of the GHG and the end of the analysis period.

Therefore, the impact of each technology on global climate change is a function of the future fraction of GHG in the atmosphere compared to the effect of CO_2 over the same period. In addition, in the case of CH_4, it is assumed that all CH_4 oxidizes into CO_2, which is not captured by the GWP calculations for CH_4, and therefore is added to the mass of CO_2 left in the atmosphere (Houghton et al. 2001).

The CO_2 PRF is used to determine the future concentration of carbon in the atmosphere. Thus, the period of analysis affects the results of the analysis, and the lifetime of a facility, which does not necessarily matches the period of analysis, is solely a function of the obsolescence of its structures and technology. Consequently, the analysis may capture effects of upgrades, changes in technology, human values, resource availability, etc. If the period of analysis is extended beyond the need for upgrades of renewable power plants, the tendency is that the GWE normalized by kilowatt hour (gCO_2eq/kWh) stabilizes at a level dictated by emissions from recurring retrofits. In contrast, the GWE for fossil fueled power plants stabilizes much sooner since it is dictated by GHG emissions during fuel combustion (Fig. 13.5).

Emission of GHGs during the decommissioning of power plants are usually neglected but depending on the technology that value may be considerable and needs to be factored in the calculation of normalized emissions. In the case of hydroelectric plants a source of concern is the potential carbon emissions from sediments accumulated in the reservoir. The mineralization of carbon in sediments releases both CH_4 and CO_2 and because of the timing of these releases their impact could be relevant when normalized over the life time of the facility (Pacca 2004).

A recent estimation of sediment organic carbon (SOC) stored in large reservoirs in the US and large lakes in Canada show that the amount of carbon in the reservoirs is considerable. The question remaining is what is the fate of that carbon during the decommissioning of the dam and the removal of the sediments from the reservoir's

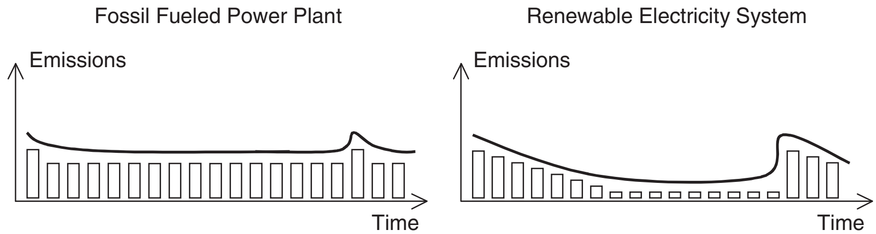

Fig. 13.5 Fossil Fuel and Renewable Energy Cycles

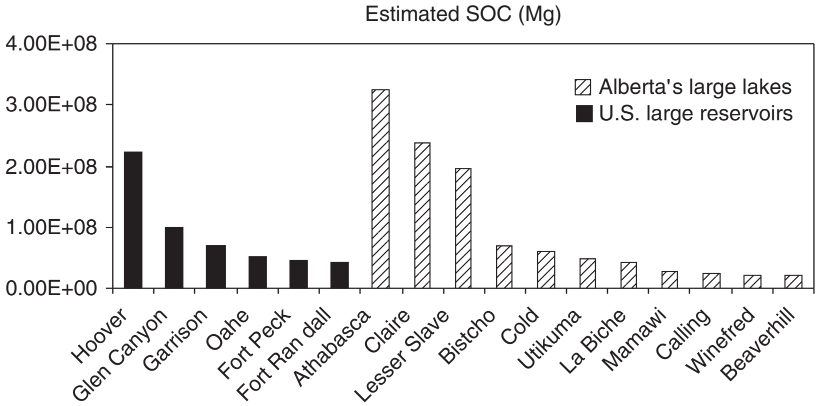

Fig. 13.6 Sediment Organic Carbon (SOC) Stored in Reservoirs and Lakes in North America

bed (Fig. 13.6)? If SOC is emitted to the atmosphere in the form of CH_4 or CO_2, the contribution of this source to the GWE of hydroelectric plants could be highly significant.

According to the GWE, the temporal distribution of emissions is more important than their spatial distribution, and the method captures this component very well. This characteristic is noteworthy because the GWE intends to be an alternative to economic analysis to make time dependent choices and extend the analysis to longer periods than those contemplated by market based discount rates. Another advantage of the method is that it works with relative comparisons instead of the ultimate/absolute impacts because it is based on GWP computations that compare the effect of GHG emissions to the emission of a similar amount of CO_2 over a chosen time horizon (Houghton et al. 2001).

The GWE method was applied to a comparative assessment of the Glen Canyon dam (GCD) hydroelectric plant and other imaginary electricity generation options that were conceived based on local resources availability as a replacement for GCD. The dam, which is located on the Colorado River close to the border of Utah and Arizona, forms the second largest reservoir in the U.S. The installed capacity of the power plant is 1.3 GW and in 1999 it produced 5.5 TWh. The LCA of a hydroelectric power plant involves the quantification of the materials and energy used in the construction of the facility. The major inputs are quantified and data from the economic input-output matrix (www.eiolca.net) is used to find out the emissions corresponding to the consumption of the inputs (Table 13.1). A similar strategy is used to evaluate impacts from the construction of the other electricity generation alternatives.

Results from the case study show that a wind farm appears to have lower GWE than the other alternatives considered, and the performance of hydroelectric plants depends on the ecosystem type displaced by the reservoir. All power plants are subject to retrofits after 20 years. Effects of retrofit appear in the 20th year of the evaluation of the wind farm (Fig. 13.7). For the Glen Canyon power plant, the upgrade 20 years after the beginning of operation increased power capacity by 39%,

Table 13.1 Major Construction Inputs and GWE (after 20 years) for Glen Canyon Hydroelectric Plant (Pacca 2002)

Inputs	Total MT	Unit cost (1992 $/MT)	Total cost (1992 $)	CO_2	$+CH_4$	$+N_2O$	=GWE
Concrete	9,906,809	30	297,652,257	400,792	751	7,898	409,441
Excavation (m^3)	4,711,405	na	114,839,000	3,812			3,812
Turbines and turbine generator sets	na	na	65,193,084	41,725	45	249	42,019
Power distribution and transformers	na	na	13,754,764	12,358	16	79	12,453
Steel	32,183	385	12,402,138	43,710	29	244	47,583
Copper	90	2,368	214,167	186	na	2	188
Aluminum	67	1,268	84,804	157	na	2	159
Total			**503,240,216**	**500,000**	**1,000**	**9,000**	**500,000**

Total emissions are rounded to one significant digit. MT, metric ton; GWE, global warming effect; na, not available.

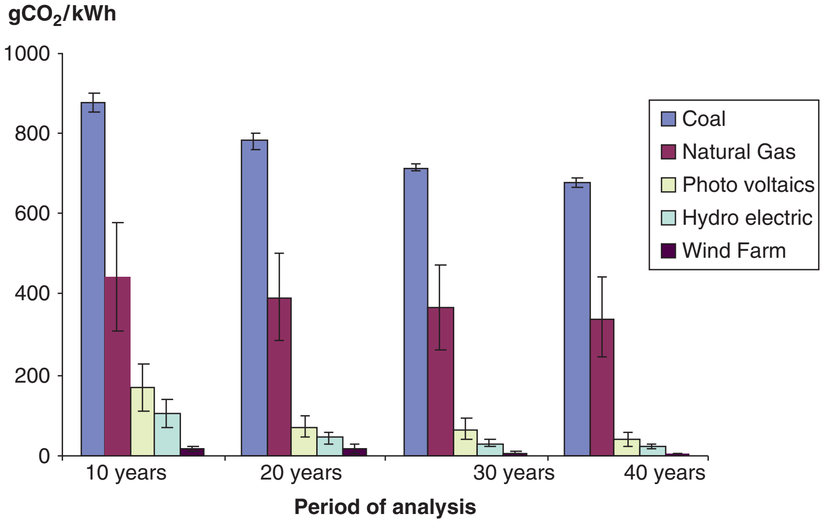

Fig. 13.7 Results from GWE Applied to the Glen Canyon Hydroelectric Plant Case Study

but resulted in about a mere 1% of the CO_2 emissions from the initial construction, and came with no additional emissions from the reservoir which accounts for the majority of the GWE (Pacca and Horvath 2002).

Long analytical periods allow the assessment of alternatives such as retrofits and upgrades that may pose a smaller environmental burden in the global environment than the construction of new structures. This logic should be considered as part of design for the environment initiatives that seek the minimization of the GWE.

However, emissions during the decommissioning of power plants should also be considered as part of the estimation of emissions normalized per energy output.

Hydropower is not an electricity source free of GHG emissions. Emissions from hydroelectric power plants may be produced by construction of the power plant, biomass decay of the vegetation flooded by the reservoir, lost net ecosystem production (NEP), and decomposition of carbon trapped in the reservoir's ecosystems during the decommissioning of the reservoir. A LCA of hydroelectric plants should include a hybrid analysis that translates land use change impacts in terms of their equivalent carbon emissions. The same approach holds for other electricity generation systems that also impact land such as large-scale massive PV installations or even road construction for maintenance of large wind farms.

Since the establishment of the Intergovernmental Panel on Climate Change in 1988, climate change science has attempted to investigate different areas of anthropogenic activities such as the ones represented in the set of IPCC special reports (Metz et al. 2000; Nakicenovic and Swart 2000; Watson 2000; Penner et al. 1999; Watson et al. 1997). The IPCC published a special report on land use change and the scientific knowledge on the issue is rapidly progressing. More recently a report with methods to Good Practice Guidance for Land Use, Land-Use Change and Forestry includes a set of models, carbon intensity, and carbon emission factors to calculate the impacts of land use change. As a concept the GWE method attempts to bridge in new scientific understanding between GHGs in the atmosphere and terrestrial ecosystems that are impacted by the footprint of large power plants such as a hydroelectric plant that rely on a large reservoir. In addition to the traditional assessment due to the combustion of fossil fuels, the GWE incorporates land use change information in the assessment of global climate change that is caused by the footprint of electricity generation technologies.

Policy Implications

The GWE method as a LCA tool has two management implications that foster sustainability in the industry. The first is the use of the GWE as a tool to compare different sources of electricity and to elect the option with the least impact on global climate change. The second is the minimization of global climate change impacts of a given activity/technology by identifying the life cycle phase/process that produces the greatest contribution to the GWE given a chosen analytical period. Results of the method are time dependent and may include an array of different greenhouse gases, which have their potential effect normalized to the potential effect of CO_2in the atmosphere. The method is conclusive when the concern is GHG emissions and sustainability.

Temporal flexibility is fundamental to support decision-makers that usually demand answers in the short run (decades). Moreover, due to unexpected outcomes shorter analytical periods than the 100-year time horizon associated with GWPs, which are usually applied to energy analyses, may be necessary to avoid an even greater problem arising from global climate change. Nevertheless, it is crucial to keep in mind that infrastructure is not perpetual and the end of life of any structure should be also part of LCA.

The GWE framework assumes a dynamic definition of technology since it intends to transform current practices into less polluting options. The continuous utilization of the framework as a management tool could feed a perpetual quest for sustainable energy technologies, which are always evolving and becoming more environmentally sound. Transparency is also important in the characterization of technologies. That is, when a technology is characterized as part of the assessment it is important to explicitly represent the chosen parameters. For example, energy conversion efficiencies of different power systems should be apparent in the analysis and reflect choices done by the analyst. That is the work should report if the analysis is based on a combined cycle or single cycle natural gas fueled turbines or on a crystalline or thin film photovoltaic modules, and the respective efficiencies should be explicitly stated.

Among the actions that could result from the application of the GWE is the use of renewable energy in the manufacturing of PV modules and the life extension of hydroelectric plants, provided that net impacts from their decommissioning are not highly cumulative over time. Impacts from decommissioning are heavily weighted by the GWE method because they are likely to occur at the end of the analytical period and they might be responsible for the release of CH_4, which has a high GWP value on the short run when compared to CO_2. The retrofit of hydroelectric power plants has been justified as a way to produce electricity at a minimal environmental cost; however, if the accumulation of sediments creates a potential emission source of GHG, the extension of the lifetime of hydroelectric plants may not be as beneficial as was expected.

The framework intends to be flexible in order to accommodate and transparently represent variability. The inclusion of a simple global carbon cycle model in the method provides a connection to socio-economic factors in the assessment and links population growth, development, technological changes, land-use change, and energy policy to the future CO_2 background concentration and the behavior of GHGs in the atmosphere over time.

Another use of the GWE method is to normalize results from previous published LCAs. There is a considerable number of energy LCAs in the literature dealing with impacts on climate change. They draw on different methods and assumptions to assess carbon dioxide emissions from electricity generation projects. Some of these studies present the primary information used to characterize a given power plant but rely on different assumptions and methods to finally calculate the contribution of the power plants. Most studies that run assessment of various GHGs use a fixed GWP to convert other GHGs to carbon dioxide equivalents; and therefore, are locked to fixed time horizons. Such strategy may constrain the use of the results and the comparison of different case studies. The use of the GWE framework to process data available from other published sources is useful to normalize and compare results without having to collect basic information about each project. This could be useful in setting up a database with various projects with different characteristics for a given power generation technology class, and establish benchmarks for various alternatives.

The use of the framework presented can be extended to other services and goods. The use of GWE decoupled from ultimate damages associated with climate change enhances the method's applicability since fewer assumptions and uncertainties are incorporated in the technology assessment. Consequently, the framework allows for a more clear presentation of its conclusions to a broad audience and instigates discussion about the conclusions. Even if the GWE method is not directly used to establish global emissions targets, its grand purpose is aligned with climate change mitigation, and its adoption gradually reduces the burden on the global environment.

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Chapter 14
Methods in the Life Cycle Inventory of a Product

Sangwon Suh and Gjalt Huppes

Introduction

Life Cycle Inventory analysis (LCI) is defined as a phase of Life Cycle Assessment (LCA) involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (ISO 14040 1998a). The concept of LCI has been adopted for cleaner production as early as the 1960s, and has had broad industrial and academic application in the last decades (Vigon et al. 1993). Compared to the other phases of LCA, LCI has been considered a rather straightforward procedure except for several issues such as allocation (see e.g. Fava et al. 1991). Reflecting this belief, the method used for LCI compilation has rarely been questioned, although a large number of software, LCI databases and case studies have been released so far. However, contrary to the common belief, different methods have been available for LCI, and they often generate significantly different results. Therefore, it is necessary to assess advantages and limitations of different LCI methods and properly select suitable one(s) for each specific application. It is the aim of this paper to review and compare available methods for LCI compilation, and guide LCA users to properly select the most relevant methods for their analyses in relation to the goal and scope of the study as well as the resources and time available. With adaptations, the results are applicable outside the realm of LCA as well.

This paper is organized as follows: first available methods of LCI compilation are presented. Two computational approaches, process flow diagram and matrix inversion, are assessed, and then methods that utilize economic Input-Output Analysis

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

(IOA) are described with special attention to hybrid analyses. Secondly, these methods are summarized and compared in terms of data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, available analytical tools, time and labor intensity, simplicity of application, required computational tools and available software tools. Finally, conclusions are drawn, and compliance of these methods to ISO standards and future outlooks are discussed.

Methods for LCI Compilation

In parallel with the direct computation using process flow diagram methods, also matrix inversion and IOA have been adopted for LCI compilation over a decade ago. In this section theory and principles of matrix representation of product systems, input-output (IO) approaches and combinations of these two are described.

Process Flow Diagram

LCI compilation using a process flow diagram appears in early LCA literatures including Fava et al. (1991), Vigon et al. (1993), and Consoli et al. (1993) and has been the most common practice among LCA practitioners. Process flow diagrams show how processes of a product system are interconnected through commodity flows. In process flow diagrams, boxes generally represent processes and arrows the commodity flows. Each process is represented as a ratio between a number of inputs and outputs. Using plain algebra, the amount of commodities for fulfilling a certain functional unit is obtained, and by multiplying the amount of environmental interventions generated to produce them, the LCI of the product system is calculated. Figure 14.1 illustrates a simple process flow diagram.

In the product system shown in Fig. 14.1, a unit of toaster is produced using 1 kg of steel and 0.5 MJ of steam, and is then used for 1,000 times and disposed of.

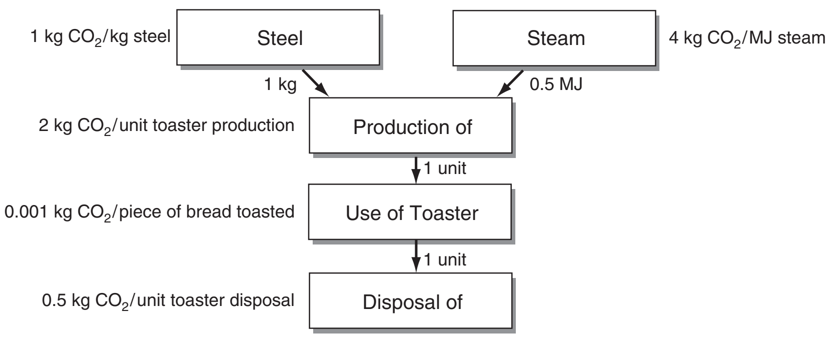

Fig. 14.1 Process Flow Diagram of a Simplified Product System

Producing1 kg of steel, 1 MJ of steam and 1 unit of toaster requires 1, 4 and 2 kg of CO_2 emission, respectively. Toasting 1 piece of bread and disposal of 1 unit of toaster emits 0.001and 0.5kg of CO_2, respectively. Suppose that the toaster under study produces 1,000 pieces of toast during its life time, and the functional unit of this product system is given by '1,000 piece of toast'. Then one can calculate the amount of commodity requirements and resulting environmental intervention as follows:

$$\begin{aligned}
&\left(\frac{1\,\text{kg CO}_2}{\text{kg steel}} \cdot 1\,\text{kg steel}\right) + \left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}} \cdot 0.5\,\text{MJ steam}\right)\\
&+\left(\frac{2\,\text{kg CO}_2}{\text{unit toaster prod.}} \cdot 1\text{unit toaster prod.}\right) + \left(\frac{0.001\,\text{kg CO}_2}{\text{piece of toast}} \cdot 1000\,\text{toast}\right)\\
&+\left(\frac{0.5\,\text{kg CO}_2}{\text{unit toaster disposed}} \cdot 1\text{unit toaster}\right) = 6.5\,\text{kg CO}_2 \qquad (14.1)
\end{aligned}$$

Computing LCI directly from a process flow diagram is not as easy as presented by Equation (14.1) if following conditions are not met:

- Each production process produces only one material or energy.
- Each waste treatment process receives only one type of waste.
- The product system under study delivers inputs to, or receives outputs from another product system.
- Material or energy flows between processes do not have loop(s).

Conditions from 'a' to 'c' are related to the multifunctionality problem. A detailed treatment of allocation as the solution to this problem is out of the scope of this paper but can be found elsewhere (Lindfors et al. 1995; Ekvall 1999; Huppes and Schneider 1994; ISO/TR14049 2000; Guinée et al. 2002). Condition 'd' requires that all processes in the product system under study do not utilize their own output indirectly. For example, suppose that production of 1 kg steel requires 0.5 MJ of steam and production of 1 MJ of steam also needs 0.5 kg of steel. This implies that the production of steel indirectly requires its own process output, steel through steam production process, and *vice versa*. A process flow diagram of this product system can be drawn as in Fig. 14.2.

Consoli et al. (1993) explicitly mentioned this problem and suggested to use an iterative method to find the solution. The example above is solved using the iterative method as follows

$$\begin{aligned}
&\left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}} \cdot 0.5\,\text{MJ steam}\right) + \left(\frac{1\text{kg CO}_2}{\text{kg steel}} \cdot 0.25\,\text{kg steel}\right)\\
&+\left(\frac{4\text{kg CO}_2}{\text{MJ steam}} \cdot 0.125\,\text{MJ steam}\right) + \cdots \left(\frac{1\text{kg CO}_2}{\text{kg steel}} \cdot 0.25\,\text{kg steel}\right)\\
&+\left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}} \cdot 0.125\,\text{MJ steam}\right) + \left(\frac{1\text{kg CO}_2}{\text{kg steel}} \cdot 0.0625\,\text{kg steel}\right) + \cdots \qquad (14.2)
\end{aligned}$$

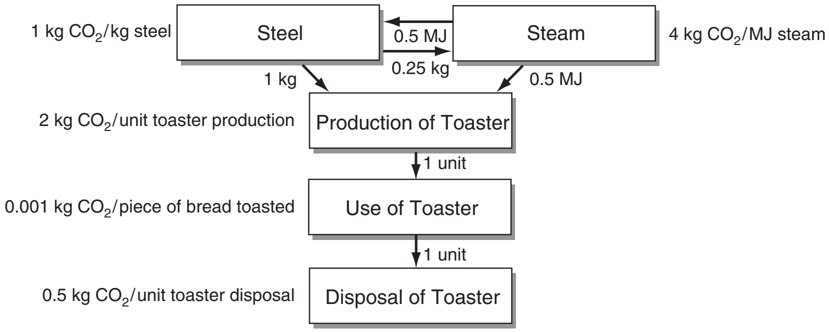

Fig. 14.2 Process Flow Diagram with an Internal Commodity Flow Loop

Up to the third iteration Equation (14.2) makes up 3.5625 kg CO_2. If added to the result in Equation (14.1), the LCI of the new product system in Fig. 14.2 becomes 10.0625 kg CO_2. As the number of iterations is increased, the result approaches the ultimate solution, although the speed of convergence becomes slower.

Instead, the exact solution can directly be calculated using infinite geometric progression. The general formula of Equation (14.2) can be written by

$$(4 \cdot 0.5) \sum_{n=0}^{\infty} 0.25^n + 0.25 \sum_{n=0}^{\infty} 0.25^n + 0.25 \sum_{n=0}^{\infty} 0.25^n + (4 \cdot 0.125) \sum_{n=0}^{\infty} 0.25^n \tag{14.3}$$

and since $\sum_{n=0}^{\infty} a^n = 1/(1-a)$ for $0 < a < 1$, the Equation (14.3) is solved by

$$= 4 \cdot \frac{0.5}{1-0.25} + 2 \cdot \frac{0.25}{1-0.25} + 4 \cdot \frac{0.125}{1-0.25} = 4 \tag{14.4}$$

Thus the total inventory of the product system shown in Fig. 14.2 becomes $6.5+4 = 10.5$ kg CO_2.

Matrix Representation of Product System

Although often overlooked, there are more computational approaches in LCI compilation using process analysis. The matrix inversion method was first introduced to LCI computation by Heijungs (1994). Basically Heijungs (1994) utilizes a system of linear equations to solve an inventory problem. We define $n \times n$ LCA technology matrix $\widetilde{\mathbf{A}} = \|a_{ij}\|$ such that an element, a_{ij} shows inflows or outflows of commodity i of process j for a certain duration of process operation, and especially inflows and outflows are noted by positive and negative values, respectively (for discussions on rectangularity see Heijungs and Suh (2002). We assume that processes at stake are being operated under a steadystate condition, so that selection of a specific temporal window for each process does not alter the relative ratio between elements in a column. Each entry of a column vector $\tilde{\mathbf{x}}$ shows the required process operation time of each process to produce the required net output of the system.[1] Then commodity net output of the system $\tilde{\mathbf{y}}$ is given by

$$\widetilde{\mathbf{A}}\tilde{\mathbf{x}} = \tilde{\mathbf{y}}, \tag{14.5}$$

which shows that the amount of a commodity delivered to outside of the system is equal to the amount produced minus the amount used within the system. Rearranging (14.5), the total operation time $\tilde{\mathbf{x}}$ required to meet the total commodity net output $\tilde{\mathbf{y}}$ is calculated by

$$\tilde{\mathbf{x}} = \widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{y}}. \tag{14.6}$$

Let us further define a $p \times n$ matrix $\widetilde{\mathbf{B}} = \left\| b_{ij} \right\|$ of which an element b_{ij} shows the amount of pollutants or natural resources i emitted or consumed by process j during the operation time that $a_{\cdot j}$ is specified. Suppose that $\widetilde{\mathbf{A}}$ is not singular then the total direct and indirect pollutant emissions and natural resources consumption by the system to deliver a certain amount of commodity output to the outside of the system is calculated by

$$\widetilde{\mathbf{M}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}}, \tag{14.7}$$

where $\widetilde{\mathbf{M}}$ is the total direct and indirect environmental intervention matrix, and $\tilde{\mathbf{k}}$ is an arbitrary vector that shows the functional unit of the system.

The commodity flows of the product system shown in Fig. 14.1 can be expressed by the LCA technology matrix as well:

$$\widetilde{\mathbf{A}} = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \tag{14.8}$$

The columns indicate steel production, steam production, toaster production, use of toaster and disposal of toaster from left to right, while each row is assigned to steel (kg), steam (MJ), toaster (unit), bread toasted (piece) and disposed toaster (unit).

The environmental intervention matrix, and the commodity net output of the system are given by

$$\widetilde{\mathbf{B}} = \begin{bmatrix} 1 & 4 & 2 & 1 & 0.5 \end{bmatrix} \tag{14.9}$$

and

$$\tilde{\mathbf{k}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix}, \tag{14.10}$$

respectively.

[1] The term 'operation time' is used here for convenience, while various synonyms including 'occurrence' (Heijungs, 1994), 'scaling factor' (Heijungs and Frischknecht, 1998) can be found in LCA literatures. In this work we followed Heijungs (1997).

The inventory result of this product system is now calculated using (14.7) as

$$\widetilde{\mathbf{M}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} = 6.5, \tag{14.11}$$

which is identical to the result shown in Equation (14.1). The matrix inversion method shows its strength as the relationships between processes become more complex. For example, Equation (14.7) directly calculates the exact solution for the system shown in Fig. 14.2 without using the iterative method or infinite progression. The LCA technology matrix in Equation (14.8) can be modified to represent the product system in Fig. 14.2 as

$$\widetilde{\mathbf{A}}' = \begin{bmatrix} 1 & -0.5 & -1 & 0 & 0 \\ -0.5 & 1 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}, \tag{14.12}$$

and the Formula (14.7) provides the inventory of the system by

$$\widetilde{\mathbf{M}}' = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}'^{-1}\tilde{\mathbf{k}} = 10.5, \tag{14.13}$$

which confirms the previous solution derived by the infinite geometric progression.

Additionally, representing product systems in a matrix provides various analytical tools as well. For instance, Heijungs and Suh (2002) provide a comprehensive treatment on matrix utilization and its analytical extensions for LCA practitioners Suh and Huppes (2002), and Suh and Huppes (2002a) introduces a supply and use framework and economic models developed by IO economists, including (Stone et al. 1963; ten Raa et al. 1984; ten Raa 1988; Kop Jansen and ten Raa 1990; Londero 1999), to deal with the allocation problem by using this matrix expression (Suh and Huppes 2002a).

IO-Based LCI

The result of the methods described in the Process Flow Diagrams and Matrix Representation of Product System sections of this chapter are referred to as LCIs based on process analysis. In principle, all processes in an economy are directly or indirectly connected with each other. In that sense, process analysis based LCI is always truncated to a certain degree, since it is practically not viable to collect process-specific data for the whole economy, and this problem has led the use of IOA in LCI.

In the original work by W. Leontief the input-output table describes how industries are inter-related though producing and consuming intermediate industry outputs that are represented by monetary transaction flows between industries

(Leontief 1936). The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output. Under this assumption, an $m \times m$ matrix $\mathbf{A}$ is defined such that each column of $\mathbf{A}$ shows domestic intermediate industry outputs in monetary values required to produce one unit of monetary output of another's. Let $\mathbf{x}$ denote the total industry output, then $\mathbf{x}$ is equal to the summation of the industry output consumed by intermediate industries, by households as final consumers, and by exports which is left out for convenience here. I.e.,

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y}, \tag{14.14}$$

where $\mathbf{y}$ denotes total household purchase of industry outputs. Then, the total domestic industry output $\mathbf{x}$ required to supply the total household purchases of domestic industry outputs is calculated by

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}, \tag{14.15}$$

where $\mathbf{I}$ denotes the $m \times m$ identity matrix. The model by Leontief has been further improved notably by R. Stone by distinguishing commodities from industry outputs (ten Raa et al. 1984; United Nations 1968). Although very rarely utilized for IO-based LCI, the supply and use framework, which has later been incorporated in the System of National Accounts (SNA) by the UN, has a particular importance for LCA applications of IOA, since LCA is an analytical tool based on the functionality of goods and services, and a supply and use framework makes it possible to distinguish different functions from an industry output (see Suh 2001).

Environmental extensions of IOA can easily be made by assuming that the amount of environmental intervention generated by an industry is proportional to the amount of output of the industry and the identity of the environmental interventions and the ratio between them are fixed. Let us define a $q \times m$ matrix $\mathbf{B}$, which shows the amount of pollutants or natural resources emitted or consumed to produce unit monetary output of each industry. Then the total direct and indirect pollutant emissions and natural resources consumption by domestic industries to deliver a certain amount of industry output is calculated by

$$\mathbf{M} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{k}, \tag{14.16}$$

where $\mathbf{M}$ is the total domestic direct and indirect environmental intervention matrix, and $\mathbf{k}$ is an arbitrary vector that shows net industry output of the system, which will be supplied to the outside of the system. IO-based LCI uses basically the Formula (14.16).

Applications of IOA to LCA started from early 1990s. (Moriguchi et al. 1993) utilized the completeness of the upstream system boundary definition of Japanese IO tables for LCA of an automobile (Moriguchi et al. 1993). Later, this line of approach has been further enriched using more comprehensive environmental data in the US (Lave et al. 1995). Since all transaction activities within a country are, in principle, recorded in the national IO table, it is often argued that the system boundary of an IO-based LCI is generally more complete than that of process analysis (see e.g. Hendrickson et al. [1998], Lave et al. [1995], Lenzen [2001]). However, this argument requires some conditions to be fulfilled. First, it should be clearly noted that the IOA itself can provide LCIs only for pre-consumer stages of the product life cycle, while the rest of the product life cycle stages are outside the system boundary of IOA. Second, the amount of imported commodities by the product system under study should be negligible. Otherwise errors due to truncation or misspecification of imports may well be more significant than that due to cut-off in process based LCI.[2] Thirdly, data age of IO-based LCIs is normally older than process-based one, since it takes 1 to 5 years to publish IO tables based on industry survey. Therefore, IO-based LCIs are a less desirable choice especially for the product systems that heavily rely on imported goods or newly developed technologies.

Another limitation of IO-based LCI is due to the aggregation of industries and commodities. Generally, IO tables distinguish not more than several hundred commodities, so that a number of heterogeneous commodities are included within a commodity category, diluting differences between them. Suh and Huppes (2001) empirically showed in a case study that due to this aggregation problem, the result of IO-based LCI can be much less than that of process based one, and the converse may be true as well (Marheineke et al. 1998).

Nonetheless, the biggest practical obstacle in applying IO technique to LCI is the lack of applicable sectoral environmental data in most countries. Although there are some fragmental emission inventory databases available, differences in the level of detail, base year and industry classification make it difficult to construct well-balanced sectoral environmental data in most countries.

So, IO-based LCI methods can provide information on the environmental aspects of a commodity on the basis of a reasonably complete system boundary using less resources and time. For a commodity of which the product system heavily relies on imports and newly developed technologies, however, applicability of IO-based LCI methods is rather limited.

Hybrid Analysis

IO-based inventory is relatively fast, and upstream system boundary is more complete within the national level, while process-based LCI provides more accurate and detailed process information with a relatively more recent data. Linking process-based and IO-based analysis, combining the strengths of both, are generally called *hybrid method* (Wilting 1996; Treloar 1997; Marheineke et al. 1998; Joshi 2000;

[2] By endogenising imports in the use matrix, it is assumed that imported goods are produced under the same input-output structure of the domestic economy, which can significantly reduce the truncation error. However, the assumption of identical input-output structure of imported goods may still induce errors.

Suh and Huppes 2002b). So far hybrid analysis has been adopted to LCI compilation in different ways, that will be distinguished here as tiered hybrid analysis; IO-based hybrid analysis; and integrated hybrid analysis.

Tiered Hybrid Analysis

The concept of tiered hybrid analysis appears from the 1970s (Bullard and Pilati 1976; Bullard et al. 1978). Bullard and Pilati (1976) and Bullard et al. (1978) combined process analysis similar to the method described in the Process Flow Diagrams section of this paper, with IOA to calculate net energy requirements of the US economy.

Tiered hybrid analysis utilizes process-based analysis for the use and disposal phase as well as for several important upstream processes, and then the remaining input requirements are imported from an IO-based LCI. Tiered hybrid analysis can be performed simply by adding IO-based LCIs to the process-based LCI result. (Moriguchi et al. 1993) introduced the tiered hybrid approach in LCA, and Marheineke et al. (1998) also used the tiered hybrid approach in a case study of a freight transport activity (Moriguchi et al. 1993; Marheineke et al. 1998). Model II by Joshi 2000) describes this approach as well (Joshi 2000). The Missing Inventory Estimation Tool (MIET) by Suh (2001) and Suh and Huppes (2002b) is a database to support tiered hybrid analysis using 1996 US IO table and environmental statistics (Suh 2001; Suh and Huppes 2000). Entering the amount of commodity used by the product system either in producers' price or purchasers' price, MIET returns inventory results as well as characterized results of the commodity.

Tiered hybrid analysis provides reasonably complete and relatively fast inventory results. However, the border between process-based system and IO-based system should be carefully selected, since significant error can be introduced if important processes are modeled using the aggregated IO information. Second, there are some double-counting problems in tiered hybrid analysis. In principle, the commodity flows of the process based system are already included in the IO table, so that those portions should be subtracted from the IO part. Third, the tiered hybrid model deals with the process-based system and the IO-based system separately, so that the interaction between them cannot be assessed in systematic way. For example the effects of different options at the end of the product life cycle, which can change the industry-interdependence by supplying materials or energy to the IO-based system, cannot be properly modeled using the tiered hybrid method.

IO-Based Hybrid Analysis

Treloar (1997) employed the IO-based hybrid approach for the analysis of energy requirements in Australia (Treloar 1997). Joshi (2000) also used the same line of approach for LCA of fuel tanks (Joshi 2000). Generally, the IO-based hybrid approach is carried out by disaggregating industry sectors in the IO table, while the tiered hybrid method is applied for the use and end-of-life stages of the product life cycle (Joshi 2000). Suppose that industry j and its primary product i in an IO table is to be disaggregated into two (e.g. j_a, j_b, i_a and i_b). Then the augmented IO table can be constructed as:

$$\mathbf{A}' = \begin{bmatrix} a_{11} & \cdots & a_{1ja} & a_{1jb} & \cdots & a_{1n} \\ \vdots & & \vdots & \vdots & & \vdots \\ a_{ia1} & \cdots & a_{iaja} & a_{iajb} & \cdots & a_{ian} \\ a_{ib1} & \cdots & a_{ibja} & a_{ibjb} & \cdots & a_{ibn} \\ \vdots & & \vdots & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nja} & a_{njb} & \cdots & a_{nn} \end{bmatrix}. \tag{14.17}$$

Columns $a_{\cdot ja}$ and $a_{\cdot jb}$ should be estimated using information on upstream requirements of the process, and rows $a_{ia\cdot}$ and $a_{ib\cdot}$ should be estimated using sales information. The environmental intervention matrix should be disaggregated as well using detailed emission data of the disaggregated processes. This procedure can be performed in an iterative way, so that the augmented IO table becomes accurate enough to perform a comprehensive analysis. The LCI up to the pre-consumer stage, using IO-based hybrid analysis, is calculated by

$$\mathbf{M}' = \mathbf{B}'(\mathbf{I} - \mathbf{A}')^{-1}\mathbf{k}'. \tag{14.18}$$

Inventory results for the remaining stages of the product life cycle, including use and disposal, should be added manually as described in section on Tiered Hybrid Analysis. Since this approach partly utilizes the tiered hybrid method, the interactive relationship between pre-consumer stages and the rest of the product life cycle is difficult to model.

The disaggregation procedure is the most essential part of IO-based hybrid approach. Joshi (2000) suggested using existing LCIs for information sources of detailed input requirements, sales structure and environmental intervention.

Integrated Hybrid Analysis

Suh and Huppes (2000) suggested using hybrid analysis from the perspective of both LCA and IOA (Suh and Huppes 2000). These authors generally assume that information from IO accounts are less reliable than process specific data due to temporal differences between IO data and current process operation, aggregation, import assumptions etc. Therefore, the IO table is interconnected with the matrix representation of the physical product system (as described in the section on Matrix Representation of Product Systems) only at upstream and downstream cut-offs where better data are not available. Since information on the process-based system is gathered by direct inspections and questionnaires, purchase and sales records for cut-offs required to link the process-based system with the IO table may be relatively easy to obtain. The general formula of this hybrid model is

$$\mathbf{M}_{\mathrm{IH}} = \mathbf{B}_{\mathrm{IH}}\mathbf{A}_{\mathrm{IH}}^{-1}\mathbf{k}_{\mathrm{IH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{Y} \\ \mathbf{X} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{0} \end{bmatrix}. \tag{14.19}$$

Matrix $\mathbf{X}$ represents upstream cut-off flows to the LCA system, linked with relevant industry sector in IO table, and $\mathbf{Y}$ does downstream cut-off flows to the IO system from the LCA system. Each element of $\mathbf{X}$ has a unit of monetary value/operation time while that of $\mathbf{Y}$ has a unit of physical unit/monetary value. This model has been applied to several recent LCI studies including Suh and Huppes (2001), Vogstad et al. (2001) and Strømman (2001).

Since all stages of the product life cycle, including use and disposal phases, can be expressed by the LCA technology matrix, $\widetilde{\mathbf{A}}$, this approach does not need to apply a tiered hybrid method to complete an LCI, and thus full interactions between individual processes and industries can be modeled in a consistent framework.

Comparison Between Methods

Methods so far described are compared with criteria of data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, available analytical tools, time and labor intensity, simplicity of application, required computational tools and available software tools. (Table 14.1). As shown in Table 14.1, it is not that one specific method is superior to all others, but decisions can be made to select the most relevant tool based on goal and scope, and available resources and time.

Since both process analysis methods require process-specific information, data requirements as well as time and labor intensity are considered to be higher than for other methods. Compared to process-based analyses, methods that utilize IOA generally show smaller data requirements, that is, assuming that IO-based LCIs are already available. Integrated hybrid analysis is an exception, since it relies on full process analysis, and then utilizes IO-based LCI only for cut-offs. For both tiered hybrid and IO-based hybrid analysis, there are several criteria for which judgment can be case specific, since the boundary between detailed process-based analysis and IO-based analysis may vary. For example, time and labor intensity will rise, and source data uncertainty will be lowered as the process-based part becomes larger for these methods.

In terms of system boundary, three criteria are distinguished. Regarding the upstream system boundary, methods that utilize IOA show higher completeness, while process-based analyses are generally superior for other system boundaries. There are numerous analytical tools that have been developed in IOA field. Most of them

Table 14.1 Comparison Between Methods for LCI Compilation

	LCI based on process analysis		Input-output based LCI	Hybrid LCI		
	Process flow diagram	Matrix representation		Tiered hybrid analysis	IO-based hybrid analysis	Integrated hybrid analysis
Data requirements	Commodity and environmental flows per process	Commodity and environmental flows per process	Commodity and environmental flows per sector	Commodity and environmental flows per sector and process	Commodity and environmental flows per sector and process-based LCIs	Commodity and environmental flows per sector and process
Uncertainty of source data	Low	Low	Medium to high	Depends	Depends	Low
Upstream system boundary	Medium to poor	Medium to poor	Complete	Complete	Complete	Complete
Technological system boundary	Complete	Complete	Medium to pore	Depends	Depends	Complete
Geographical system boundary	Not limited	Not limited	Domestic activities only	Depends	Domestic activities only	Not limited
Applicable analytical tools	Rare	Abundant, e.g. in Heijungs and Suh (2002) [10]	Rare	Rare	Abundant	Abundant

Time- and labor intensity	High	High	Low, if environmental data available	Depends	Depends	High
Simplicity of application	Simple	Simple	Simple	Simple	Complex	Complex
Required computational tools	Excel or similar (no matrix inversion)	Matrix inversion (e.g. MatLab, Mathematical)	Excel similar	Excel or similar	Matrix inversion (e.g. MatLab, Mathematical)	Matrix inversion (e.g. MatLab, Mathematical)
Available software tools	Most available LCA software tools	CMLCA	MIET, EIOLCA	MIET + LCA software tool	–	CMLCA

can be applied for part of IO-based hybrid analysis, although use and disposal phases should be treated separately.

In terms of the simplicity of computation both IO-based and integrated hybrid analysis are considered to be more complicated than other methods, since these two approaches require some understanding on IOA. There are several computational tools and databases mentioned in Table 14.1. Chain Management by Life Cycle Assessment (CMLCA) is a software tool originally developed for education purposes although it can be successfully utilized for real case studies (Heijungs 2000). Economic Input-Output Life Cycle Assessment (EIOLCA) is a web-based IO-based inventory calculator that provides the amount of water usage, conventional pollutants emission, global warming gas releases and toxic pollutants emissions per sector output in monetary unit (Green Design Initiative 2008). Currently 1997 US environmental IO data is available from their web site. The Comprehensive Environmental Data Archive (CEDA) database is a commodity-based environmental IO database containing over 1,300 environmental intervention that are connected to over 80 major Life Cycle Impact Assessment (LCIA) methods (Suh 2004, 2005). The CEDA 3.0 database uses 1998 annual IO table of the US that distinguishes 480 commodities, and its new version uses 2002 IO table and environmental emission data. Abundant analytical tools from both matrix representations of product system as well as IOA can be applied to integrated hybrid analysis.

Finally, the mechanisms of the three hybrid methods in linking the process-based system part with the IO-based system part are compared. The computational structure of tiered hybrid, IO-based hybrid and integrated hybrid approach can be noted by matrix expressions shown in Equations (14.20), (14.21) and (14.19), respectively, with Equation (14.19) here repeated for easier comparison.

$$\mathbf{M}_{\mathrm{TH}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} + \mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{k} \tag{14.20}$$

$$\mathbf{M}_{\mathrm{IOH}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} + \mathbf{B}(\mathbf{I}-\mathbf{A}')^{-1}\mathbf{k}' \tag{14.21}$$

$$\mathbf{M}_{\mathrm{IH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{Y} \\ \mathbf{X} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{0} \end{bmatrix}. \tag{14.19a}$$

By arranging (14.20) and (14.21) for better comparison they can be noted as

$$\mathbf{M}_{\mathrm{TH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{k} \end{bmatrix} \tag{14.20a}$$

$$\mathbf{M}_{\mathrm{IOH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B}' \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}-\mathbf{A}' \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{k}' \end{bmatrix} \tag{14.21a}$$

Equations (14.20′), (14.21′) and (14.19) show the solution model of tiered hybrid analysis, IO-based hybrid analysis and integrated hybrid analysis, respectively. $\widetilde{\mathbf{B}}$, $\widetilde{\mathbf{A}}$

and $\tilde{\mathbf{k}}$ represent the environmental matrix, technology matrix and arbitrary final demand vector of the process-based part, respectively, while **B**, **A** and **k** those of the IO part. Prime (′) indicates an augmented (disaggregated) matrix or vector. Especially, $\widetilde{\mathbf{B}}$ and $\widetilde{\mathbf{A}}$ for IO-based hybrid analysis (Equation (14.21)) contain environmental interventions and commodity flows for the use and disposal phase of the product life cycle.

It is not difficult to see, by substituting **X** and **Y** in (14.19) with **0**, that the tiered and IO-based hybrid approaches in (14.20′) and (14.21′) are special cases of the more general formulation of hybrid approach in (14.19). Note here that **k** and **k**′ in (14.20′) and (14.21′) are equivalent with **X** in (14.19) (see Heijungs and Suh 2002). Two differences are that first, the tiered hybrid and IO-based hybrid analyses contains **0** matrices in the hybrid technology matrix, while the integrated hybrid analysis shows **X** and **Y** instead of **0**s. This difference clearly points out that there are no formal linkages between process-based system and IO-based system within the models of tiered and IO-based hybrid analysis. Instead, the linkages are given outside of the model by the final demand vector, which is the second visible difference. The final demand vector which is exogenously given for the net external demand contains **0** for integrated hybrid analysis, while others have **k** or **k**′ instead of **0**. The vectors **k** and **k**′ in Equation (14.20′) and (14.21′) show the amount of the commodities in the IO system that is used by the process-based system. In contrast, **X** and **Y** of integrated hybrid analysis show the commodity flows both from the IO system to the process-based system and from process-based system to the input output system, in Equation (14.19). In case the flows outgoing from the process-based system to the IO-based system are negligible, Equation (14.19) may generate a similar result with that from Equation (14.20), although often it is not the case, as large scale processes, such as steel or electricity generation processes, that are dealt with in the process-based system may supply only small portion of their outputs to the process-based system under study. These differences are graphically illustrated in Fig. 14.3.

The bold outer line shows the overall system boundary and the dotted line shows the boundary between the process-based system part and the IO system part. The shaded area indicates the IO system and the white one the process-based system. The dotted area in (b) indicates the disaggregated IO system, while the full white

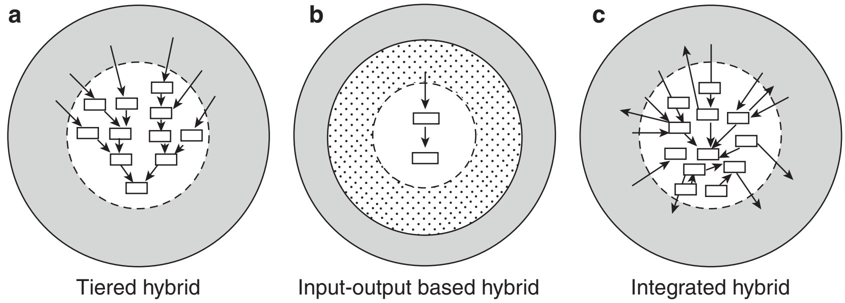

Fig. 14.3 Interactions Between Process-Based System and IO System of Hybrid Analyses

refers to use and post-use processes only. In the tiered hybrid analysis, commodities going into the process-based system are modeled using the IO-based system. Notice that only one direction of arrows, from the IO-based system to process-based system, is possible in tiered hybrid analysis. In the IO-based hybrid analysis, only two process types, for use and disposal, are described by the process-based system, in white, while many commodity flows are described in the disaggregated IO part, the dotted area. In the integrated hybrid analysis, the major part of commodity flows are represented by the process-based system, and cut-offs are linked with the IO-based system. Notice that here arrows can go both directions, from the IO-based system to the process-based system (upstream cut-offs/links) and from the process-based system to the IO-based system (downstream cut-offs/links) forming a network structure rather than a tree.

ISO Compliance

The issue related to compliance with ISO standards is briefly discussed. ISO 14040 and ISO 14041 generally define the framework without specifying which computation method is to be used (ISO 14040 1998a; Green Design Initiative 2008). Therefore, both LCI computation methods using process flow diagram and matrix representation are considered to be compatible with ISO standards. Methods that utilize IOA can be considered differently. According to ISO, LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system *throughout its life cycle*[3] (ISO 14040 1998a). Thus, what is so-called cradle-to-gate analysis, which is the case for IO-based LCI is not an LCA study in strict sense of ISO standards, since it does not contain the use and disposal phase within its scope. This implies that IO-based inventory alone is not considered as ISO compatible LCI in general sense. However, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. Then the ISO compliance of introducing external model such as IO accounts can be questioned for hybrid methods. ISO 14041 (clause 4.5), "Modeling product systems" mentioned about the practical difficulties of describing all the relationships between all the unit processes in a product system and opens up possibilities of using models to describe key elements of physical system (ISO 14041 1998b). Hence, in principle, there are no restrictions in using IO accounts to describe upstream process relationships if the model and assumptions are clearly noted.

A second issue where non-compliance might occur is in allocation (ISO 14041 1998b). However, in ISO 14041, a range of options is given, with a requirement on transparency and on application of several methods if more of them apply. Such refinements are not yet discussed in this paper. However, the options of allocation by substitution or by partitioning both can be developed in pure IOA and

[3] Italics by current authors.

in hybrid analysis as well, which suggests possible compliance to ISO standards (see Suh and Huppes 2002a). For more detailed discussion on the issue of ISO compliance and system boundary problem, see Suh et al. (2004).

Conclusions and Discussion

Having made the survey, which methods for inventory construction can be recommended for LCA users? Although this very much depends on the specific features of the case at hand, especially considering goal and scope and available resources and time, some main guidelines can be given.

Matrix representation of product systems clearly is superior to the flow diagram method for all but the most simplified systems. Pure IO-based LCI can at best be used as a first proxy. So the next question is how does hybrid LCI compares to process-based analysis?

When comparing this pure process-based LCI with the integrated hybrid analysis, the latter has a clear advantage in terms of the quality of the result, especially in terms of system completeness. With information on the monetary value only for cut-off flows and with improved availability of environmentally extended IO data, preferably regionalized, the additional data requirements and the added complexity both may become quite limited. This seems a best choice for the future, if not for now already. However, it adds to the cost of already expensive and time-consuming full process LCA.

What may be the role of the other two types of hybrid analysis? The tiered hybrid analysis has the appeal of easy extension on existing simple partial LCA systems in filling in the gaps. However, the connection between the two inventory subsystems is made externally, ‘by hand’. The only partial links between the systems remain a source of error which is difficult to assess. The IO-based hybrid analysis is conceptually more mature. Although use and post-use processes are not incorporated in the IO part, and the links between the systems remains external, the IO-based hybrid analysis shows higher resolution for the IO-based system and does not have problems of overlap: the processes based system does not contain commodity flows represented in the IO table.

With time and money available, the choice clearly is for the integrated hybrid analysis. However, what if time and money are scarce? Then a different choice can be made. A rational strategy at a case level could be to consider a step-wise approach, where tiered hybrid approach is performed first by specifying upstream cut-offs ($\mathbf{k}$ or $\mathbf{X}$). With additional resources and time available, then the next step will be specifying downstream cut-offs ($\mathbf{Y}$) and further disaggregating IO table ($\mathbf{A}'$). The step-wise approach can start with few important processes worked out in detail, that is quite cheap and fast. Then, focused on where main contributions and uncertainties are, a stepwise build-up of resolution can follow, until a sufficient quality of result has been developed. In this development, there always is a full and consistent system definition, with resolution being added as required.

Prerequisites for this highly important development are in the field of databases and software. LCA databases are to be adapted to the integrated hybrid method by supplying monetary data on process flows. IO data bases, still available mainly at the single country level, should develop into a regionalized, trade-linked global system. High-quality IO database can be set up on the basis of supply and use tables, with detailed commodity flows available in most primary data sources where the supply and use tables are constructed from. Also, the environmental data in the IO part, present now for a few countries only in greater detail, can become available for many more countries. Since most commercially available LCA software is not able to handle matrix inversion for LCI computation, a software tool development that enables hybrid analysis by broader LCA users is also required.

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Part IV
Sustainable Consumption

Chapter 15
Principal Methodological Approaches to Studying Sustainable Consumption: Scenario Analysis, Ecological Footprints and Structural Decomposition Analysis

Richard Wood and Manfred Lenzen

Introduction

The environmental impact of a person, whether measured in terms of average energy consumption, specific CO_2 emissions, or a person's occupation of ecological space, has received sustained interest at least since the 1970s. The need for quantifying drivers, key impact segments and leverage points from a consumption perspective lead to the formulation of various indicator concepts and analysis techniques, amongst which are scenario analysis, the ecological footprint, and structural decomposition analysis. Since *sustainable consumption* has become a key interest of environmental policy makers, not at least through the 2002 World Summit on Sustainable Development, there is an increased interest in such investigations.

Rather than providing a broad literature review of the issue, the purpose of this paper is to concurrently demonstrate example applications of the three input-output based methods mentioned above – scenario analysis, the ecological footprint, and structural decomposition analysis – and by so doing, provide a means for comparison and critique. Whilst all three analysis techniques are concerned with the overall theme of the study of sustainable consumption, they each provide a different focus for assessment and interpretation, and are thus suited to diverging purposes and research questions.

The distinguishing facet of *scenario analysis* is that it is principally used in assessment by describing hypothetical states – generally about the future, and often for purposes relating to identifying bottlenecks, potential problems and opportunities, and for analyzing comparative benefits/losses between hypothetical states, or between hypothetical and present states.

In contrast, the *ecological footprint* is principally used to analyze the effect of current (or past) consumption. By converting all impacts into a single index (land),

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the ecological footprint also allows comparison to a finite upper limit of available land space/biocapacity, and provides a more easily interpret result for use in education and communication.

Structural decomposition analysis (SDA), however, extends beyond the basic static model in order to reveal the driving forces for changes in the economy over time. For this purpose, decomposition techniques can be applied "by means of a set of comparative static changes in key parameters" (Rose and Miernyk 1989). This provides results on progress towards/away from goals of sustainable consumption, but due to its greater complexity, often only considers one impact indicator type at a time.

The main aim of the applications demonstrated in this paper is to study some of the effects of consumption in terms of the goal of 'sustainable consumption'. In order to illustrate the different foci of the three methods, we present an Australian case study for each. Since the research questions addressed by each method differ to a certain degree, it is difficult to find a unifying 'theme' to compare them. Firstly, the scenario analysis investigates the effects of a current and hypothetical diet. The ecological footprint investigates the land and energy use of the current Australian consumption pattern, and the structural decomposition analysis focuses on contributing factors to greenhouse gas emissions induced by the consumption of the last 30 years.

Having sketched the principal commonalities and distinctions in this section, we describe the three techniques separately in section "Methodology", with an introduction and critique, and the methodology for an application of each technique. The results of these applications are presented in section "Structural Decomposition Analysis", along with brief analysis, once again methodologically separately. Finally, in section "Australian Case Studies", the three techniques are once again merged, in being compared and critiqued against each other.

Methodology

Scenario Analysis

Both consumers and policy-makers often face conflicts between economic and environmental issues arising from apparent compromises between, for example, the environmental pollution from industries and the employment and revenue those industries provide. For example, potential employment reductions are often used as poorly substantiated threats in public debates on greenhouse gas emissions. A reliable scenario analysis methodology that can assess competing factors such as these is desirable for making the inherent comprises more transparent, and thus better informing decision-making.

Historically, attempts to employ scenario analysis were stimulated by the oil price shocks of the early 1970s to resolve conflicting energy and employment issues of consumption. Numerous energy analyses of specific tasks were carried out,[1] using process or input-output analysis (Chapman 1974), or hybrid methods (Bullard et al. 1978). Based on theoretical work by (Leontief and Ford 1970), Hannon and co-workers extended input-output-based energy analysis in order to investigate so-called *dollar-energy-labor (DEL) impacts* of personal consumption decisions. These DEL impacts characterize energy and labor inputs, which are, directly or indirectly, required to produce the output that is needed to meet consumer demand. For example, (Bezdek and Hannon 1974) examined the effects of re-investing government spending on road infrastructure into six other types of governmental programs such as health insurance, education, water and waste treatment, tax relief, and law enforcement. One of the alternatives was to divert the funding to railway and mass-transit spending which was considered a direct substitute for the road construction. Five of six alternative spending options were associated with reduced energy use, while all alternatives required an increase in employment. In these and other studies,[2] DEL impacts were calculated by multiplying monetary expenditure data with *energy and labor intensities*, which were obtained from input-output analysis. While the studies mentioned above were mainly motivated by the substantial increase in energy prices at that time, recent research is more concerned about the environmental consequences of energy use, such as climate change. (Laitner et al. 1998) use input-output-based multipliers to determine the emissions, employment, and other macroeconomic benefits of innovation-led investments in energy-efficient and low-carbon technologies. They conclude that such re-directing of investments provides economic efficiency and productivity gains directly, and that the associated "shift in spending pattern away from fossil-fuel-based energy supply has an inherently employment-enhancing effect, since these traditional energy supply sectors are substantially less labor-intensive than the rest of the US economy, and one of them (petroleum) is heavily import-dependent". Another recent study of future scenarios was completed by Duchin and Lange (1994). They evaluated the feasibility of the recommendations of the Brundtland Report, and found them unrealistic. Using an input-output model of the world economy, closed for international trade, they found that the considerable savings from technological improvements were more than offset by both population increases, and increases in standards of living, particularly in the developing world.

As an example application, in this work, input-output based multipliers are applied to examine the impacts of alternative dietary options for the Australian population in terms of energy and employment, and in addition, greenhouse gas emissions, income, imports and taxes. A current and an environmentally motivated diet are investigated. Both alternatives were chosen to satisfy the perfect-substitutes criterion.

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[1] Herendeen (1973, 1978), Berry and Fels (1973), Chapman et al. (1974), Bullard and Herendeen (1975b), Rotty et al. (1975), Chapman (1975), Pilati (1976), Herendeen and Tanaka (1976), Perry et al. (1977).

[2] Bullard and Herendeen (1975a), Folk (1972), Hannon (1972), Hannon et al. (1975, 1978, 1980), Hannon and Puleo (1974), Herendeen and Sebald (1975), Herendeen and Sebald (1973). This chapter builds on, extends and updates a similar introduction in the *Handbook of Industrial Ecology* (Lifset and Graedel 2002).

Input-output analysis shall be applied here to the following exogenous *production factors*: primary energy (E, in units of megajoules, MJ), greenhouse gas emissions (G, in units of kilograms of carbon dioxide equivalent, kg CO_2-e), employment (or "labor", L, in units of full-time equivalent employment-hours (emp-h), as well as income W (wages and salaries), indirect taxes less subsidies T, and imports M (all in units of Australian dollars, A$). For a detailed description of the respective data sources, closure type, and treatment of margins and imports see (Lenzen 2001).

In order to evaluate the two alternative diets, a set of production factor multipliers $\{f_k\}$ are derived from the basic input-output identity and are applied to data on food consumption baskets $\{c_k\}$ of $k = 1, \ldots N$ commodities expressed, in this case, in the Australian input-output classification. The overall factor embodiment C_f in terms production factor f (i.e. the overall energy, labor, etc.) contained in each option is

$$C_f = \sum_k c_k \ f_k.$$

Changes in consumption, whether initiated by voluntary consumer action or as a result of government policy, have associated changes in household monetary expenditure. For example, it can be assumed that money saved in one area will be spent elsewhere. The opposite holds for increased household costs, where money has to be withdrawn from some purposes. These spending increases or cuts will have further impacts in addition to those of the initial change. We refer to these impacts as rebounds. Within consumer rebounds, we examine three different household income quintiles[3] (lowest 20%, middle 20%, and highest 20%). This differentiation is useful because household consumption patterns vary considerably with household income. Therefore, different rebound effects should be expected depending on whether the impact analysis is applied to a rich or a poor household.

Cuts or savings are most likely to affect only the marginal consumption, which are items bought after all necessities are satisfied. Therefore, rebounds have to be calculated using factor multipliers of household expenditures at the upper expenditure limit. In a first step, production factor budgets $B_f(H) = \sum_k y_k(H) \ f_k$ were calculated using expenditure data $y_k(H)$ of households with different income H.[4] Second, these factor budgets were regressed as a function of per-capita household expenditure y

$$B_f(y) = r_f y^{\eta f}, \tag{15.1}$$

where r_f is a regression constant and

$$\eta_f = (\partial B_f/\partial y)/(B_f/y) \tag{15.2}$$

is called the elasticity of production factor f with regard to per-capita household expenditure y.[5] It was then assumed that rebounds occur at marginal factor multipliers

[3] Household incomes are A$9,880 for the lowest quintile, A$11,315 for the middle quintile, and A$18,813 for the highest quintile (Australian Bureau of Statistics 1995a).

[4] Based on the 1993–1994 Australian Household Expenditure Survey (Australian Bureau of Statistics 1995a).

[5] Compare Wier et al. (2001).

$$\partial B_f/\partial y = \eta_f B_f(y)/y = \eta_f r_f y^{\eta_{ftx}}. \tag{15.3}$$

When using static input-output analysis, scenario analyses are associated with certain limitations: it is impossible to precisely quantify changes in production factors, which would occur under real-economy shifts in consumption. The difference between production factor embodiments of two alternative diets calculated as above would be equal to real production factor changes caused by the corresponding shift from the current to the alternative diet only if during that shift (1) all commodity prices stayed constant, (2) there were no changes in technology, no input substitution, and hence no change in production factor intensities, (3) there were no constraints on production factors, such as a rigid labor supply, and (4) production costs were linear functions of production output (as inherently assumed in input-output analysis). The latter condition applies to production situations where there are no economies of scale, and where average costs equal variable costs, that is, fixed costs are zero. Since none of the above conditions are satisfied in practice, the difference in production factor embodiments, calculated for the alternative diets, is only indicative of the effect that real-economy demand or supply shifts would have on production factors (compare Laitner et al. 1998, p. 431). Nevertheless, taken as a proxy, the scenario differences illustrate compromises between various impacts of alternative consumer choices. The results demonstrate that, at least in principle, shifts between these choices may for example lead to reductions in energy use whilst increasing employment. Similarly, other comparisons may suggest the possibility of reducing greenhouse gas emissions or imports.

The Ecological Footprint

The ecological footprint was originally conceived as a simple and elegant method for comparing the sustainability of resource use among different populations (Rees 1992). The consumption of these populations is converted into a single index: the land area that would be needed to sustain that population indefinitely. This area is then compared to the actual area of productive land that the given population inhabits, and the difference is calculated between available and required land. Ecological footprints calculated according to the original method have become important educational tools in highlighting the unsustainability of global consumption (Costanza 2000). It was also proposed that ecological footprints could be used for policy design and planning (Wackernagel 1997; Wackernagel and Silverstein 2000).

Since the formulation of the ecological footprint, however, a number of researchers have criticized the method as originally proposed.[6] The criticisms largely refer to the oversimplification in ecological footprints of the complex task of measuring sustainability of consumption, or comparisons among populations

[6] Levett (1998), van den Bergh and Verbruggen (1999), Ayres (2000), Moffatt (2000), Opschoor (2000), Rapport (2000), van Kooten and Bulte (2000).

being misleading.[7] In addition, the aggregated form of the final ecological footprint makes it difficult to understand the specific reasons for the unsustainability of the consumption of a given population, and to formulate appropriate policy responses. In response to the problems highlighted, the concept has undergone significant modification (Bicknell et al. 1998; Lenzen and Murray 2001; Simpson et al. 2000). Development of, and debate about, the method is continuing.

The original ecological footprint is defined as a land area that would be needed to meet the consumption of a population and to absorb all their waste (Wackernagel and Rees 1995). Consumption is divided into five categories: food, housing, transportation, consumer goods, and services. Land is divided into eight categories: energy land, degraded or built land, gardens, crop land, pastures and managed forests, and 'land of limited availability', considered to be untouched forests and 'non-productive areas'. The ecological footprint is calculated by compiling a matrix in which a land area is allocated to each consumption category. In order to calculate the per-capita ecological footprint, all land areas are added up, and then divided by the population, giving a result in 'global hectares' per capita.

In the original ecological footprint method, the land areas included were mainly those directly required by households, and those required by the producers of consumer items. Beyond this boundary however, these producers draw on numerous input items themselves, and the producers of these inputs also require land. (Bicknell et al. 1998) were the first to apply a boundary-free input-output-based ecological footprint method in their study of the New Zealand population. Using Australian data, input-output-based ecological footprints have been calculated for more than 100 industry sectors and product groups, for states, local areas and cities, and for companies and households (Lenzen and Murray 2001). Another advantage of using input-output analysis is that imports and exports can be easily accounted for.

In the original method, the areas of forest, pasture and crop land do not represent local land, but areas that would be needed to support the consumption of the population, if local farming and forestry was conducted at 'world average productivity'.[8] Proceeding as such makes it easy to compare ecological footprints of different countries or populations (Wackernagel et al. 1999). However, the loss in detail through the conversion to world-average productivity precludes formulating regional policies, because the latter always involve region-specific economic, political, technological, environmental and climatic aspects (Lenzen and Murray 2001).

Furthermore, ecological footprints addressing the question of human demand on global productivity does not reflect the intensity of human-induced changes to land

[7] For example, as a result of calculations by Wackernagel (1997), some countries with extremely high land clearing rates (Australia, Brazil, Indonesia, Malaysia) exhibit a positive balance between available and required land, thus suggesting that these populations are using their land at least sustainably.

[8] In order to express an ecological footprint at world-average productivity, the consumption of the reference population is assessed in weight units, which are subsequently translated into units of area by multiplication with local yield factors. Different land types (pasture, crop land, forest) are then converted into land at world-average biomass productivity by multiplication with an equivalence factor (Wackernagel et al. 2002).

compare (van den Bergh and Verbruggen 1999). Intensive land use patterns such as cropping – no matter how productive – drastically alter ecosystems, whereas land used for example for non-intensive grazing or native forestry may be only slightly altered. This land condition, or the deviation from a pristine state, is not captured in the productivity-based approach. Assuming equal productivity, sustainable growing of organic wheat (and for example, not causing salinity), would attract the same ecological footprint in the original method as wheat grown conventionally and causing salinity.

For this reason, (Lenzen and Murray 2001) have argued that a better approach is to base the ecological footprint on land condition, using actual areas of land used by the respective population. They derive a list of disturbance weightings (see Table 15.1) for different types of land use ranging from 0 (undisturbed or slightly disturbed) to 1 (completely disturbed).[9]

Table 15.1 Basic Weighting Factors for Land Use Patterns, Reflecting Land Condition in Australia (After Lenzen and Murray 2001)

Land use type	Land condition
CONSUMED	1.0
Built	
DEGRADED	0.8
Degraded pasture or crop land	
Mined land	
REPLACED	0.6
Cleared pasture and crop land	
Non-native plantations	
SIGNIFICANTLY DISTURBED	0.4
Thinned pasture	
Urban parks and gardens	
Native plantations	
PARTIALLY DISTURBED	0.2
Partially disturbed grazing land	
SLIGHTLY DISTURBED	0.0
Reserves and unused Crown land	
Slightly disturbed grazing land	

[9] The measurement of land condition forms a field of investigation in itself, and a number of approaches have been made in studies incorporating land use into life-cycle assessment. Amongst others (Lindeijer 2000a, b), ecosystem biodiversity and bioproductivity measures (Swan and Pettersson 1998) as well as species diversity of a particular group of plants (Köllner 2000; (van Dobben et al. 1998) have been proposed as suitable indicators. For Australia, the degree of land-cover disturbance may be a useful proxy for land condition at a very broad scale, as it indicates processes such as biotic erosion that lead to land degradation. A comprehensive survey of land-cover disturbance over the Australian continent has been conducted by Graetz et al. (1995) using satellite imagery to compare the current coverage of vegetation with the 'natural' state, taken to be that of 1,788.

Table 15.2 Description of Structural Decomposition Components; C = Change in Greenhouse Gas Emissions (After Wood 2003)

Parameter and simplified notation	Description
$\Delta\mathbf{cF} = \Delta(\mathbf{cF})\mathbf{E}\,(\mathbf{I}-\mathbf{A})^{-1}\,(\mathbf{uv}YP+\mathbf{b}Z)$	ΔC due to changes in relative fuel mix in industrial production.
$\Delta\mathbf{E} = (\mathbf{cF}\Delta\mathbf{E}\ell)\,(\mathbf{I}-\mathbf{A})^{-1}\,(\mathbf{uv}YP+\mathbf{b}Z)$	ΔC due to changes in the absolute level of industrial consumption of energy.
$\Delta\mathbf{L} = \mathbf{cFE}\Delta\,(\mathbf{I}-\mathbf{A})^{-1}\,(\mathbf{uv}YP+\mathbf{b}Z)$	ΔC due to the change in the industrial structure.
$\Delta\mathbf{u} = \mathbf{cFE}\,(\mathbf{I}-\mathbf{A})^{-1}\,\Delta\mathbf{uv}YP$	ΔC due to the change in the mix of final demand of goods and services from the industries.
$\Delta\mathbf{v} = \mathbf{cFE}\,(\mathbf{I}-\mathbf{A})^{-1}\,\mathbf{u}\Delta\mathbf{v}YP$	ΔC due to the relative change in destination of final demand.
$\Delta Y = \mathbf{cFE}\,(\mathbf{I}-\mathbf{A})^{-1}\,\mathbf{uv}\Delta YP$	ΔC due to the change in the per-capita final demand.
$\Delta cF_{res} = \Delta\,(\mathbf{c}_{res}\mathbf{F}_{res})\,E_{res}P$	ΔC due to the change in the residential fuel mix.
$\Delta E_{res} = (\mathbf{c}_{res}\mathbf{F}_{res})\Delta E_{res}P$	ΔC due to the change in total residential energy consumption.
$\Delta P = \Big((\mathbf{cF}\Delta\mathbf{E}\ell)\ \ (\mathbf{I}-\mathbf{A})^{-1}\,\mathbf{uv}Y + (\mathbf{c}_{res}\mathbf{F}_{res})\,E_{res}\Big)\,\Delta P$	ΔC due to the change in population.
$\Delta\mathbf{b} = \mathbf{cFE}\,(\mathbf{I}-\mathbf{A})^{-1}\,\Delta\mathbf{b}Z$	ΔC due to the change in the mix of exports.
$\Delta Z = \mathbf{cFE}\,(\mathbf{I}-\mathbf{A})^{-1}\,\mathbf{b}\Delta Z$	ΔC due to the change in the total level of exports.
ΔC_{tot}	Total change in greenhouse gas emissions (summation of above terms)

Similarly, the emissions component of an ecological footprint can be determined as the projected land disturbance due to climate change caused by the greenhouse gas emissions (Table 15.2). To obtain a disturbance-based ecological footprint, each area of land is multiplied by its land condition factor. For extensions and further details see (Lenzen and Murray 2001), or http://www.isa.org.usyd.edu.au.

In this work, an example application is given for the population of Australia, based on consumption data of the national accounts. National Accounts provide a systematic annual summary of national economic activity. They map key economic flows: production, income, consumption, investment, imports and exports. Currently, the most important measure of overall economic performance is the Gross Domestic Product, or GDP. One way of measuring GDP is the expenditure approach, in which GDP is described as

$$\mathrm{GDP} + \mathrm{M} = \mathrm{GNE} + \mathrm{X} = \mathrm{GNE} + \mathrm{PFC} + \mathrm{GFC} + \mathrm{GFCE} + \mathrm{CS} + \mathrm{X} \qquad (15.4)$$

where M are imports, GNE Gross National Expenditure, X exports, PFC private final consumption, GFC government final consumption, $GFCE$ gross fixed capital expenditure, and CS are changes in stocks.

These tables are of course expressed in monetary terms, but after calculating ecological footprint multipliers ef_k for commodities k in the usual way (Lenzen and Murray 2001), the financial National Accounts can be converted into a National Ecological Footprint Account with values EF_k in area units (Table 15.5), according to $EF_k = y_k\ ef_k$.

Structural Decomposition Analysis

Two strains of time series decomposition can be found in the literature: Index Decomposition Analysis (IDA) and SDA. Both are comparative static methods (i.e. comparing differences between two sets of data) that use either aggregate sector-level or country-level data (IDA) or input-output data (SDA). IDA is generally less data-intensive, but also less detailed since indirect inter-industry effects cannot be resolved. Even though IDA and SDA have developed independently, their techniques and indices can be mutually applied (Hoekstra and van den Bergh 2003; Liu and Ang 2003). IDA and SDA studies have been carried out on a wide range of variables, such as energy, CO_2 emissions, labor, productivity, imports, and many others. A number of comprehensive literature reviews have been completed.[10]

The principle purpose of SDA (or IDA) is to break down the total changes in an indicator of interest (in the example of this study, it will be greenhouse gas emissions) into a number of independent contributing factors – for example, an SDA is designed to express changes in emissions by changes in industrial structure, energy efficiency, consumption levels, or other factors.

In this work we present a Structural Decomposition Analysis of greenhouse gas emissions for 11 factors – fuel mix, energy intensity, industrial interdependence, final demand commodity mix, final demand destination, final demand level, population, export commodity mix, export level, residential fuel mix and residential energy consumption. This is done for a time series combining data on greenhouse gas emissions from energy use, and input-output tables of the Australian economy from 1968 to 1997.

[10] For example Ang (1995a, b, p. 41), Hoekstra and van den Bergh (2002, Sect. 6), and Liu and Ang (2003). Rose and Casler (1996), summary in Rose (1999) discuss additional issues such as trade changes, price changes, model closure, hybrid units, projection and forecasting, and the relationship to neoclassical production functions. Ang (1999) deals with method selection, the zero-values problem, periods versus years, and sector aggregation. Ang (2000) gives a historical overview, lists 124 studies, and classifies these according to application area, indicator type and decomposition scheme. Ang (2004) reviews selection criteria and application areas, and attempts a taxonomy of methods.

Factorization

As for any given time t, total industrial greenhouse gas emissions C_{tot} can be represented by the fundamental input-output relation $C_{tot} = f\ (\mathbf{I} - \mathbf{A})^{-1}\,Y$, which can subsequently be decomposed into a range of determinants[11]:

$$C_{tot} = (\mathbf{c}.\mathbf{F})\ \mathbf{E}\ (\mathbf{I} - \mathbf{A})^{-1}\ (\mathbf{uv}YP + \mathbf{b}Z) + \mathbf{c}_{res}\mathbf{F}_{res}E_{res}P \tag{15.5}$$

with the determinants being:

Emission coefficients c_{ij} $(f \times n)$: emission of greenhouse gases in CO_2-equivalents resulting from the usage of fuels $i = 1, \ldots, f$ in industries $j = 1, \ldots, n$ per unit of total usage of fuels i; c is a weighted sum over three gases with different global warming potentials w: $c = c_{CO2} + w_1\ c_{CH4} + w_2\ c_{N20}$; there is a variation of c_{ij} across industries because of equipment-specific emission factors for non-CO_2 gases, and industry-specific equipment mix.

Fuel mix F_{ij} $(f \times n)$: usage of fuels i in industries j per unit of total usage of energy in industries j;. denotes element-wise multiplication.

Energy intensity E_{jj} $(n \times n)$: diagonalized vector of total energy usage per unit of gross output of industry sectors j.

Industrial interdependence $\{(I - A)^{-1}\}_{jk}$ $(n \times n)$: gross output required from industry sectors j by industry sectors k per unit of final demand from industry sectors k.

Final demand commodity mix u_{kl} $(n \times d)$: final demand of commodities from industry sectors k in final demand destinations[12] $l = 1, \ldots, d$ per unit of total final demand from industry sectors k; this matrix excludes exports.

Final demand destination mix v_l $(d \times 1)$: final demand of commodities from destinations l per unit of total final demand.

Final demand level Y (1×1): total final demand (all commodities, industry sectors destinations), per capita.

Population P (1×1): Australian population.

Export commodity mix b_l $(n \times 1)$: export of commodities by industry sectors l per unit of total exports.

Export level Z (1×1): total exports (all commodities).

Similarly, residential emissions are described by $c_{res}F_{res}E_{res}$, where c_{res} $(1 \times f)$ contains the emission coefficients for residential fuels, $F_{res}(f \times 1)$ the residential fuel mix, and E_{res} (scalar) the per-capita residential energy consumption. Note that

[11] In this work we decompose absolute levels, because we only deal with one country, Australia. In cross-country comparisons, decompositions of relative changes, intensities, elasticities or other coefficients may be more appropriate (Ang and Lee 1996). Similarly, in cases where level effects overly dominate other structural effects, a decomposition of intensities or elasticities yields better information (Ang 1994), for an example see Skolka (1977).

[12] In the case of Australia, but also for many other countries, final demand destinations are (1) private final consumption, (2) government final consumption, (3) gross fixed capital formation, (4) changes in inventories, and (5) exports.

changes in economic structure, that is the input-output coefficients can be a result of technological change as well as changes in the product mix within sector aggregations (Afrasiabi and Casler 1991; Bezdek and Dunham 1976; Dietzenbacher and Los 1997). These effects can however only be distinguished if corresponding disaggregated information is available.

In (temporal [13]) SDA, we are interested in the changes over time, hence the analysis employed is really a derivative of Equation (15.5) with respect to time, solved for the time period bordered by the years with data available. i.e. $\Delta C_{tot} = \int_{C_0}^{C_1} \mathrm{d}C$. The complication in this calculation, is that the path the integral takes is not known (i.e. whether all the changes, in, say, fuel mix, occur at the start of the period, the end of the period, gradually in between, or along some other random path – in application, this refers to whether the comparison in changes is made between the terminal value, the initial value, or other values in between). As a result, a large array of different methods of decomposition according to different integral paths have been published. Most simply, constant values can be assumed along the integral path. Using base weights (initial values) is known as the Laspeyres method, using mid-point weight (average values) is the Marshall-Edgeworth, and using terminal weights (final values) is the Paasche method. The Laspeyres and Paasche decompositions, however, are never exact, leaving residuals due to joint terms of the derivative. The Marshall-Edgeworth decomposition is only exact for $n = 2$, but produces a residual for $n > 2$. Zero residuals however are a desirable property of decompositions, in addition to linear homogeneity (invariance under determinants scaling, see Hoekstra and van den Bergh 2002, Note 6), invariance under time reversal, and zero-value robustness (see Hoekstra and van den Bergh 2003, pp. 6–7 and Table 15.2; Ang 2000, Table 15.6).

An *exact* decomposition results when the integral follows a path where all changes in the determinants are proportional to each other. A number of more complex decomposition methodologies exist: the Mean Rate-of-Change method (Chung and Rhee 2001; Lenzen 2006); the Logarithmic Mean Divisia method (Ang and Choi 1997; Ang and Liu 2001; Ang et al. 1998; Wood and Lenzen 2006); the $n!$-comninatoric integral path method, see (Albrecht 2002; Dietzenbacher and Los 1997).

Application to Australian Greenhouse Gas Emissions

In this work we will give an example of applying the Marshall-Edgeworth SDA variant. Carrying out the decomposition (Equation (15.9)) of the factorization of Australian greenhouse gas emissions (Equation (15.4) yields

[13] Rather than temporal, a structural comparison is also possible across countries or regions. However, this approach is difficult to implement for SDA because of the requirement of aligning input-output table classifications (Alcántara and Duarte 2004; de Nooij et al. 2003; Zhang and Ang 2001).

$$
\begin{aligned}
\Delta C_{tot} = {} & \Delta\left(\mathbf{cF}\right)\, \mathbf{E}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \left(\mathbf{uv}YP + \mathbf{b}Z\right) \\
& + \mathbf{cF}\Delta\mathbf{E}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \left(\mathbf{uv}YP + \mathbf{b}Z\right) \\
& + \mathbf{cFE}\, \Delta\left(\mathbf{I}-\mathbf{A}\right)^{-1} \left(\mathbf{uv}YP + \mathbf{b}Z\right) \\
& + \mathbf{cFE}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \Delta\mathbf{uv}YP \\
& + \mathbf{cFE}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \mathbf{u}\Delta\mathbf{v}YP \\
& + \mathbf{cFE}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \mathbf{uv}\Delta YP \\
& + \Delta\left(\mathbf{c}_{res}\mathbf{F}_{res}\right) E_{res}P \\
& + \mathbf{c}_{res}\mathbf{F}_{res}\Delta E_{res}P \\
& + \left(\left(\mathbf{cF}\right)\, \mathbf{E}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \mathbf{uv}Y + \mathbf{c}_{res}\mathbf{F}_{res}E_{res}\right) \Delta P \\
& + \mathbf{cFE}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \Delta\mathbf{bz} \\
& + \mathbf{cFE}\, \left(\mathbf{I}-\mathbf{A}\right)^{-1} \mathbf{b}\Delta Z \\
& + R
\end{aligned}
\tag{15.6}
$$

where R is the residual term due to joint effects in higher order terms. The interpretation of residuals is difficult, but fortunately their values have been found to be small. In order to simplify the presentation of the results, the components of Equation (15.6) are given simplified notations (Table 15.3).

Finally, the SDA model of course shares all shortcomings of the static input-output framework, that is, it does not allow for dynamic forecasts and is also limited by the assumption of linearity (ignores economies of scale), not accounting for constraints on production factors (such as limited capital and labor), the assumption of constancy of commodity prices, and the assumption of fixed input structure in each industry.

Australian Case Studies

In the following, the results of case studies are presented for the methods and applications introduced in the section on Australian Case Studies. In order to provide some common ground, we let all studies deal with the production and consumption of food in the Australian economy.

As the underlying input-output data set, the 1994–1995 Australian input-output tables (ABS 1999b) were used. These are the first set of tables to be based on the System of National Accounts 1993 (SNA93). Within SNA93, National Income, National Expenditure and National Product are now benchmarked on input-output tables by employing the commodity flow method, which is an input-output approach for compiling National Accounts (Barbetti and De Zilva 1998). The characteristic feature of the commodity flow method is that it balances total supply and use for each commodity while simultaneously balancing total production and input for each industry. In practice, the reconciliation of the three GDP estimates based on income,

Table 15.3 Factor Embodiment Comparison Between the Current Average Australian Diet and a Recommended Diet (After Lenzen and Dey 2002). The Effects of Consumer Rebounds Are Shown in the Lower Part of the Table Where the Net Effect of the Change Is Also Shown as a Percentage

	CONSUMPTION		FACTOR EMBODIMENTS					
				Greenhouse				
	Food intake ($g\ d^{-1}\ cap^{-1}$)	Expenditure ($A\$y^{-1}\ cap^{-1}$)	Energy (GJ)	gases (t CO_2-e)	Labor (emp-h)	Income (A$)	Imports (A$)	Taxes (A$)
Current Australian diet								
Meat and meat products	305	308	3.26	2.8	14.3	163	37	54
Dairy products	368	193	2.44	0.5	7.0	91	26	35
Fruit and vegetable products	743	272	3.30	0.4	8.3	133	39	52
Oils and fats	52	26	0.32	0.1	0.7	12	5.6	4.2
Flour mill products and cereal foods	248	63	0.75	0.1	2.2	31	8.7	11
Bakery products	149	189	1.81	0.3	8.3	108	23	36
Sugar and confectionery	125	139	1.36	0.2	4.9	75	20	33
Other food (seafood, jam, honey)	35	253	2.64	0.6	8.3	123	37	46
Soft drinks, cordials and syrups	275	171	2.11	0.2	4.6	77	24	42
Beer and malt	267	184	0.69	0.1	2.5	35	7.7	127
Wine and spirits	53	162	0.88	0.1	3.6	49	11	92
Meals out and take-away		583	5.5	0.8	22.2	304	77	146
Sum	2,621	2,541	25.0	6.0	87	1,201	316	679
Recommended diet								
Meat and meat products	155	157	1.66	1.4	7.3	83	19	28
Dairy products	214	112	1.42	0.3	4.1	53	15	21
Fruit and vegetable products	570	209	2.53	0.3	6.4	102	30	40
Oils and fats	30	15	0.19	0.0	0.4	7	3.3	2.4
Flour mill products and cereal foods	175	44	0.53	0.1	1.6	22	6.2	8

(continued)

Table 15.3 (continued)

	CONSUMPTION		FACTOR EMBODIMENTS					
				Greenhouse				
	Food intake ($g\ d^{-1}\ cap^{-1}$)	Expenditure ($A\$y^{-1}\ cap^{-1}$)	Energy (GJ)	gases (t CO_2-e)	Labor (emp-h)	Income (A$)	Imports (A$)	Taxes (A$)
Bakery products	105	134	1.28	0.2	5.9	76	16	25
Sugar and confectionery	53	59	0.57	0.1	2.1	32	9	14
Other food (seafood, jam, honey)	28	202	2.11	0.5	6.7	99	29	37
Soft drinks, cordials and syrups	116	72	0.89	0.1	2.0	32	10	18
Beer and malt	128	88	0.33	0.0	1.2	17	3.7	61
Wine and spirits	26	78	0.42	0.1	1.7	23	5	44
Meals out and take-away		583	5.5	0.8	22.2	304	77	146
Sum	1,602	1,753	17.4	3.8	61	850	224	444
Difference between scenarios	−1,019	−788	−7.6	−2.2	−26	−350	−92	−236
Rebound, lowest income quintile		788	9.4	1.2	23	373	103	201
Not effect		0	1.7	−1.1	−3	23	10	−35
			7%	−18%	−3%	2%	3%	−5%
Rebound, middle income quintile		788	9.2	1.1	23	372	103	200
Not effect		0	1.6	−1.1	−3	22	10	−35
			6%	−18%	−3%	2%	3%	−5%
Rebound, highest income quintile		788	8.5	1.0	23	370	101	199
Not effect		0	0.9	−1.2	−3	19	9	−37
			4%	−20%	−4%	2%	3%	−5%

expenditure and production is achieved by an iterative confrontation and balancing process involving approximately 1,000 commodities and 107 industries. As a result of this approach, previously common discrepancies within the National Accounts and between input-output tables and the National Accounts no longer occur. Furthermore, an Economic Activity Survey incorporating taxation statistics has been specifically designed by the ABS (Australian Bureau of Statistics 1999) to support the input-output approach from 1994–1995 onwards by expanding and detailing the industry data collection, and by facilitating the production of annual input-output tables (previously triennial).

Scenario Analysis

As an example for the first approach illustrated in this work, we present a scenario analysis of the typical Australian diet. The provision of food to Australians in 1994 entailed the consumption of 280 PJ of primary energy (7% of the Australian total) and the emission of 85 Mt CO_2-e of greenhouse gases (15% of the Australian total; see (Lenzen 1998)). However, over the last century, food intake has changed markedly, with cereal and vegetable intake decreasing in favor of a marked increase in consumption of animal products and refined sugar (Department of Health 1984). As a result, the nutritional energy intake in 1993 was 40% in excess of the recommended dietary intake (RDI), while the protein intake was 118% in excess of the RDI (Australian Bureau of Statistics 1995b). These changes in the provision of food have had important implications for environmental factors as diverse as land and water use, greenhouse gas emissions, soil erosion and desertification, logging of rainforests, and pesticide use (EarthSave Foundation 1992; Pimentel and Hall 1989). The problem of increasing energy requirements for food production was already recognized in the 1970s (Cambel and Warder 1976), and has been studied more recently (Coley et al. 1998; Organisation for Economic Co-operation and Development 1982; Stout 1992).

In light of these problems, a worthwhile research question would ask what are the differences between the impacts of the current diet and a hypothetical diet, based on the RDI? Utilizing scenario analysis to answer this question, Table 15.4 shows the results of such an analysis for a current Australian diet and a recommended diet. The columns contain various items concerning annual food intake and expenditure on food, as well as the associated factor embodiments for both scenarios. The rows in the lower third of the table contain the difference between the current Australian and the recommended diet, and the rebound impact for households in three different income quintiles. The consumption data were taken from (Australian Bureau of Statistics 1995b) for food intake and from (Australian Bureau of Statistics 1995a) for expenditure. A recommended diet was derived from figures given by (Watt 1979) and (Thomas and Corden 1977). The expenditure on the recommended diet was calculated using the ratio of expenditure to food intake of the current Australian diet. The net effect of a diet change is given as the sum of the scenario difference and the rebound impact. Net effects are shown as a percentage of the current Australian scenario.

Table 15.4 is self-explanatory, so that here only a few features are discussed specifically. It can be seen that an adjustment of their eating pattern would save the average Australian about A$790 per year. Compared with the current diet, the recommended diet generates ~20% fewer greenhouse gas emissions, with all other factors generally unaffected, when rebounds are included. It is interesting to note, that differences in the rebound effect between the quintiles, were found to actually be small.

A National Ecological Footprint Account for Australia

The results of the second case study, The National Ecological Footprint Account of Australia with values EF_k in area units is shown in Table 15.5. Important footprints can be observed within the private final consumption of meat products, clothing, retail goods, and meals out, and the export of wool and meat products. Note that multipliers of domestically produced commodities and imports are assumed to be identical. As a consequence, embodiments in imports of yarns, fabrics and other textile products are probably overestimated. This is because processed wool is classified together with yarns and fabrics, which, when produced overseas, are likely to require much less land than for their production in Australia. Moreover, the domestic consumption of meat is based on more densely stocked pastures in the South-East of Australia, while the majority of pastures in the ELZ produce meat for exports. Hence, the embodiments in domestic consumption as given in Table 15.5 are probably too high, and those in exports too low. Nevertheless, Australia is a net 'disturbance exporter'.

Amongst other features, this Ecological Footprint Account shows that almost half of Australia's national ecological footprint is caused by producing exports of products from sheep and beef cattle grazing. The total export-related footprint amounts to about 110 million hectares. The fact of Australia exploiting a considerable part of its natural assets for exports is the result of a history of economic planning: since the 1980s, Australia has sought to escape from increasing foreign debt and falling primary commodity prices by expanding the volume of meat, wool and other primary exports in order to maintain total export revenues and living standards (Daly 1993; Daniels 1992; Muradian and Martinez-Alier 2001), paraphrased this strategy as entering into an environmental 'race to the bottom'. Moreover, primary exports generally neither promote technological innovation and development of labor skills, nor positively influence economic growth, mainly because the respective producing industries are poorly linked back to other domestic, value-adding sectors (Fosu 1996; Lenzen 2003), and thus exert little economic impetus. In this respect, Australia is sharing the predicament of many developing countries that are locked into an environmental-economic dilemma through increasing dependency on environmentally degrading production and further erosion of environmental quality (Daniels 1992; Muradian and Martinez-Alier (2001). The environmental degradation associated with this situation is now slowly emerging, and will be

Table 15.4 A National Ecological Footprint Account (after Lenzen and Murray 2001). The Table Is Organized In Order To Reflect the National Accounting Identity (Equation (15.17))

	Private final cons.	+ Gvmt final cons.	+ Change in stocks	= GNE	+ Exports	= GNT	− Consumer imports	− Import stocks	− Industrial imports	= GDP
Sheep and shorn wool	0.23	0	−5.41	−5.2	35.18	30	0	0	0	30
Grains	0.33	0	−1.01	−0.7	4.91	4.2	0.01	0.02	0.37	3.8
Beef cattle	0.92	0	2.58	3.5	3.94	7.4	0	0	0	7.4
Other agriculture	1.39	0.04	−0.07	1.4	0.33	1.7	0.05	−0.01	0.11	1.5
Forestry	0.11	3.5	−0.01	3.6	0.11	3.7	0.02	0	0.12	3.6
Fishing	0.21	0.02	0	0.2	0.11	0.3	0.01	0	0	0.3
Coal mining	0	0	−0.08	−0.1	1.71	1.6	0	0	0	1.6
Crude oil, natural gas and LPG	0.09	0	−0.11	0	0.49	0.5	0	−0.05	0.53	0
Other mining	0	0.01	−0.07	−0.1	1.35	1.3	0	0.09	0.06	1.1
Meat products	38.3	0	0.97	39.3	40.37	79.6	0.59	0.03	0.33	78.7
Dairy products	2.09	0	−0.02	2.1	1.05	3.1	0.12	0.02	0.05	2.9
Sugar	3.75	0	0.01	3.8	2.25	6	0.84	0.03	0.1	5
Other food products	4.58	0	0.04	4.6	0.73	5.4	0.53	0	0.45	4.4
Alcohol and tobacco	0.84	0	0.09	0.9	0.36	1.3	0.24	0.03	0.2	0.8
Processed wool, yarns, fabrics	3.75	0	−0.09	3.7	6.11	9.8	1.22	−0.1	11.52	−2.9
Textile products and footwear	19.83	0	0.44	20.3	4.36	24.6	7.75	0.19	2.59	14.1
Saw mill products	0.01	0	0.01	0	0.28	0.3	0.01	0	0.44	−0.2
Paper products	0.79	0.02	−0.06	0.7	0.13	0.9	0.18	−0.02	1.4	−0.7
Refinery products	0.58	0	0.11	0.7	0.17	0.9	0.07	0.02	0.35	0.4
Chemical products	1.6	0.62	0.2	2.4	1.04	3.5	0.48	0.1	4.03	−1.1

(continued)

Table 15.4 (continued)

	Private final cons	+ Gvmt final cons.	+ Change in stocks	= GNE	+ Exports	= GNT	− Consumer imports	− Import stocks	− Industrial imports	= GDP
Non-metal construction materials	0.06	0	0.02	0.1	0.05	0.1	0.03	0	0.22	−0.1
Basic iron and steel	0	0	0.04	0	0.44	0.5	0	0	0.47	0
Aluminium	0	0	0.02	0	1.02	1	0	0	0.01	1
Other non-ferrous basic metals	0.08	0	−0.01	0.1	1.09	1.2	0.01	0.01	0.21	0.9
Metal products	0.1	0	0.01	0.1	0.11	0.2	0.04	0	0.34	−0.2
Motor vehicles	0.83	0	0.13	1	0.18	1.1	0.34	0.06	1.11	−0.4
Other transport equipment	0.03	0	−0.01	0	0.1	0.1	0.01	0	0.21	−0.1
Other manufacturing	2.02	0	0.15	2.2	0.66	2.8	0.82	0.1	3.54	−1.6
Electricity supply	3.85	0.14	0	4	0.02	4	0	0	0	4
Gas supply	0.1	0	0	0.1	0	0.1	0	0	0	0.1
Water supply	0.52	0.01	0	0.5	0	0.5	0	0	0	0.5
Construction	0	0.25	0	0.3	0.07	0.3	0	0	0.02	0.3
Wholesale and retail trade	13.34	0	0.04	13.4	1.09	14.5	0.09	0	0	14.4
Accommodation and restaurants	9	0	0	9	0.98	10	0.37	0	0.28	9.3
Road transport	0.43	0.1	0.01	0.5	0.19	0.7	0.04	0	0.01	0.7
Rail transport	0.28	0.07	−0.01	0.3	0.19	0.5	0.03	0	0	0.5
Water transport	0.05	0	0	0	0.47	0.5	−0.04	0	0.39	0.2
Air transport	0.81	0	0	0.8	0.6	1.4	0.29	0	0.28	0.8

Ownership of dwellings[a]	4.42	0	0	4.4	0	4.4	0	0	0	4.4
Commercial services	3.33	0.57	0	3.9	0.56	4.5	0.1	0	0.5	3.9
Public administration and services	2.51	6.59	0	9.1	0.13	9.2	0.03	0	0.02	9.2
All industries	121.2	11.9	−2.1	131	112.9	244	14.3	0.5	30.3	198.9
Natural processes[b]	−5.3			−5.3		−5.3				−5.3
Residential usage	2			2		2				2
Private vehicle usage	2.5			2.5		2.5				2.5
Ecological footprint	120.4	11.9	−2.1	130.2	112.9	243.1	14.3	0.5	30.3	198.1
Ecological footprint/cap	6.7	0.66	−0.11	7.2	6.25	13.5	0.8	0	1.7	11

Notes: All figures in Mha; GNE = gross national expenditure; GNT = gross national turnover; GDP = gross domestic product.

[a]Output of industry is rent for dwellings.

[b]Includes CO_2 sequestration, soil carbon uptake, prescribed burning, and wildfires.

Table 15.5 Richard Wood and Manfred Lenzen

Industrial						Residential		Population	Exports		Total
ΔcF	ΔE	ΔL	Δu	Δv	ΔY	$\Delta cF_{(res)}$	$\Delta E_{(res)}$	ΔP	Δb	ΔZ	ΔC
−0.3%	−1.3%	1.0%	−0.2%	−0.2%	1.5%	0.0%	0.1%	1.1%	−0.1%	0.8%	2.3%

exacerbated unless the national income is drawn from more sustainable production and trade, for example by internalizing environmental cost into export prices, or by shifting towards alternative production structures, that is establishing strong value-adding secondary sectors through fostering education and research (Muradian and Martinez-Alier 2001).

Structural Decomposition Analysis

Results from the third methodological approach, SDA, applied to the total changes in Australian greenhouse gas emissions between 1968 and 1997 (according to Equation (15.16)) are presented in Table 15.6. The results at the whole-economy scale show that the most important determinants of overall greenhouse gas emissions increase (+2.3%/year) across the whole economy are: per-capita final consumption (affluence, +1.5%/year); energy intensity improvements (−1.3%/year); population growth (+1.1%/year); structural economic change (+1.0%/year); and export growth (+0.8%/year). All other determinants contributed less than 0.5%/year to the total increase rate.

The above values are averages over the analysis period, and there have been fluctuations in trends over the years (Fig. 15.1). Changes in fuel mix (ΔcF, top left diagram) generally had a negative forcing on aggregate emissions (averaging −0.3%). During the analysis period the fuel share of natural gas increased across the economy from 0.2% in 1969 to 26% in 1997, and the fuel shares of the emissions-intensive fuel oil and leaded petroleum decreased from 10% to 1%, and from 10% to 2%, respectively. The largest negative point covers the years of the second oil price shock of 1978–1979, when the shares of the primary fuel refinery feedstock decreased by 1.5%, which in turn affected the share of secondary oil fuels, with diesel and other petroleum products decreasing by roughly 0.5%. More recently, a sharp increase in Δ cF occurred in the period 1995–1997, which was mainly driven by an increase in the share of brown coal and a decrease in the share of natural gas. Also during this period, a conservative stance on greenhouse issues was being taken by the Australian Government in the years leading up to the Kyoto conference. The graph shows that significant reductions in greenhouse emissions can be achieved quite quickly when responding to pricing factors (for example during the oil price shocks), and can conversely increase quite quickly when there is no impetus for change (as in the most recent trends).

Table 15.6 Structural Decomposition of Changes in 1993/1994–1994/1995 Australian Greenhouse Gas Emissions into Industry Contributions (After Wood 2003); Top 19 Industries with Contributions of $|\Delta| > 0.5\%$

1994–95	ΔcF	ΔE	ΔL	Δu	Δv	ΔY	ΔP	Δb	Δz	ΔC
Meat and meat products		−0.17%						−0.19%	0.11%	0.05%
Beer and malt				−0.29%						−0.26%
Motor vehicles and parts					0.05%					0.07%
Electricity supply	−0.08%	−0.23%	0.69%	1.06%	−0.53%	0.64%	0.19%			1.74%
Water sewerage and drainage				0.42%						0.29%
Residential building		−0.57%	0.79%		0.26%	0.19%	0.06%			0.50%
Other construction		−0.46%			0.26%	0.16%				−0.01%
Wholesale trade		−0.16%	0.81%	0.51%		0.08%		0.14%	0.05%	1.26%
Retail trade		−0.23%	0.85%		−0.12%	0.14%		0.10%		0.75%
Restaurents, hotels, clubs		−0.18%		0.53%	−0.09%	0.10%		0.28%		0.40%
Road transport		−1.57%	0.62%	−0.90%	−0.13%	0.22%	0.07%	−0.19%	0.18%	−1.70%
Water transport	−0.06%	0.32%						−0.28%	0.08%	0.09%
Ownership of dwelling		−0.14%		−0.27%	−0.06%	0.07%				−0.60%
Technical and computer				0.43%						0.31%
Government administration	0.08%		−1.82%	−0.41%	0.06%	0.13%				−1.94%
Defense			−0.31%	−0.26%						−0.48%
Education			0.90%							0.81%
Health services			−1.53%			0.09%				−1.67%
Community services			−0.49%							0.42%
Total changes	**−0.41%**	**−5.20%**	**3.64%**	**0.12%**	**−0.65%**	**2.85%**	**0.86%**	**−1.36%**	**2.25%**	**1.21%**

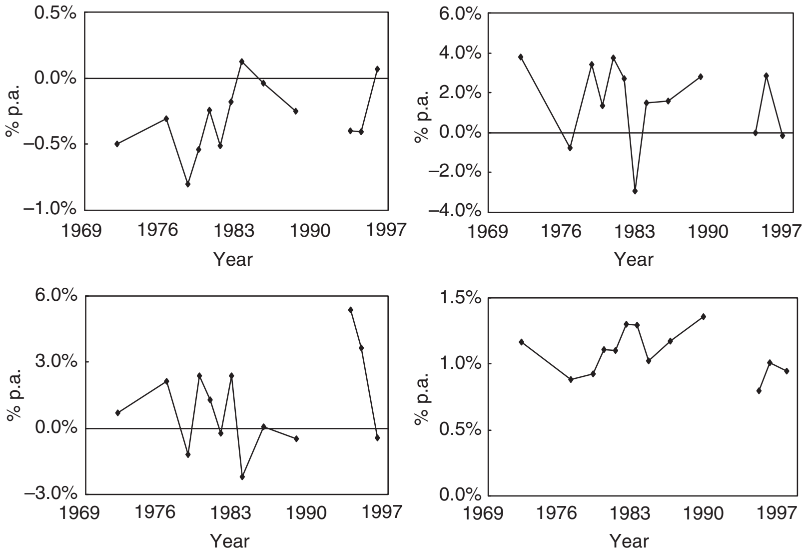

Fig. 15.1 Trends in Contributions to the Change Rate of Greenhouse Gas Emissions in Australia, 1968–1997 (ΔcF *Top Left*, ΔL *Bottom Left*, ΔY *Top Right*, ΔP *Bottom Right*; after Wood 2003). A Gap in the Time Series Appears for the Period 1990–1993. This Is Due To a Significant Change in Data Classification by the Australian Bureau of Statistics Between the 1990 and 1993 Input-Output Tables Which Was Not Reconcilable

Industrial interdependence (ΔL) has shifted to be more energy intensive over the period 1969–1997. Once again, a notable dip occurs during the 1978–1979 oil price shock, reflecting the structural response towards lower requirements of oil. More recently, there has been a significant positive forcing on emission levels by changes in industrial structure. Interestingly, these have occurred during negative fuel mix and energy intensity trends. This would tend to suggest that substitution between energy and non-energy inputs can be achieved within the Australian economy.[14] This is an important result, as considerable credit is given to industries that reduce their fuel use, yet based on these historical results, this credit may be unfounded, as the overall effect on emissions levels is diminished by the need to source other non-energy inputs but which have higher embodied energy/emissions content.

A general positive forcing on emission levels by ΔY (affluence) is discernible, except for 1975–1978 and 1982–1983 (recessions in the Australian economy). The effect of a further recession in the early 1990s is unfortunately not captured in this analysis due to the data gap. The magnitude of this determinant reiterates the importance of the link between affluence, economic growth and emissions (Lenzen and

[14] A more complete description is that when $\Delta\mathbf{E}$ causes a downturn in emissions (caused by a reduction in industrial fuel use), $\Delta\mathbf{L}$ causes a contrary upward forcing on emissions. As $\Delta\mathbf{E}$ reflects the direct use of energy in industrial production, and $\Delta\mathbf{L}$ reflects the embodied emissions in the industrial inputs into production, this converse forcing by the two factors suggests an inverse relationship between the fuel and industrial inputs.

Smith 2000). As expected, population growth over the study period has resulted in positive contributions to emission levels, averaging about 1.1% p.a. The variability is almost wholly due to changes in the level of immigration into Australia.

A further interesting analysis is the inclusion of export level ΔZ into the private final demand variable ΔY, allowing the investigation of the effect of total economic activity. The result is a reduction in the variability of the trends, which implies that when domestic demand decreases, surplus product (with its embodied emissions) is exported in order to maintain a moderately stable level of production. The notable exceptions to this are for the recession years.

A more specific breakdown into contributing industries (Table 15.6) is shown for 1994–1995, a period fairly representative of trends of consistent dominance by specific sectors of the economy that is noticeable over the whole time series. First, changes due to primary industries such as agriculture, forestry, fishing and mining are small. This is due to low end uses of the products of these sectors, and the emissions incurred during the production of these commodities being embodied in intermediate inputs of other industries.

Second, the manufacturing sector has a mixed history, with little representation in later years, whilst in earlier years the effect of the industry was considerably larger. The prominent industries include meat products, petroleum and coal products, and motor vehicles and machinery. In terms of exports driving emissions, meat products are significant. Third, amongst the utilities sectors, electricity supply is always represented, consistently representing a large contribution to change in overall emissions for each period. Construction is also consistently represented, as are the transport sectors. Fourth, within the service sector, government administration, defense, education, health and community (or welfare) services have consistently contributed to change, often forcing emissions upwards.

Conclusions

In this paper, demonstrations of the application of scenario analysis, the ecological footprint and structural decomposition analysis have been presented for Australian consumption patterns.

In all three applications, the desired objective was the options for moving towards a sustainable level of consumption. Utilizing scenario analysis, a comparison was made between the impacts of current diet, and the impacts of an environmentally motivated diet. Results were able to show the compromises that would be made if the Australian diet was suddenly changed. In this example, significant savings were found in terms of greenhouse gases and slight increases in levels of income and imports, but at the expense of decreases in employment and taxes.

Applying the ecological footprint to similar data, but this time encompassing all forms of consumption in Australia, was able to show the absolute land impacts, and the relative importance of differing forms of consumption. As a result, impacts from agricultural products, particularly form meat products, were found to be the largest contributors to both domestic and exported land disturbance.

Finally, the application of structural decomposition analysis compared the level of impacts over time, thus allowing to separate likely factors influencing greenhouse emission levels, and thus to gain insights into the underlying causes of changes. As a result, the upward trends of population growth and GDP were distinguished from industrial effects, such as industrial structure and industrial energy efficiency. Whilst the overall impacts of all effects has unsurprisingly been towards increased emissions over the last 30 years, the variability in some factors, and the average reducing effect of other factors has mitigated increases to an extent, and provides hope for future improvements.

Thus the three methodologies, whilst all focusing on levels of Australian consumption, have provided a variety of results – compromises from the scenario analysis, space impacts from the EF, and disaggregated trends from the SDA. An important question then, is if there is value in using these methodologies in conjunction – whether they are complementary approaches or substitutes for each other.

Firstly, the disadvantage of using more than one approach simultaneously is obviously the increased time/costs involved. The first two approaches, scenario analysis and the ecological footprint, however, have the advantage of similar base data and similar application. Once impact indicator and land disturbance data is available, the calculation of the same consumption data sets may be performed for each method. This provides the advantage of an easily interpretable result from the ecological footprint, coupled with the possible compromises of environmental, social and economic indicators and the effects of rebounds in a scenario analysis of response strategies.

Structural decomposition analysis does not share the advantage of significantly overlapping data sets; it relies on historical data and as such provides two important complementary facets to the other methodologies. Firstly, it is concerned with historical trends, an important input into the construction of hypothetical scenarios. Secondly, pure consumption-induced impacts can be differentiated from other factors. For example, if the result of an ecological footprint study incites action, it may be more poignant to target industrial processes rather than household consumption if the results of an SDA show (for arguments sake) that final demand induced impacts have been decreasing whilst industrial structure induced impacts have been increasing.

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Chapter 16
Global Environmental Impact of Dutch Private Consumption

Durk Nijdam and Harry C. Wilting

Introduction

Worldwide ecosystems are under pressure of economic activities. The main impetus for this is human demand for food, other goods and services. How household spend their money is an important factor in the magnitude of the damage inflicted on the environment. The distribution of environmental damage among the different household expenditures can provide insight in how this damage can be reduced.

On the issue of consumption related environmental impacts many studies have been performed. However, most of these studies only focus on a specific part of our consumption (e.g. assessments [LCAs] of goods and services), on a specific impact category (e.g. energy or greenhouse gases) or on consumption on an aggregated level (e.g. footprint assessments of nations or cities). A comprehensive assessment covering the whole of consumption, while allowing detailed insight into its composition, and taking many environmental impacts into account, has not yet been performed.

As early as 1976, Herendeen and Tanaka (1976) published their 'energy cost of living', using input-output (IO) based energy intensities of household expenditures. Several studies in this field were performed, for example in Europe (e.g. Weber and Fahl 1993; Reinders et al. 2003), India (Pachauri et al. 2002) Australia (Lenzen 1998) and New Zealand (Peet et al. 1985). Besides energy, emissions have been analyzed in a similar fashion (e.g. Morioka and Yoshida 1995; Breuil 1992; Munksgaard 2000; Alfredsson 2002). Later on, as LCA data became available, IO based data were complemented with process-based data to allow hybrid analysis.

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In the Netherlands, energy intensities derived from hybrid analysis were calculated in the mid-1990s for over 360 expenditure categories by a consortium of institutes. The results were published by Vringer and Blok (1995), who combined them with expenditure surveys to perform detailed assessments. In 2001, Kok et al. (2001) updated these intensities. In Joshi (2000) methods were described to complement LCA's with IO data, e.g. for background processes in the life cycle.

Blonk et al. (1997) performed an IO assessment of consumption related environmental impacts using an economic IO table of 60 industries and environmental data from the Dutch emission inventory system. Their reference year was 1993. Their goal was to calculate the total environmental load of Dutch private consumption. These data were needed for normalization in LCA methodology.

In order to gain more insight into the distribution of environmental loads among the different household expenditures, we developed a method to calculate the direct and indirect environmental load of consumption categories. The indirect environmental load is calculated by linking four economic IO tables with environmental data from several databases, covering worldwide impacts. The environmental load per Euro turnover of ultimate supply industries is linked to consumer expenditures obtained from the expenditure survey of Statistics Netherlands. The direct environmental load is taken from literature and environmental databases. Some of the environmental loads are aggregated into a single indicator: the ecoclaim.

This chapter describes the method and the application of it to Dutch household consumption in 2000. First we describe the method, then the detailed results. In the discussion we compare the results to other studies. Background data can be obtained from the authors. Some results of this work were first published in Dutch in 2003 (Nijdam and Wilting 2003).

Method

Expenditure Survey

In many countries, detailed information on consumer expenditures is available. In the Netherlands a survey is carried out by Statistics Netherlands amongst approximately 2,000 households every year. For this study, we used data from the surveys of the years 1995 (CBS 1995) and 2000 (CBS 2000). The effect of inflation between these years was corrected on the basis of price-indices for goods from Statistics Netherlands. The surveys report on expenditures of about 360 categories (products and services). For subsidized expenditures, such as medical care and public transport, only the contribution of private expenditures was taken into account. This implies that most of the environmental load of medical care and about 50% of the environmental load of public transport are not included in our results. All public expenditures are excluded from our study, which in the Netherlands in the year 2000 accounted for about 30% of total expenditures.

Consumption Domains

The 360 expenditure categories were grouped into seven consumption domains, following Vringer et al. (2003). These domains are related to the classification that the Dutch government uses in its policy strategy on sustainable consumption. The consumption domains are:

– Clothing (clothes and shoes, including washing, drying and ironing)
– Food (food, refrigerating, cooking, washing up and catering)
– Housing (rent, mortgage, local housing taxes, housing insurance, maintenance, heating, ventilation and lighting)
– Furnishing (furniture, upholstery, bedding, decoration, garden)
– Leisure (reading matter, day trips, family visits, sports, holidays, audio and video equipment, communication, pets)
– Personal care (health care [but only the part funded by the consumer], self medication, cosmetics, toiletries, towels, toilet, shower, bath)
– Labor (college fees and – books, courses, commuting)

Use of transport, fuels and electricity were allocated to their various functions, following Vringer et al. (2003). For instance, car use for recreation and grocery shopping were allocated to the domains leisure and food respectively. Gas use for hot tap water was allocated to the domains food and personal care. Electricity is used in almost all domains, except labor and furnishing.

Direct and Indirect Load

We distinguished between direct and indirect environmental load:

- The direct environmental load is the load that occurs during use of the product by the consumer.
- The indirect environmental load is the load that occurs before the product or service has been purchased, or after it has been collected for waste treatment. Basically, this is the load caused by enterprises and institutions.

This distinction can be clarified with an example. When a consumer purchases paint to decorate the house, the indirect environmental load is the load associated with production, packaging and distribution of the paint. The direct environmental load is the load due to the emission of solvents during and after painting. Similarly, the production of fuels for a private car is regarded as an indirect load, but the exhaust fumes from the car are regarded as direct environmental load. On the other hand, the load associated with household electricity use is regarded as indirect; the emissions occur in the electricity plants. Emissions from waste treatment and waste water treatment were not allocated to products, but to communal taxes.

To determine the **direct** environmental load, all consumer products were screened individually. The main products here are fuels, paints, cosmetics, cleaning products, household pesticides, cigarettes and pets. Most of the direct loads are reported in the Dutch emission inventory system (VROM 1997).

The **indirect** load was quantified by using IO analysis that traces economic flows up to the point the consumer purchases a product. For this purpose expenditures were linked to their ultimate supply industries by using the Make table from the Statistics Netherlands National Accounts. This table links commodities and products to the corresponding industries. From the Make table it can be seen for example that 85% of the cheese purchased by Dutch households comes from the Dutch dairy industry, 1% comes from farms and 14% comes from imports (of which 84% is from Europe, 11% from other OECD countries, and 5% from other countries).

Economic Regions

The environmental load related to Dutch production and consumption is caused by a large amount of production processes in many countries. In many studies (for example in Blonk et al. [1997]) it is assumed that imports are produced with technologies similar to those in the Netherlands. In general, however, production technologies differ between countries. In order to take these differences into account, we distinguished three different technologies for our imports. So the model consists of four regions, each one of them with its own technology, viz. the Netherlands, OECD-Europe, the other OECD countries and the non-OECD countries. In each foreign region production takes place for Dutch consumption, either by imports of products or by imports of commodities by Dutch industries.

Figure 16.1 presents the general calculation scheme for the indirect environmental load. The environmental load intensities of expenditures were calculated as a weighted average of the environmental load intensities of the corresponding supply industries and regions. The environmental load intensity of expenditure c, e_c, is determined as follows:

$$e_c = \sum_i \alpha_{c,i}^{NL} e_i^{NL} + \sum_{i,j} \alpha_{c,i}^{Ri} e_i^{Rj} \tag{16.1}$$

where

e_i^{NL} = the environmental load intensities of industry i in the Netherlands
e_i^{Ri} = the environmental load intensities of industry i in foreign region R_j
$\alpha_{c,i}$ = the share per industry i and per region (NL or R_j) in supplying expenditure c

The sum of all α's is 1 and they were derived from the Make table and import statistics. The environmental load intensities of each industry were calculated with IO analysis. For the Netherlands we used 105 industries and for the three foreign regions we used 30 industries.

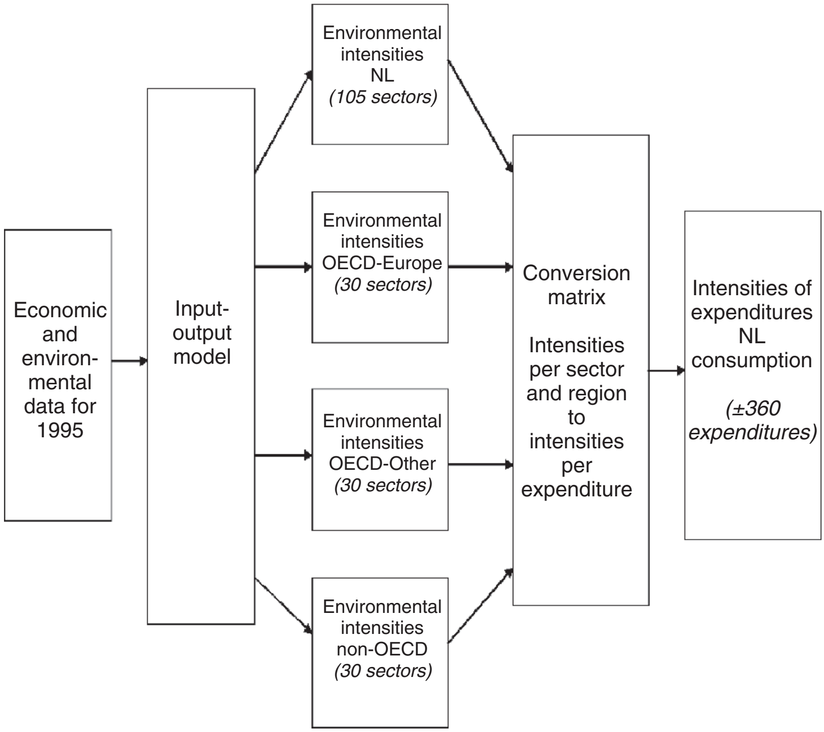

Fig. 16.1 General Calculation Scheme for the Indirect Load Intensities

IO Analysis

In this study environmental load intensities of industries were calculated using multiplier analysis (see for example Bullard and Herendeen 1975). The row vector of total environmental load intensities per industry in foreign region R_i, e_{Ri}, was calculated with:

$$e_{Ri} = d_{Ri}(I - A_{Ri})^{-1} \tag{16.2}$$

with d_{Ri} a row vector of direct environmental intensities per industry in region R_i, I is the identity matrix and A_{Ri} a technology matrix for the production in region R_i. The technology matrices for the three foreign regions were derived from IO tables at a 30-industry level. These tables were constructed using IO tables of countries and sub-regions from the international economic GTAP (global trade analysis project) database (Dimaranan and McDougall 2002).

The method described is a simplification of reality, since we did not take into account the trade flows between the three foreign regions. We assumed for the imports of a foreign region that they were produced with the same technology as installed in that region. Because we used large foreign regions, imports are relatively small compared to total production. Furthermore the technology differences between the two OECD regions are expected to be relatively small. So the errors that were introduced are expected to be very small.

For the intensities of Dutch industries we distinguished a domestic part and a foreign part corresponding with the environmental load from production in the Netherlands and from imports respectively. The domestic part of the Dutch intensities, $e_{NL,d}$, is calculated as follows:

$$e_{NL,d} = d_{NL}(I - A_{NL})^{-1} \tag{16.3}$$

with d_{NL} a row vector of direct environmental intensities per industry in the Netherlands and A_{NL} a direct requirements matrix for the Dutch production, excluding imports. This matrix was derived from an IO table for the Netherlands at the level of 105 industries (Statistics Netherlands 1998). We determined the requirements of imports per unit of production in Dutch industries from the tables of competitive and non-competitive imports for the Netherlands obtained from Statistics Netherlands (1998). Using import statistics, we assigned the imports per industry to one of the three foreign regions and created matrices describing the requirements of imports per region for Dutch production. By using these matrices, we calculated the foreign part of the intensities of Dutch industries per region R_i, $e_{NL,Ri}$:

$$e_{NL,Ri} = e_{Ri} M_{NL,Ri}(I - A_{NL})^{-1} \tag{16.4}$$

with e_{Ri} the row vector of total environmental load intensities per industry and $M_{NL,Ri}$ a matrix describing the direct inputs per unit of production from all industries in region R_i for all Dutch industries.

Environmental Stressors and Databases

On the basis of availability and general use in environmental studies we specified a list of elementary flows or “stressors”. These stressors were inventoried by Pré Consultants (Goedkoop et al. 2002). The list of elementary flows contains chemical as well as physical stressors:

- Emissions of CO_2, CH_4, NO_x, SO_x, N_2O, NH_3, HCFC’s and VOC to air; nitrogen and phosphate to land and water
- Land use, use of fresh water, extraction of fish, use of pesticides, road traffic kilometers

The Dutch emission inventory system (VROM 1997) contains a detailed data inventory for industrial activities and other pollution sources. For a number of environmental stressors, such as land use and fishing, no data were available from the emission inventory system. For these stressors other data from Statistics Netherlands were used.

For the foreign regions, environmental data were mainly taken from the EDGAR database (Olivier et al. 1996). This database contains data on CO_2, NO_x and SO_x per country and per industry. A wide range of sources has been consulted to cover other environmental stressors, e.g. the World Resources Institute (WRI, www.wri.org), the Food and Agriculture Organization (FAO, www.fao.org), the European Environment Agency (EEA, www.eea.eu.int), the Environmental Protection Agency (EPA, www.epa.gov) and Environment Canada (www.ecgc.ca).

Environmental Impact Categories

Mid-point Categories

The chemical stressors were aggregated in environmental impact categories using the life-cycle impact assessment method of Leiden University (Guinée 2001). Road-traffic noise was aggregated using equivalence factors provided by traffic noise specialists within the Netherlands Environmental Assessment Agency (MNP-RIVM).

Land use was classified into three classes, as defined by the World Conservation Union IUCN (IUCN 1991):

- Type II semi-cultivated (for example extensive grasslands)
- Type III cultivated (for example cropland, production forests, pastures)
- Type IV built-up land

The IUCN classification also includes type I (natural areas) and type V (degraded land). Because these areas are not (yet) contributing to our physical consumption they are not included in our study. The land use types were aggregated to type III equivalents with equivalence factors based on biodiversity by (Tekelenburg and Simons 2005). The FAO forestry land use statistics include production forests as well as non-productive natural forests. The latter cannot be allocated to our physical consumption, so it was excluded by recalculating forestry land use to average world production equivalents according to (Stolp and Eppenga 1998). This production area was classified as type III land use.

Multiplying the emissions of stressors with equivalence factors results in an environmental impact score for the following impact categories:

- Land use (cultivated land equivalents during a year, type III-hectares*year)
- Greenhouse gas emissions (kg CO_2 equivalents)
- Acidification (kg SO_2 equivalents)
- Eutrophication (kg PO_4 equivalents)
- Photochemical ozone creation (summer smog, kg ethene equivalents)
- Fish extraction (kg fish)
- Freshwater use (m^3 water)
- Pesticide use (g active ingredient)
- Road traffic (km car-equivalents)

Land use is expressed in area during a year (ha*year). As the household expenditures also cover 1 year, the quantified land use represents the area needed in a steady state situation to maintain our consumption. We only included land occupation, that is, the state during use, not the conversion of land types (the increase or intensification of land use due to increasing population and consumption). During this occupation the biodiversity amounts to about 5% of its pristine state for type IV land use, and up to 90% for type II land use. For type III land use this ranges from 30% to 50%. (Tekelenburg and Simons, in prep).

Freshwater use is a proxy indicator of several environmental problems (for example lowering of groundwater levels in natural areas, depletion of deep aquiver reserves, salinification, habitat loss for aquatic life, soil erosion, etc.). The quantified pesticide use gives a limited indication of ultimate effects, because there are large differences in toxicity, degradability and accumulativeness between pesticides. Eutrophication of soil and water is a major problem in North-western Europe, in particular in the Netherlands and Belgium.

Endpoint: The Ecoclaim

We provisionally aggregated the most important environmental impacts into one 'biodiversity decrease indicator', also referred to as 'ecoclaim' (Rood et al. 2004). These impacts are land use, emission of greenhouse gases (climate change), acidifying nitrogen deposition, fishery and eutrophication.

According to the GLOBIO 3 model (Tekelenburg et al. 2003) the natural capital of the planet has decreased to two thirds of its original value. The natural capital is defined by Ten Brink (2000) as area (quantity) times biodiversity (quality) of all ecosystems. By far the most of the global loss can be ascribed to land use (cultivation of areas) and its adverse fragmentation-effect on the remaining nature in the surroundings, partly also due to the required infrastructure. To a lesser extend the decline is due to other factors such as climate change, acidification, eutrophication, and fishery (Tekelenburg and Simons 2004). The shares of other impact categories, such as summer smog and toxic pollutions are yet unknown. The ecoclaim is expressed as hectares of lost nature. For example the use of 1 ha of cropland with a biodiversity value of 20% of its pristine state results in an ecoclaim of 0.8 ha. The fragmentation effect of this field and the required infrastructure add another 0.2–0.35 ha to the effect of this hectare of cropland. The emission of a kg CO_2 results in an ecoclaim of $0.14\,m^2$; the emission of a kg SO_2 equivalents results in an ecoclaim of $1.3\,m^2$; the emission of a kg phosphate results in an ecoclaim of $49\,m^2$ water surface; the catch of a kg fish results in an ecoclaim of $40\,m^2$ water surface. Ecoclaims for water and land are added up to one single indicator.

Results

Introduction

The results of the calculation method are five lists of environmental load intensities of expenditure categories. One list contains direct load intensities and four lists contain indirect load intensities (The Netherlands, OECD-Europe, other OECD countries and non-OECD countries). They add up to the total environmental load intensity per expenditure category.

From these tables the results can be presented in different ways. First we present the total loads, which can be regarded as our extended footprint. Then the ecoclaim-intensities are presented. In the section on Share of Consumption Domains, the relative share of the different consumption domains is presented. Next the part of the world where the environmental load occurs is presented. Finally the consumption domains are presented in more detail.

Our Footprint Profile

The total annual environmental load per capita of Dutch private consumption is recorded below:

Ecoclaim: 0.9 ha, consisting of

- Land use 0.7 ha*year type III equivalents (equal to an ecoclaim of 0.56 ha)
- Greenhouse effect 11 t CO_2-equivalents (equal to an ecoclaim of 0.15 ha)
- Eutrophication 29 kg PO_4-equivalents (equal to an ecoclaim of 0.14 ha)
- Fish extraction 13 kg fish (equal to an ecoclaim of 520 m^2)
- Acidification 73 kg SO_2-equivalents (equal to an ecoclaim of 95 m^2)

Other environmental impacts (not incorporated in the ecoclaim):

- Summer smog 16 kg ethene-equivalents
- Water extraction 989 m^3 water
- Road traffic noise 12,000 motor car km-equivalents
- Pesticide use 437 g (active ingredient)

These figures represent the 'ecological footprint profile' of the average Dutch consumer in the late 1990s, based on the expenditure survey of the year 2000 (price level 1995) and environmental load intensities of 1995. In this way the results are a mixture of years, but they are closer to 'actual' environmental loads than if we had only used the expenditure survey of 1995. Consumer expenditures amounted to €8,432/per capita/year in 1995 and €8,890 in 2000 (price level 1995).

Ecoclaim per Euro

From the calculations the weighted average ecoclaim intensity amounts to $1.2\,m^2/€$. The 25 expenditure categories with the lowest ecoclaim per euro are presented in Table 16.1. The list contains mostly services, products with high trade-margins and products with little natural materials. As the ecoclaim is heavily dominated by land use, materials with low land use (plastics and metals) have relatively low scores. The expenditures are 50% of total expenditures, but cover only 19% of the total ecoclaim.

Table 16.1 Bottom 25 Expenditure Categories (Lowest Ecoclaim per Euro

Expenditure category	Expenditure (€/year/capita)	Ecoclaim intensity (m^2/€)
Domestic services	147	0.2
Communication	206	0.2
Private medical insurance	27	0.2
Self medication	65	0.3
Hair care and hairdressers	90	0.3
Medical care	62	0.3
Schooling	141	0.4
Cleaning articles	95	0.4
Fixed equipment	71	0.4
Cars and accessories (excl. fuel)	547	0.4
Cosmetics and perfumery	53	0.4
Mopeds, motor-cycles etc. (excl. fuel)	20	0.5
Maintenance (of house and garden)	63	0.5
Rent and rental value	1,505	0.5
Other costs of personal transport (incl. fuels)	544	0.6
Music and theatre	33	0.6
Other household appliances and tools	34	0.6
Sports and games	90	0.6
Lighting appliances	38	0.6
Cooking appliances	19	0.6
Cutlery, kitchenware and kitchen appliances	69	0.6
General body care	76	0.6
Bicycles	47	0.7
Other leisure costs	197	0.7
Public transport	96	0.7

The 25 expenditure categories with the highest ecoclaim per euro are listed in Table 16.2. As to be expected products with high land use have high scores. As yields are generally low in non-OECD countries, the so called ‘colonial’ goods such as coffee and tea show relatively high scores. Also products with relatively low trade margins, such as basic food products, have relatively high scores. The expenditures are 19% of total expenditures, but cover 53% of the total ecoclaim.

In general basic food products have relatively high ecoclaim intensities. Services, taxes, rent and mortgage have relatively low ecoclaim intensities. It may however be clear that these expenditures are fulfilling very different consumer needs. Within the same function (e.g. transport) the differences in ecoclaim intensities are much smaller.

Currently the ecoclaims of fuels and electricity are relatively low. These may increase significantly in the near future as impacts of climate change are expected to increase very strongly (Thomas et al. 2004). Also the share of land-consuming renewable energy in our energy-supply will increase due to climate-measures and depletion of fossil fuels.

Table 16.2 Top 25 Expenditure Categories with Highest Ecoclaim per Euro

Expenditure category	Expenditure (€/year/capita)	Ecoclaim intensity (m^2/€)
Nuts, dried fruits etc.	12	9.2
Coffee, tea and cacao	43	6.8
Potatoes	51	6.0
Chocolate	32	6.0
Oils and fats	23	4.6
Fresh fruit	54	4.5
Flour and corn chandlers ware	23	4.4
Butter, cheese and eggs	97	4.4
Game and poultry	32	4.3
Cake biscuit and pastry	108	4.3
Sugar and confectionary	32	4.3
Condiments, soups and oriental foods	68	4.1
Bread and rusk	88	4.0
Fresh meat	125	3.9
Milk and milk products	103	3.7
Meat products and meat dishes	85	3.7
Preserved fruits	11	3.7
Preserved vegetables	21	3.7
Fresh vegetables	69	3.1
Fish	30	2.7
Garden and flowers	141	2.2
Clothing accessories	14	2.1
Heating and lighting costs not spec	32	2.0
Smoking	74	1.8
Beverages	214	1.6
Furnishings	116	1.6

Share of Consumption Domains

Figure 16.2 presents the share of consumption domains in the total environmental load. The food domain is dominant in the environmental load for most impact categories. This is mainly caused by agriculture and horticulture. Use of natural gas for room heating plays an important part in the housing domain. For leisure and labor most of the environmental load is caused by travel.

Direct and Indirect Impacts

Another result is the analysis of the direct versus the indirect environmental load. Figure 16.3 shows that for most impact categories the indirect load is by far the most important. Only road noise is mostly associated with direct environmental load. For summer smog the direct emissions of volatile organic compounds (VOC) from car exhausts, paints, cosmetics, cleaning agents and other household products are significant, but still less than the indirect emissions.

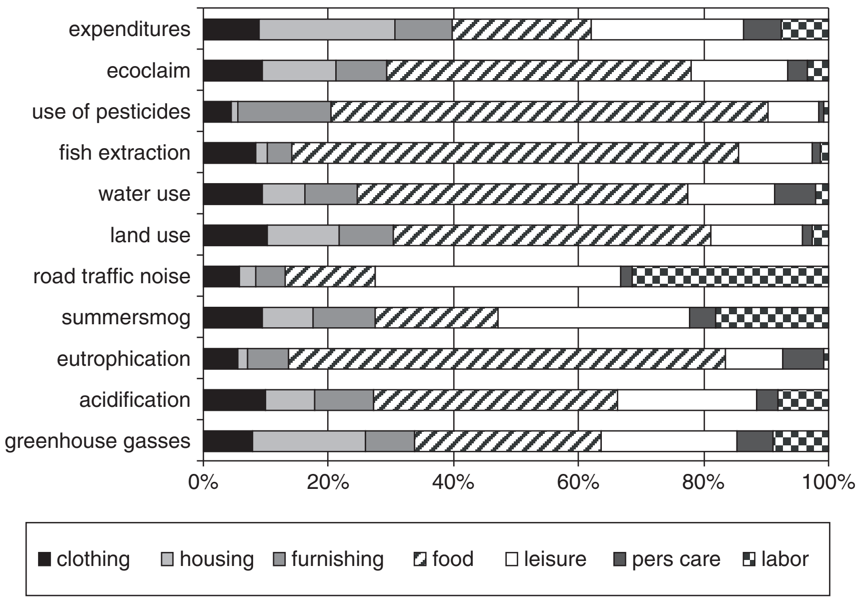

Fig. 16.2 Share of the Consumption Domains in the Environmental Load (Direct and Indirect, All Regions)

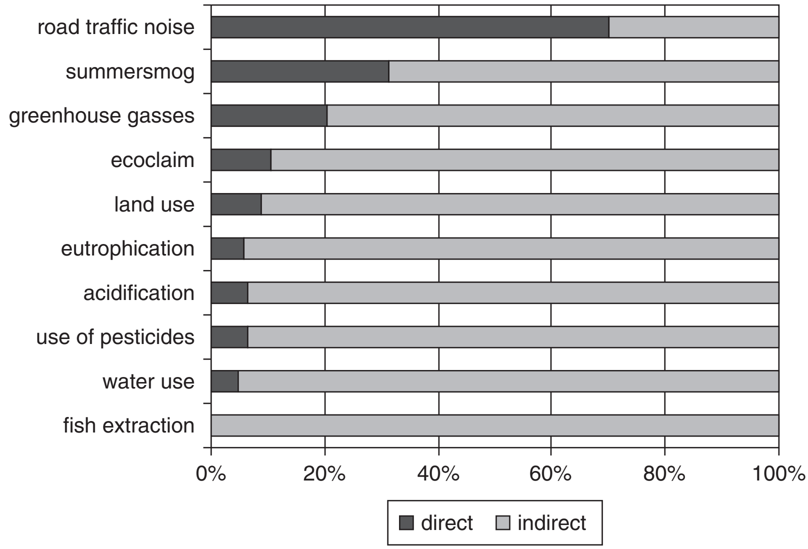

Fig. 16.3 Comparison of the Direct and Indirect Environmental Load

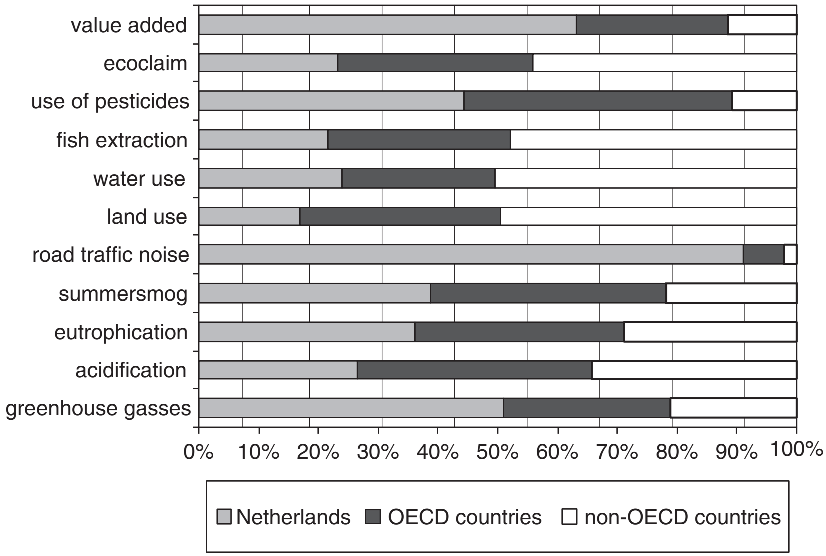

Fig. 16.4 Share of the World Regions in the Environmental Load from Dutch Private Consumption

Distribution of Loads between the Economic Regions

Next we present the relative contribution of the environmental load per region. Figure 16.4 shows that, except for greenhouse gases and road traffic noise, most of the impacts take place abroad. The non-OECD countries have a relatively high share in land use, fish extraction and water use. In proportion to this, their value added is relatively low. For greenhouse gases the share of the Netherlands is relatively high. About half of this share is caused by direct emissions (residential energy use and private use of petrol). The other half is caused by indirect emissions (Dutch production). The acidification associated with non-OECD imports is relatively high. This is partly due to the use of acidifying fertilizers in these countries and partly due to the use of relatively 'unclean' fuels such as wood, coal and lignite.

Consumption Domains in Detail

The results provide insight into the composition of the environmental load within consumption domains. We disaggregated the consumption domains into several sub-domains. The results for the sub-domains, however, have to be regarded as indicative. For reasons of presentations the results are limited to the ecoclaim, sometimes complemented with an impact relevant to the consumption domain (e.g. summer smog from solvents in the personal care domain).

Figure 16.5 shows the main contributors to expenditures and some selected impact categories within the food domain. The percentages of the food sub-domains add up to 100% for each category. Protein rich foodstuffs such as meat and dairy products are main contributors to the ecoclaim. Pesticide use is relatively high for fruits and vegetables (including potatoes). In proportion to expenditures, catering (including outdoor consumptions and delivered meals) has relatively low impacts.

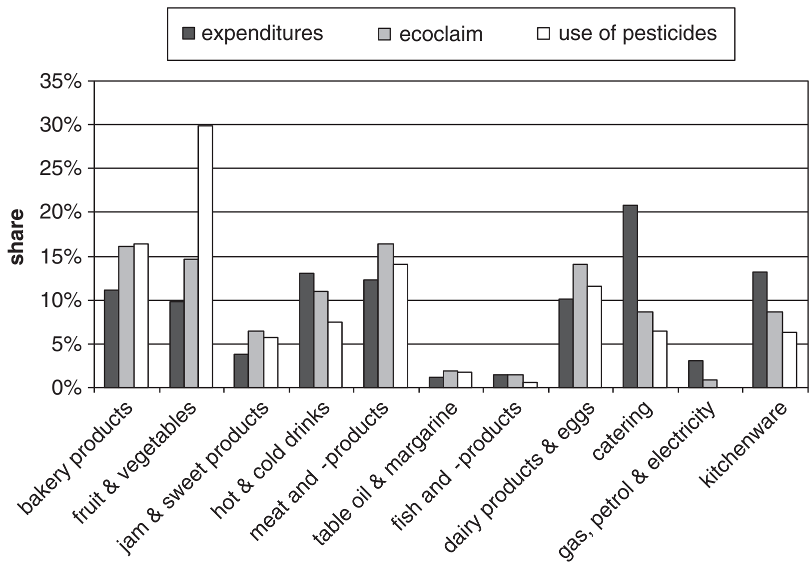

Fig. 16.5 Contribution of Sub-domains in the Environmental Load of the Food Domain

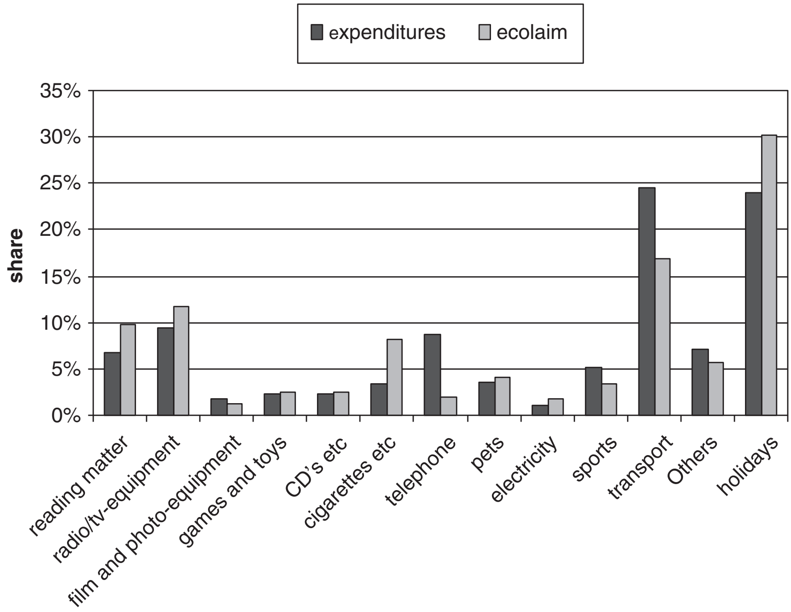

Fig. 16.6 Contribution of Sub-domains in the Environmental Load of the Leisure Domain

Figure 16.6 shows the main contributors within the leisure domain. Travel-related expenditures such as transport (day trips and weekend trips) and holidays (trips lasting more than four nights) form the main part of the ecoclaim. The expenditures in the sub-domain 'holidays' cover both travel items (for example airline tickets) as well as accommodation costs (including meals). These are not separated in the Dutch expenditure survey, because it is difficult to require detailed housekeeping books from holiday-makers.

Figure 16.7 shows the main contributors within the clothing domain. The indirect load, that is the production chain of clothes, is much larger than the direct environmental load of washing, drying and ironing. Vringer et al. (2003) already found the same with regard to energy requirements within the clothing domain.

Figure 16.8 shows the main contributors within the personal care domain. The use of fuels and electricity (mainly natural gas for hot tap water) is important here. In proportion to expenditures, hairdressers have relatively low impacts. Smog creating emissions like solvents and propellants are visible in the subdomains toiletries (antiperspirants and after shave), hair care products (hairsprays) and cosmetics and perfumes.

Figure 16.9 gives the main contributors within the furnishing domain. The sub-domain 'furniture' appears to be relatively important. In proportion to expenditures the subdomains 'painting & decorating' and 'indoor plants & flowers' have high environmental loads. The ecoclaim of the subdomains 'indoor plants & flowers' and 'garden' mainly originate from greenhouse horticulture (purchase of flowers and plants). Services show relatively low impacts.

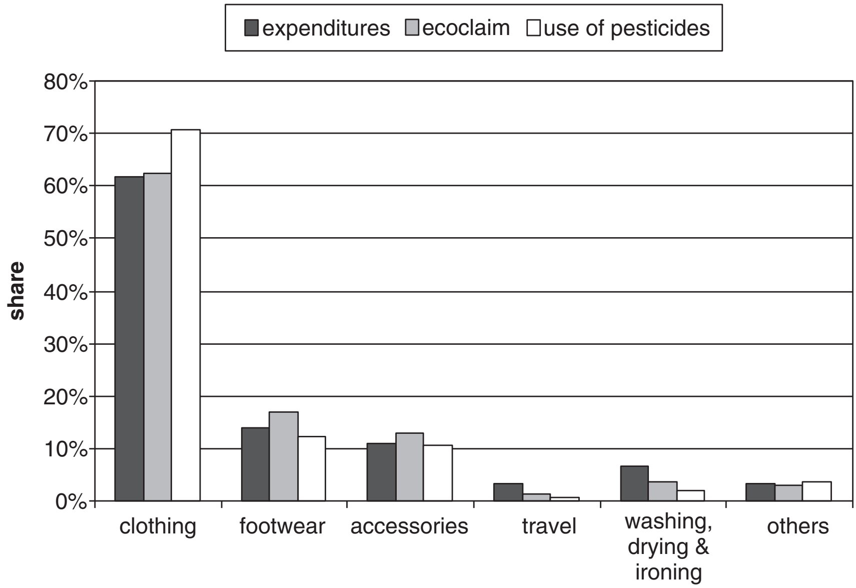

Fig. 16.7 Contribution of Sub-domains in the Environmental Load of the Clothing Domain

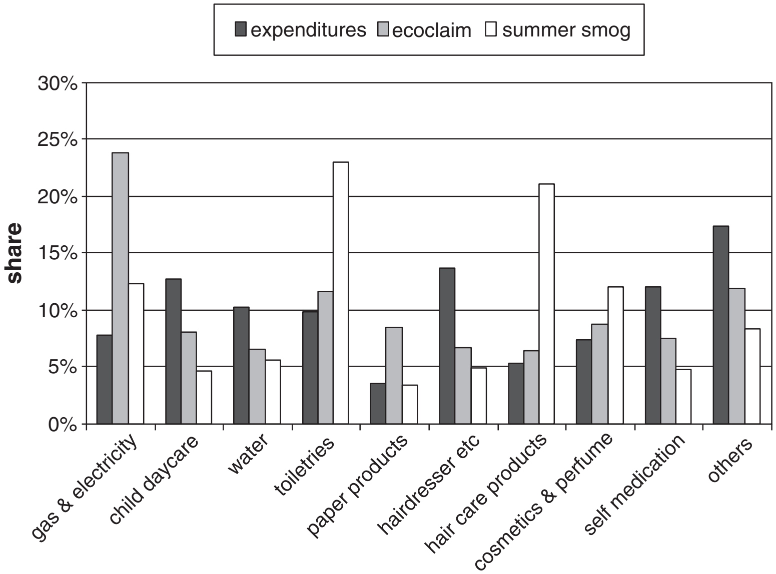

Fig. 16.8 Contribution of Sub-domains in the Environmental Load of the Personal Care Domain

Within the housing domain expenditures on rent and mortgage are by far the most important (71% of ecoclaim). They include the environmental load associated with the building of houses and all the production activities behind this. The ecoclaim

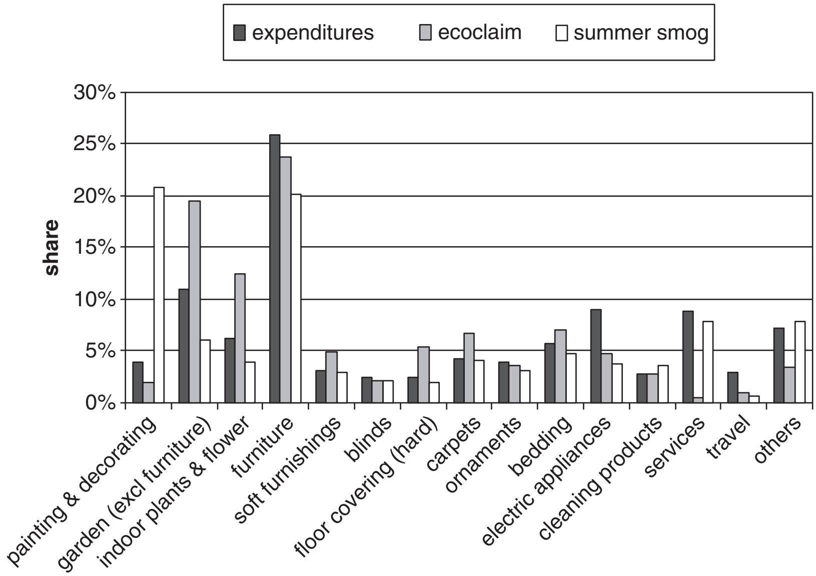

Fig. 16.9 Contribution of Sub-domains in the Environmental Load of the Furnishing Domain

associated with rent and mortgage mainly lies in the use of wood for construction. Room heating (14% of ecoclaim) is the major cause of greenhouse gas emissions in this domain. Local taxes (7% of ecoclaim) include impacts of waste treatment and waste water treatment.

Within the labor domain private transport (mainly car use for commuting) is by far the most important (75% of ecoclaim).

Comparison of Results to Other Studies

In this study national and international environmental statistics were combined with national and international economic statistics and the Dutch expenditure surveys. In this section we compare our results to outcomes of other studies and discuss the possible applications of the results.

First a comparison was made with the results of (Blonk et al. 1997). Blonk et al. used IO tables from 1993, containing 60 industries, and used only Dutch emission data. They did not disaggregate data to household expenditures, but only looked at the level of total Dutch private consumption. So we can only compare totals. In order to be able to make a valid comparison we recalculated our results using exclusively Dutch emission data. The results were very similar for greenhouse gases and summer smog (1% difference). Acidification and eutrophication were in the same order of magnitude (12% and 35% difference respectively). This indicates that the conversion does not generate unacceptable systematic deformation of the data.

Table 16.3 Energy Use of Dutch Private Consumption in the Year 1995 According to Current Study (IO Analysis) and Vringer et al. (2003) (Hybrid Analysis) (GJ/capita/year)

Domain	IO analysis	Hybrid analysis
Clothing	6.7	5.3
Housing	32.0	30.0
Furnishing	9.2	8.2
Food	22.5	23.9
Leisure	20.7	20.4
Personal care	9.5	7.2
Labor	8.4	7.9
Total	**109.0**	**102.9**

Tukker et al. (2005) calculated environmental impacts of consumption in the EU-25. Although Dutch consumption is not completely comparable to average European consumption, a comparison was made. For greenhouse gases Tukker et al. find 9 t CO_2-equivalents per capita, which is comparable to our 11 t per capita. For acidification Tukker et al. find 109 kg SO_2-equivalents per capita, which is in the same order of magnitude as our 79 kg per capita. For an extensive comparison we refer to their report.

For purpose of validation, the energy use of all industries was entered in the calculation method. Most of these data were available from Wilting et al. (2001). For the Netherlands additional data from Statistics Netherlands were used. These calculations allow us to make a comparison with the results of the hybrid energy analysis performed by Vringer et al. (2003). The results, presented in Table 16.3, indicate that the two methods give outcomes in the same order of magnitude.

The quantified land use was compared to several ‘footprint’ studies. Van Vuuren et al. (1999) present three footprints for the Netherlands from different studies varying from 0.5 to 2.5 ha/capita (excluding land use for CO_2 fixation from fossil fuels). The land use that we calculated for private consumption (0.9 ha/capita) results in 1.3 ha/capita for total consumption, that is including 30% public consumption. This value lies well within the aforementioned range. In the WWF study ‘Europe 2005’ a footprint of 1.7 ha/capita (excluding fossil CO_2 fixation) is given for the Netherlands (Wackernagel 2005).

Conclusions

The calculation method described produces insight into the amount and distribution of the environmental load of private consumption. From the validation it can be concluded that the method produces realistic results on the level of the consumption domains. On the level of products or sub-domains the results should be regarded as indicative.

The most remarkable results are:

- Within the endpoint-indicator ‘ecoclaim’, representing damage to ecosystems, occupation of land is the most important factor.
- A large proportion of the environmental load of Dutch private consumption takes place abroad.
  – For greenhouse gases this amounts to 49%
  – for pesticide use this amounts to 56%
  – for summer smog this amounts to 61%
  – for eutrophication this amounts to 64%
  – for acidification this amounts to 74%
  – for the ecoclaim this amounts to 77%
  – for land use this amounts to 84%
- The consumption domain food has high environmental loads. Within this domain the part attributable to protein rich foodstuffs is relatively high.
- Fuel use for room heating and transportation are important domestic sources of environmental load from a consumption based perspective.

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Part V
Policy Applications

Chapter 17
A Hybrid IO Energy Model to Analyze CO_2 Reduction Policies: A Case of Germany

Stefan Vögele, Wilhelm Kuckshinrichs, and Peter Markewitz

In recent years a lot of new energy models have been developed to analyze climate change mitigation strategies and the effects such strategies have on economic and technological development. Two main types of models can be identified: Top-down models that focus on the economic interactions within different sectors in an economy and bottom-up models that focus more on physical energy flows and technological aspects. One way of exploiting the advantages of each of these approaches is to link them to create a hybrid approach. Due to their main characteristics (e.g. high degree of disaggregating) input-output models are suitable for integrating technological data in an economic model in a special manner. Therefore, a class of models exists, linking input-output models with disaggregated energy system models. In this paper we present such a hybrid approach which consists of the input-output model Macroeconomic Information System (MIS) and the bottom-up model Instruments for Greenhouse Gas Reduction Strategies (IKARUS) – Market Allocation (MARKAL). For the hybrid MIS/IKARUS-MARKAL model a soft-linking approach is used, where the MIS model supplies data about the development of the different industry and service sectors and the IKARUS-MARKAL model calculates the energy demand of these sectors and the cost-optimal energy production structure. Two different examples for the use of the hybrid MIS/IKARUS-MARKAL approach will be presented: our first example focuses on the question of whether a given emission target (like the Kyoto one) can be reached assuming a desired growth rate and taking technological restrictions into account. The focus of the second example is on the economic impacts of a CO_2 mitigation strategy. In this example, we ask which industries will benefit from the decision of policymakers to take measures to reduce CO_2 emissions and which ones will lose (in the sense of economic growth).

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Introduction

In order to be able to help policymakers in assessing developments with a view to cross-disciplinary targets and to show them possible ways towards a national economy focusing on multi-criteria considerations, interdisciplinary approaches are required in which technological, economic and social aspects are taken into account, including their interrelations. A contribution can be made by models that do not only consider economic or technological parameters and which specifically focus on interdisciplinary issues.

With this focus a lot of new energy models have been developed in recent years. These models are targeted to analyze climate change mitigation strategies and the effects that such strategies have on economic and technological development. Two main types of energy models can be identified: *top-down models* that focus on the economic interactions on an aggregated level and *bottom-up models* that focus more on physical energy flows and technological aspects (see e.g. McFarland et al. 2004).

Both types have advantages and disadvantages. One strength of top-down models is that they take the effects of structural changes on the economic development of each sector into account.[1] On the other hand, technological aspects such as vintage structures, load and availability factors are more or less ignored or only taken into account in an aggregated way. Bottom-up models are used to describe the supply of and demand for energy on a very disaggregated and technology-oriented level. However, the effects of changes in the energy system on the economic development of the different industrial sectors are not, or only in a very aggregated way, taken into consideration.

One way of exploiting the advantages of each of these approaches is to link them. Therefore, a class of models exists, linking input-output models with disaggregated energy system models.

Such a hybrid modelling approach will be presented in the following. The focus is on the analysis of the impacts of energy and environmental policy measures taking technological and economic relationships into consideration.

Methodological Concept

Objectives

Complex, interdisciplinary issues resulting from energy and environmental policies place high demands on model designers. The desire that a model should be applicable to a wide range of complex issues is opposed to the requirement of easy comprehensibility of the interactions within the model, of a high topicality of the

[1] This holds particularly for dynamic models but it also applies to approaches with flexible production coefficients.

data basis used and transparency. The diversified and in part contradictory demands has to meet on a model lead to the fact that the models concentrate on specific issues and can only be used for other purposes to a limited extent. The approach presented in the following is also to be seen against the background of special issues, including the effects of energy and environmental policy measures on:

- The technological structure of the energy system (considering also the influence of political measures on the introduction and dissemination of new technologies) and the economic effects thus induced in the individual sectors of industry and
- The development of individual sectors of industry and of the induced technological and ecological effects

Starting out from a specific issue, each model represents a simplified image of reality. According to the issue to be investigated and the perspective from which the issue is to be analyzed, it is necessary to go into detail in certain areas, whereas in other areas elements and their cause–effect relationships can be modeled in the form of a larger aggregate. For the above-mentioned issues, the use of hybrid models is recommended in which technological and economic information is linked.

The decision on the choice of the approach used in the following and its concrete form is based on the following, empirically verifiable theses:

- The short- and medium-term potentials for structural changes in the energy sector do not only depend on economic but also on the technological conditions. Of particular importance is the vintage structure of the capital stock.
- Changes in the energy system can also have an effect on the economic structure of a national economy. Thus, high investments are sometimes required for energy-saving measures, which tend to increase the production activities in the capital goods industry and the building sector.
- Changes in the economic activities of individual sectors generally also have effects on their demand for energy and thus on the energy economy.

In order to assess the impacts of energy and environmental policy decisions at the macroeconomic and sectoral level, a modelling approach are required which allows for the complexity of both economic and technological interrelations. A relevant example is the approach developed as part of the IKARUS project, which fulfills these demands and has proved efficient within the framework of "realistic" analyses of energy and environmental policies. This approach will be presented in the following.

Methodological Procedure

By definition, each hybrid model is a combination of different model types. The individual sub-models may be coupled with each other by either a soft or a hard link. In the case of a soft link, two or more separate models are involved, which can be used independently of each other. The data exchange between the models takes place via specially defined interfaces. The problem is that a complete model run, i.e. calculations with several feedbacks until a convergence criterion is fulfilled, is very time-consuming. In the hard-link approach, the individual models are firmly linked with each other. The calculations take place simultaneously. The time required for the calculations thus tends to decrease. Moreover, major inconsistencies are avoided through a well-defined linking approach. A disadvantage is that the complexity of the model system clearly increases. In addition, a hard-link approach greatly limits the flexibility with respect to alternative model couplings and model extensions (IEA/ETSAP 1993; ECN 1999; McFarland et al. 2004; Wilting et al. 2004). The hybrid approach presented in the following is based on a combination of an energy system and an input-output model linked by means of a soft link.[2]

Energy system models like MARKAL (Fishbone1983), TIMES (Fahl et al. 2002), MESSAGE III (Messner and Strubegger 1995) and PRIMES (European Commission 1995) are based on very detailed information about different kinds of energy conversion, distribution and end-user technologies, about the availability of resources and the interactions between the technologies, different kinds of technological constraints and the vintage structure of the capital stock. They thus provide a very extensive possibility of analysis for assessing the influence of technological restrictions on the substitution possibilities between the different energy carriers and between energy and other input factors (e.g. capital). In general, the energy system models are based on an economic optimization calculation. The models thus normally determine the cheapest technology mix under the given boundary conditions (also including political requirements). The results of a calculation include information on the input factors and investments required for an optimum-cost energy supply from the macroeconomic perspective. Since the macroeconomic effects of changes in the energy system and indirectly induced effects on the national economy are normally not or only very rudimentarily taken into account in the energy system models and the effects of environmental policy measures on the developments of individual sectors can thus also only be determined to a limited extent, as a rule, a different type of model has to be used.

The experience made with input-output models shows that due to their main characteristics (e.g. high degree of disaggregating) these models are suitable for integrating technological data in an economic model in a special manner (see e.g. James et al. 1986; Duchin and Lange 1994; Wilting et al. 2004). These kinds of models enable a reproduction of the national economy cycle and the determination of macroeconomic effects induced by economic and technological changes. Therefore we use an input-output model as a tool to assess economic effects of developments on a technological and macroeconomic level.

Priority is given to the electricity sector, which is responsible for a large proportion of CO_2 emissions and is thus often at the centre of energy and environmental policy analyses. The use of an energy system model makes it possible to determine fairly realistically the development of the electricity sector, since this model type

[2] For other hybrid approaches see Chapter 10 (Nathani), Chapter 14 (Suh and Huppes), Chapter 13 (Pacca), Chapter 24 (Vringer et al.), and Chapter 35 (Moll et al.).

takes technological and economic restrictions into account on a very disaggregated level. Within the hybrid approach, the information from the energy system model on the electricity production mix deployed at the individual dates under consideration is used to modify the input structure stored in the IO model for this sector. In order to be able to adapt the input structure, data on technology-specific input structures (i.e. the input structure of coal, gas, wind power, biomass and nuclear power plants broken down according to the sectors of the IO model) are used and combined according to the mix determined by the energy system model. Simultaneously a correction of the demand for capital goods is made on the basis of the investment costs anticipated for the individual technologies and of the demand mix determined for new power plants (see Fig. 17.1). This procedure is necessary since the individual technologies in the conversion sector differ both in the volume and the composition of the inputs and investments required for them.

In addition to the correction of the input structure of the electricity sector and the demand of this sector for investments, the demand of the other industrial sectors for energy is modified. The autonomous energy efficiency improvement (AEEI) factors play an important role here. These factors reflect improvement in energy efficiency at sectoral level. By specifying the AEEI factors it is easily possible to model the development of sector-specific energy consumption in the IO model. It should be noted that a change in the demand for energy also changes the relative fraction of

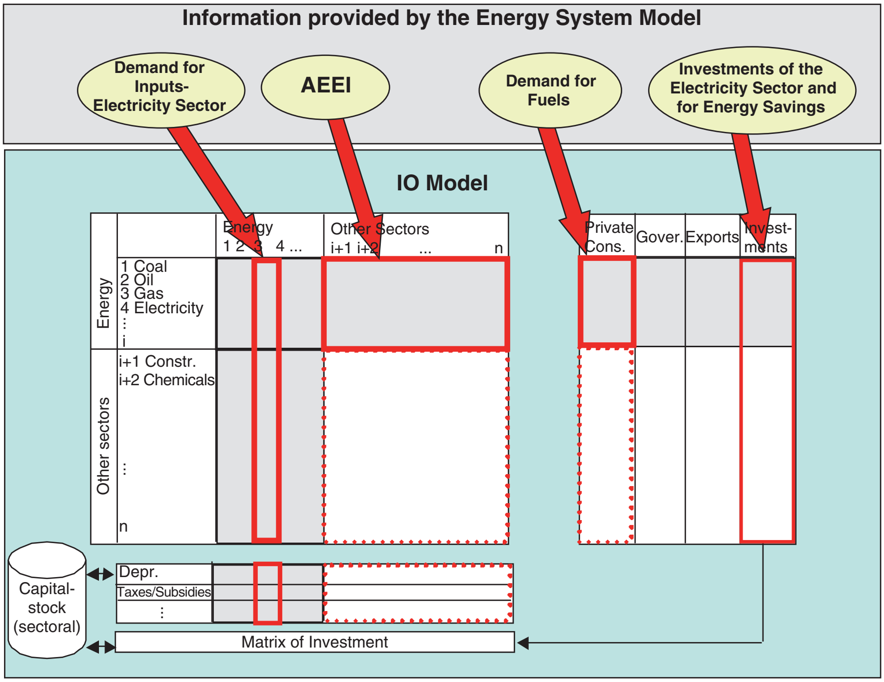

Fig. 17.1 Structure of the IO Model and its Links to the Energy System Model

other input factors, which may make it necessary to correct the whole input structure. This also applies, in particular, to adaptations concerning the demand of private households. Thus, as a rule, changes in the households' demand for oil, electricity or gas change the total consumption structure.

In principle, apart from the modifications already mentioned, the IO model can also be "corrected" in other areas using information from the energy system model. This applies, in particular, to the prices of individual goods and the development of electricity and energy carrier exports and imports. The rules for recoding the information from the energy system model are also important in this connection. Thus, it is necessary, for example, to break down the energy demand according to the sectoral structure of the IO model used (see Appendix).

Based on the specifications from the energy system model, it is possible to estimate the economic development of the individual industrial sectors using the input-output model. In order to determine price effects and dynamic effects, it is advisable to use an input-output model with price-dependent production coefficients or a dynamic IO model. The decision on the model to be used or whether to add price dependencies and dynamic aspects will depend on the respective issue.

Within our hybrid approach, the information obtained from the input-output model on economic developments is used for specifying the "demand" for energy services of the energy system model (see Fig. 17.2). Subsequently, new calculations will be performed with the energy system model. The result obtained will be the cheapest energy system among the economic developments anticipated from the macroeconomic perspective.

Apart from the "demand" for energy services, the energy system model can also be coupled in other areas with IO and energy industry models. It is, for example,

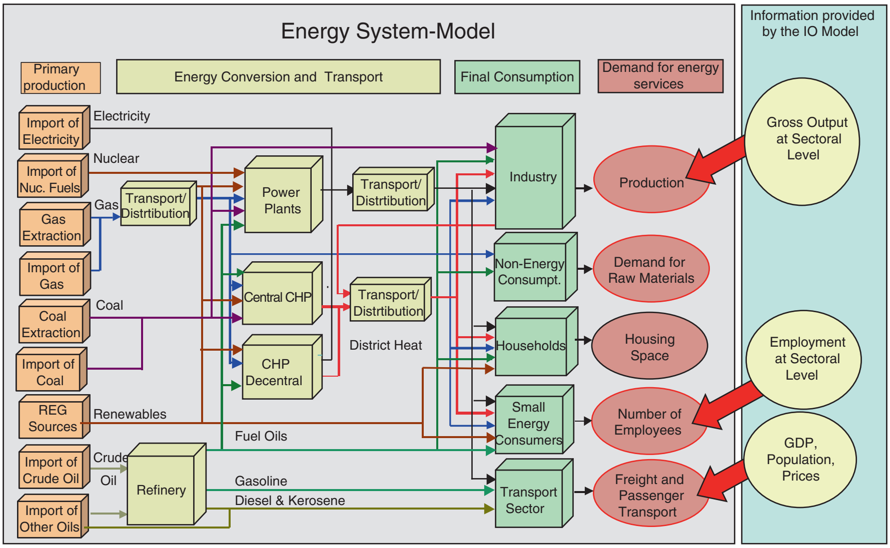

Fig. 17.2 Structure of the Energy System Model and its Links to the IO Model

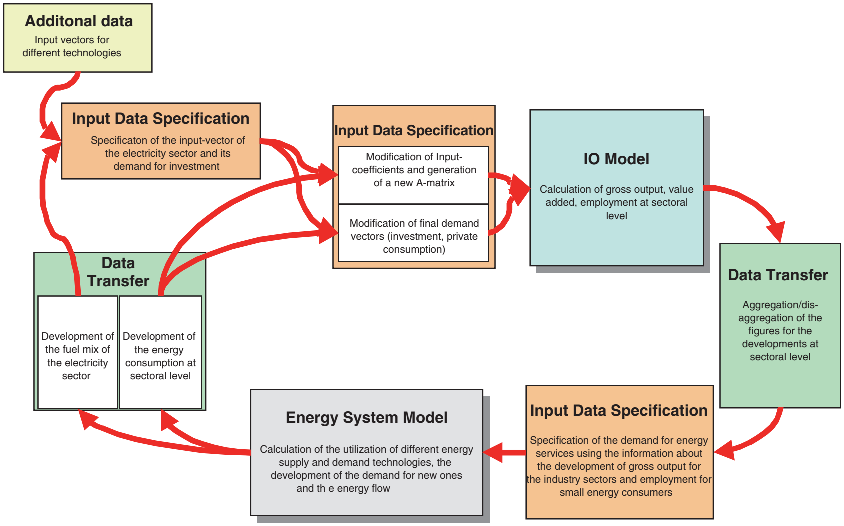

Fig. 17.3 Interactions Between Input-Output and Energy System Model Using a Hybrid Approach

possible to adapt the costs of individual technologies to the costs of capital goods according to results of economic models.

If desired, based on the results of the energy system model, it is possible to again calculate new energy input coefficients in the form of AEEI factors in a next iteration round. The new AEEI factors can again be passed on to the IO model to take the efficiency increase estimated by the energy system model into account. In addition to the AEEI factors, the information about the corresponding electricity mix and on the consumption structure of private households is also verified and modified in the approach described when performing an iteration round (Fig. 17.3).

In principle, an iterative process can thus be started extending over several rounds. The process is disrupted as soon as a convergence criterion is fulfilled.

Possible Applications and Restrictions

The hybrid approach described, whose core is a combined input-output and energy system model, can be used to deal with a variety of technological and economic issues. The chosen soft-link approach enables a flexible use of different sub-models. It should be noted, however, that

- The individual models are in part based on different model philosophies, which may lead to inconsistencies.
- Terms such as “costs” and “prices” are used differently in the individual models.

Moreover, although the simplifications made especially in linking the models make it possible to represent complex facts in a simple and transparent manner, the aggregations made may also lead to information losses and wrong conclusions. Furthermore, attention must be paid to the assumptions and restrictions underlying the individual sub-models. In energy system models these are, for example:

- Exclusive orientation to macroeconomic optimization calculations: Generally, the optimization procedures used in the energy system models minimize total cost of the system, neglecting that in many cases decision-makers have to solve multi-criteria problems on different levels.
- All of the economic and technological features of the different technologies considered in the model are well-known: most approaches do not consider aspects of uncertainty, neither as structural nor as data uncertainty.

For IO models the following restrictions should be noted:

- The macroeconomic development is primarily governed by the development of demand, and generally, economic growth is defined exogenously.
- Dynamic processes are only taken into account in an aggregated form or only rudimentarily.
- Within an IO model "technologies" are usually described by average sector parameters which are based on aggregated data. For example, non-ferrous metal production covers highly energy-intensive primary aluminium production as well as less energy-intensive copper production in one average IO-sector-coefficient. Furthermore, additional production is calculated by average instead of using marginal coefficients.

In spite of these restrictions, an IO energy system hybrid approach is suitable for a variety of technological and economic issues. Some examples of the possible applications of an IO energy system hybrid model will be shown in the following using the approach developed within the framework of the IKARUS project.

The IKARUS Project as a Prominent Application of the Model Approach

Aim of the IKARUS Project

In 1990 the German Federal Ministry of Education, Science, Research and Technology initiated the IKARUS (Instruments for Greenhouse Gas Reduction Strategies) project. The aim of this project was to provide tools for developing strategies to reduce energy-related emissions of greenhouse gases in Germany (Markewitz et al. 1996; Markewitz and Stein 2003; Hake 1998).

The background for the project was the request of political decision-makers for a set of instruments enabling the transparent and consistent development and analysis of greenhouse gas mitigation strategies. One element of the IKARUS instruments is a classical bottom-up energy system model describing the energy system on a national level. In addition to the energy model, a dynamic input-output model was installed for the macroeconomic embedding of the results of the energy system model and to take into consideration the mutual links between the energy system and the rest of an economy. In particular, the IO model was used to provide a consistent set of variables which describe economic developments on a sectoral level and to check the macroeconomic consistency of the IKARUS-MARKAL calculations. MIS/IKARUS-MARKAL can thus be used as a standard example of a hybrid approach.

The hybrid model was completed in 1995 and used in numerous studies (Kuckshinrichs and Kemfert 1996; Kraft et al. 2002; Markewitz and Ziesing 2004). It was mainly applied to the development of greenhouse gas strategies to achieve given emission targets. Based on these results, political instruments were then derived outside the model, with which the reduction measures can be implemented. The results, which are also contained in the Federal Government's national climate protection reports, were discussed in detail with the policymakers.

A climate protection strategy decisively depends on the underlying energy policy boundary conditions (e.g. energy prices, nuclear energy use, role of renewables etc.). Based on different boundary conditions, corresponding climate protection scenarios have been developed with the aid of the hybrid model. Of particular significance in this connection was the role of future nuclear energy use, which is to be phased out by 2020 according to the agreement between Federal Government and power plant operators. Relevant scenario results were presented to the decision-makers, indicating the impacts of a withdrawal from nuclear energy on climate protection strategies. Another focal point was the enhanced use of renewable energies as well as options of efficient energy application and energy conversion. Sensitivity analyses were carried out to obtain information about the robustness of the results. Against the background of increasing unemployment figures, the impacts of climate protection strategies on employment play an ever-increasing role. The hybrid model was also successfully used to answer these questions. The model results serve as rough guidelines and show policymakers the impacts of different energy and economic policies in the form of scenarios ("What would happen if . . . ?"). The hybrid model reproduces the macroeconomic and energy-economy interlinkage of the Federal Republic of Germany and operates at a corresponding aggregation level. The limits of the model are in the detailed statement, which must be made with the aid of other more disaggregated sectoral models. The MIS/IKARUS-MARKAL hybrid model and some example of its use will be presented in the following.

Description of the Two Sub-models and the Links Between Them

The Input-Output Model MIS

MIS is a demand-driven, dynamic IO model with endogenously determined demand for investments (Pfaffenberger and Ströbele 1995). The development of other categories of final demand depends on exogenously given information.

The aggregation of the sectors mainly depends on the structure of the official IO tables of the Federal Statistical Office of Germany. However, in order to improve the possibilities of using the model for the analysis of energy policies, additional sectors (e.g. "space heat", "nuclear") were introduced. At the moment, besides 9 energy sectors, 15 industrial and 8 service sectors are considered. Some sub-modules were also used to integrate technological information such as housing space, lifetime of buildings and to specify technology-oriented development paths of selected sectors (e.g. for electricity and transport).[3] In the demand tool, for example, the user can either specify his own ideas about the dynamics of certain components or alternatively he may rely on substitution processes and structural change shown in a model-endogenous manner and represented by elasticities.

To represent substitution processes according to changes of relative prices MIS is based on CES production functions, which allow the replacement of energy by capital and the replacement of energy carriers by other energy carriers.[4] Additionally, autonomous energy efficiency improvement (AEEI) factors are included to describe non-price-induced efficiency gains.

Based on the specified assumption concerning the development of final demand (excluding investment), technological and demographic parameters, energy prices, etc., MIS provides information about the production activities of each sector, employment and other macroeconomic figures.

The Energy System Model IKARUS-MARKAL

IKARUS-MARKAL is a process-based optimization approach of the linear programming type, representing (bottom-up) energy technologies along the conversion chains (Fishbone 1983; Kraft et al. 2002). Primary energy supply, energy conversion, transport and the end use of energy as well as technological restrictions are described in a very detailed manner. At the moment, the model contains information on more than 500 technologies and processes. Approximately 90 energy carriers are also available in the model to describe the final energy supply or the provision of useful energy. Inter-linkages between energy flows are achieved with the help of techniques, which are described by the specific input per output. Besides technological parameters, all techniques and processes are characterized by costs and emissions. Therefore, cost and emission flows are modelled simultaneously. Based on exogenously determined energy demand the model offers a cost-minimizing solution for the energy system fulfilling this demand. This includes the optimum energy technology structure as well as the optimum energy carrier mix.

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[3] The submodels contain technology specific information on the demand for inputs (incl. demand for investments). Based on exogenous technology scenarios, new input-output coefficients will be calculated. If necessary, the structure of private consumption and the demand for investments will be changed, too.

[4] Details on the structure of the CES-function used in MIS can be found in Pfaffenberger and Ströbele (1995).

To be able to use the model it is necessary to specify the demand for energy services on a sectoral level. This can be done by using the results of an economic model like MIS.

Description of the Hybrid Approach

For the hybrid MIS/IKARUS-MARKAL model a soft-linking approach is used whereby the MIS model provides data on the economic development of the different industrial and service sectors and the IKARUS-MARKAL model calculates the energy demand of these sectors and the optimum-cost energy production structure (see Grundmann 1999). The central information passed on from the IKARUS-MARKAL energy system model to MIS via the soft link includes:

- AEEI factors: These are calculated taking the different sector breakdown into consideration and then inserted in MIS. Modifications of specific energy consumption are taken into account both on the production and the consumption side. To take the cost of changes in the AEEI-factors into account, information about marginal abatement costs for CO_2, calculated in the energy-system model, is used to specify a CO_2-tax which is implemented in the IO model to be able to analyze substitution effects of CO_2-avoidance strategies in more detail.
- Information about the electricity production mix: This is used to specify the input structure of the electricity sector underlying the IO model on the basis of fuel-specific input vectors stored in MIS and the sector's demand for investments.

MIS Supplies to IKARUS-MARKAL:

- Gross output and employment figures as well as
- Information about the developments in the transport sector

The results of the respective sub-models are adapted to the sectoral breakdown of the partner model and converted into parameters that can be used in the corresponding model. Technological information is transformed into economic parameters and vice versa.

Regarding the demographic trends we assume a significant reduction of the population taking into account projections of the Federal Statistical Office. Due to the development of the population, we expect that the growth rate of the GDP will drop in the long term. In the transport sector we assume a strong increase of 50% in freight transport and a considerable increase of 15% in passenger transport. In addition, it is assumed that after a peak in 2000, energy prices will increase moderately (see Table 17.1).

The reduction measures already introduced by the Federal Government (e.g. energy-saving regulation, additional use of combined heat and power) and the political framework set by the Federal Government (e.g. agreement between the Federal Government and utilities concerning nuclear phase-out, the minimized generation of electricity from lignite in East Germany) are also included in the considerations.

Table 17.1 Key Factors Used for the Scenarios

	Unit	2000	2010	2020	2030
Population	Million	82.0	81.5	80.3	78.0
Number of households	Million	37.5	38.5	38.8	38.1
Total floor space	Million m^2	3,117	3,409	3,637	3,839
Gross domestic product	10^9 €(95)	1,964	2,367	2,798	3,190
Passenger transport	Billion pkm	926	1,025	1,116	1,190
Freight transport	Billion tkm	489	613	750	889
Hard coal	€/GJ (2000)	1.32	1.76	1.80	1.87
Crude oil	€/GJ (2000)	5.32	4.39	4.49	4.68
Gasoline	€/GJ (2000)	7.06	6.28	6.51	6.79
Diesel	€/GJ (2000)	6.95	5.45	5.61	5.85
Domestic fuel oil	€/GJ (2000)	6.95	5.45	5.61	5.85
Residual fuel oil	€/GJ (2000)	5.06	3.51	3.60	3.75
Natural gas A	€/GJ (2000)	3.27	3.65	3.82	3.98
Natural gas B	€/GJ (2000)	4.11	4.56	4.77	4.97
Lignite	€/GJ (2000)	1.44	1.51	1.64	1.68

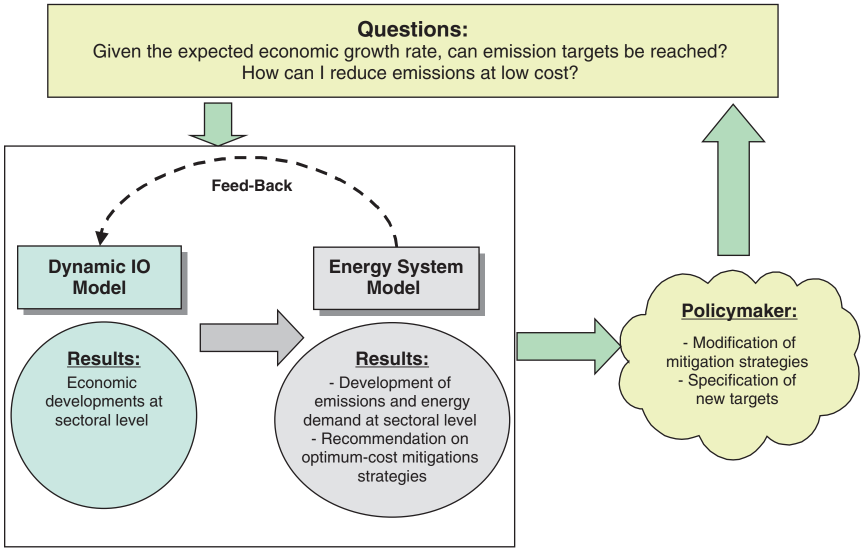

Fig. 17.4 Use of the Hybrid Approach in Example 1

Example 1. Effects of economic growth on CO_2

Our first example focuses on the question of whether a given emission target (like the one assigned under the Kyoto protocol) can be reached assuming a desired growth rate and taking technological restrictions into account (Fig. 17.4).

Taking an economic growth rate as a given figure, the IO model is used to describe the development of the different industrial and service sectors in detail by breaking down the assumed GDP. In a second step, the information about the development of the sectors is converted into values which can be used in the energy system model to quantify the demand for energy services. With the help of the energy system model it is possible to calculate CO_2 emissions taking into consideration technological aspects like the vintage structure of the existing power plant stock, load and availability factors etc. As mentioned above, in economic models such aspects are ignored in most cases. Therefore, potentials of short- and long-term substitution options are often not considered in an accurate way. Even the IO model MIS with its technology-oriented sub modules has a lot of limitations regarding the calculation of CO_2 emissions. The restrictions concerning the reproduction of non-energy consumption and the vintage structure of the capital stock should be mentioned here.

The CO_2 emissions calculated with the hybrid model are presented in Fig. 17.5. This figure shows the development of the CO_2 emissions of three different scenarios, including the BAU scenario reflecting the business-as-usual development taking into account all figures listed in Table 17.1, and the other two scenarios calculated assuming lower and higher GDP growth rates.

In our example we assume that in Germany the CO_2 emissions should be reduced by 6% up to 2010.[5] In the BAU scenario the reduction target will be reached. Assuming higher GDP growth rates, the target will be missed more or less significantly. On the other hand, lower growth rates will help to reach the target.

In addition, Fig. 17.5 shows that modifications of the growth rates do not affect the emissions of the different sectors in the same way. An increase of the growth

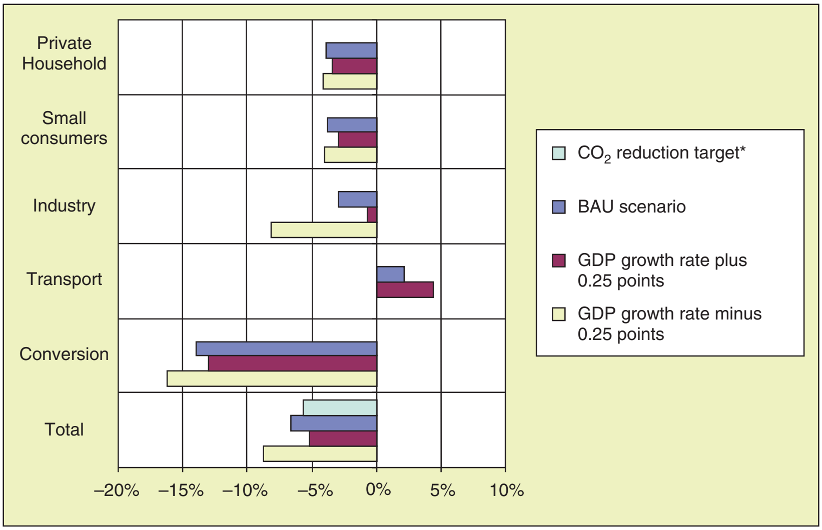

Fig. 17.5 Changes in CO_2-Emissions in 2010 Assuming Different GDP-Growth Rates (2010). Note: *CO_2 Reduction Target: Reduction in CO_2 Emissions of 6% in Comparison to 2000. (This Target Corresponds to a Reduction in CO_2 Emissions of 21% in Comparison to 1990)

[5] This target is chosen referring to the German CO_2 burden-sharing target.

rates of 0.25 points, for example, will lead to an increase of the emissions of the industry of 2.3%. However, the emissions of the small energy consumers will only rise by 0.8%.

Example 2. Effects of mitigation strategies on the development of industries

The focus of our second example is on the economic impacts of a CO_2 mitigation strategy. In this example, we ask which industries will benefit from the decision of policymakers to take measures to reduce CO_2 emissions and which ones will lose (in the sense of economic growth).

In our example, we assume that the policymakers want to reduce CO_2 emissions in Germany by 40% up to 2030 (compared to 1990). This requirement was made following the current discussion about the "post-Kyoto" targets.

The schematic procedure chosen for this example is presented in Fig. 17.6.

At first we use the energy system model to identify "optimum-cost" measures. Taking the different options to reduce CO_2 emissions into account, this model provides information as to the sectors in which measures should be taken. Besides information about the use of fuel at sectoral and technological level, the model also provides data about the demand for investments and other input factors. Part of these data can be used directly in the IO model, others have to be specified more precisely by splitting up the data or translating them into "economic" values (such as expenditures on oil, investment demand).

Table 17.2 shows some results of the energy system model comparing the 40% mitigation and the BAU scenario. Besides "optimum-cost" measures to reduce CO_2 emissions, the table also contains information on which sectors/industries are directly affected by the measures.

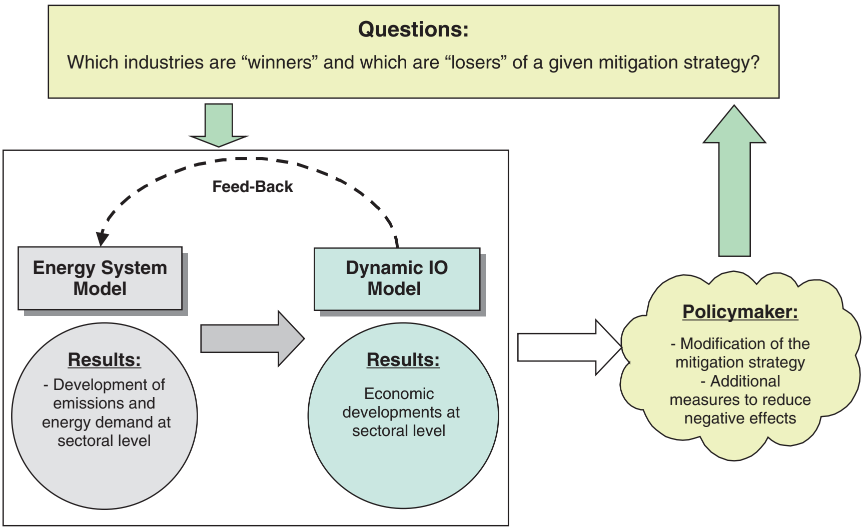

Fig. 17.6 Use of the Hybrid Approach in Example 2

Table 17.2 CO_2 Mitigation Measures and Directly Affected Sectors

Sector	Measures	Affected sector/industry
Conversion	Additional wind power plants Power plants and CHP plants fired with biogas, biomass and waste Gas-fired power plants and CHP plants (gas combined cycle) replacing coal-fired plants Other savings (also refinery, coal conversion etc.)	Electricity production (changes in total output, changes in the demand for fuels and investments) Mining Imports of fuels
Industry	Replacement of oil and coal by gas and biomass Energy saving (different processes)	All industries (decrease in the demand for fuels, increase in the demand for investments)
Small consumers	Replacement of oil and coal by gas, district heating and renewables, extended use of heat pumps	Service sectors (decrease in the demand for fuels, increase in the demand for investments)
	Energy saving (heat insulation)	Agriculture, forestry (decrease in the demand for fuels, increase in the demand for investments)
Residential	Replacement of oil, coal and gas by district heating and biomass, use of gas condensing boilers Heat insulation	Private households (change in the structure of consumption)
Transport	Alternative fuels (biofuel, bio-ethanol) LPG and methanol, replacement of gasoline and diesel Goods transport by train Energy saving due to highly efficient cars	Private households (changes in the structure of consumption and private transport) Transport sector (decrease in the use of fuels, changes in the fuel mix)
All sectors	Increased use of renewables Substitution processes Energy saving measures	

See Markewitz and Ziesing (2004) for a more detailed description of the different measures.

In our approach we use the results of the energy system model to calculate new AEEI factors. These factors reflect improvement in energy efficiency at sectoral level. The results of the energy system model are also used to specify the input mix of the electricity sector and its demand for investment as well as the induced changes in the consumption structure of private households. The modifications in the structure of consumption, in the demand for fuels and other inputs affect the whole economy due to the interactions between the different sectors.

In this example the "winners" in the sense of changes in gross output and employment are the sectors "renewable energies", "other fuels", "service of central and local government" and "machinery/vehicles/electrical machinery". Especially in the coal industry and in the other energy sectors the production activities and therefore employment will decrease significantly (see Table 17.3).

Table 17.3 Differences in Gross Output and Employment (Calculated for the Year 2030)

	Gross output (in million euros)			Employment (in persons)		
	BAU scenario	Mitigation scenario	Diff.	BAU scenario	Mitigation scenario	Diff.
Other fuels	252	958	280%	269	1,020	280%
Renewable energies	1,195	3,797	218%	5,001	15,886	218%
Nuclear fuels	0	0	0%	0	0	0%
Real estate renting service	443,413	433,219	−2%	473,687	462,797	−2%
Water transport services	8,907	8,585	−4%	19,371	18,889	−2%
Road transport services	48,985	46,554	−5%	598,474	583,372	−3%
Agricultural products, forestry	53,014	50,127	−5%	539,851	524,967	−3%
Railway services	17,330	16,352	−6%	250,430	243,235	−3%
Heating	21,136	19,895	−6%	0	0	0%
Other transport services	20,178	18,948	−6%	44,218	42,139	−5%
Food products	192,158	179,174	−7%	775,497	748,778	−3%
Private transport (MIV)	134,096	124,041	−7%	0	0	0%
Refined petroleum products	29,119	26,830	−8%	19,193	18,509	−4%
Other market service	1,293,476	1,185,064	−8%	5,109,886	4,890,112	−4%
Iron and steel, metal products	139,579	127,212	−9%	920,337	868,472	−6%
Services of wholesale and retail trade and hotels	692,778	630,815	−9%	6,765,512	6.046,496	−11%
Glass and glass products	12,213	11,092	−9%	68,958	58,017	−16%
Other industrial products	221,681	200,852	−9%	1,253,200	1.192,690	−5%
Rubber products, plastic products	76,224	68,973	−10%	434,901	345,413	−21%
Wood products, pulp, paper	45,286	40,918	−10%	147,711	140,417	−5%
Service of central and local government	531,876	479,653	−10%	8,472,963	7,766,373	−8%
Stone and clay	43,622	39,269	−10%	202,464	191,524	−5%
Non-ferrous metals	31,839	28,657	−10%	66,121	61,260	−7%
Foundry products	13,072	11,752	−10%	61,518	56,024	−9%
Chemical products	188,043	167,676	−11%	466,202	440,513	−6%
Building and civil engineering works	307,258	272,975	−11%	2,712,782	2,439,343	−10%
Machinery/vehicles/ electrical machinery	925,587	814,699	−12%	3,381,234	3,082,778	−9%
Gas	13,345	11,736	−12%	38,695	36,270	−6%
Electric power, steam and hot water	51,351	43,917	−14%	103,616	84,721	−18%
Coal, products of coal mining	8,214	3,594	−56%	74,591	33,190	−56%
Total	5,565,228	5,067,336	−9%	33,006,682	30,393,207	−8%

The results show that an ambitious environmental policy does not only affect the structure of the energy system (e.g. the fuel mix in the electricity sector) but also leads to structural changes at the macroeconomic level. Information about the induced economic effects is very helpful for policymakers to identify which sectors will get into trouble if they decide to extend their reduction targets and which will profit. Thus, using this information they become aware of negative effects at sectoral level and are able to take measures to reduce or avoid negative effects early on.

Conclusions

Politicians normally have to take different goals into consideration in their decisions. This also includes the pursuit of adequate economic growth. At the same time, they aim to reduce environmental pollutions and to conserve resources. A just income distribution, the highest possible employment level and stable prices are additional aims pursued within the framework of a policy focusing on multicriterial considerations. In order to help decision-makers, interdisciplinary approaches are required in which technological, economic and social aspects including their interactions are taken into account. So-called hybrid models can provide a contribution.

With the hybrid presented in this paper it is possible to assess the impacts of energy and environmental policy decisions at the macroeconomic and sectoral level, taking into consideration the complexity of both economic and technological interrelations.

On the one hand there is a need for a simple and transparent modelling approach, on the other hand there is a request for the highest possible number of parameters (including their interactions), which must definitely be taken into account from the decision-makers' point of view. Although the existing modelling approaches have clearly been further developed in recent years and still contain high potentials for further extensions, they will never be able to completely fulfill the requirements. Naturally, model reproductions and simulations always represent a simplified image of reality restricted to the essential parameters. It must therefore be verified whether e.g. existing company structures, the legal situation and acceptance by those concerned make the recommendation in question appear relevant. The results of the modelling category described must therefore never be interpreted as a direct recommendation; they only represent one component among others within a political decision-making process.

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Appendix

List of MIS Sectors

1	Coal, products of coal mining
2	Refined petroleum products
3	Gas
4	Electric power, steam and hot water
5	Space heat
6	Nuclear fuels
7	Renewable energies
8	Other fuels
9	Private transport (MIV)
10	Railway services
11	Road transport services (truck, bus)
12	Water transport services
13	Other transport services
14	Water, repair of motor vehicles, hotels and restaurants
15	Glass and glass products
16	Rubber products, plastic products
17	Agricultural products, forestry
18	Chemical products
19	Stone and clay
20	Other industrial products
21	Non-ferrous metals
22	Iron and steel, metal products
23	Wood products, pulp, paper
24	Machinery/vehicles/electrical machinery
25	Food products
26	Foundry products
27	Building and civil engineering works
28	Real estate renting service
29	Other market service
30	Service of central and local government

List of IKARUS-MARKAL Sectors

	Industry sectors
1	Aluminum
2	Other non-iron metals
3	Other mining
4	Chlorine
5	Soda
6	Olefine
7	Other basic chemicals
8	Other chemical industries
9	Other basics goods
10	Investment goods
11	Glass
12	Other consumer goods
13	Sugar
14	Other food
15	Cellulose
16	Other papers
17	Cement
18	Lime
19	Brick
20	Other stone
21	Electr. iron
22	Raw iron
23	Sintered steel
24	Rolled steel
25	Other iron
	Small-scale consumers
27	Public service
28	Trade and commerce
29	Military and others
30	Handicraft/small-scale industry
31	Building and civil engineering works
32	Agriculture
	Transport
33	Passenger transport, local
34	Passenger transport, long distance
35	Freight transport, local
36	Freight transport, long distance
	Private households

Chapter 18
Carbon Tax and its Short-Term Effects in Italy: An Evaluation Through the Input-Output Model

Ignazio Mongelli, Giuseppe Tassielli, and Bruno Notarnicola

Economists and policy makers refer to carbon tax as an efficient instrument to control CO_2 emissions, but concerns about possible negative effects of its implementation, as for instance the loss of competitiveness on the international market, have been expressed.

In the present chapter the IO model is used to estimate the short-term effects of a carbon tax in Italy (the results can be easily extended to the case of a permission trading scheme), which include the percentage increase in prices and the increase in the imports of commodities to substitute domestically produced ones as intermediate input. The present study is not "behavioral", in the sense that the change in the consumers' behavior and choice, induced by higher prices, is not taken into account.

The results of the study show that a carbon tax of 20 €/t CO_2 in Italy would produce a modest increase in prices and a small reduction in the emitted CO_2 determined by the substitution of domestically produced intermediate inputs with imported ones. Moreover, due to the assumption underlying the applied model, the results have to be considered as an upper bound estimation or pessimistic forecast as well as restricted to a short-run time horizon, which means before any technological adjustments are possible.

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Introduction

The third IPCC report clearly states that: "increasing body of observations gives a collective picture of a warming world and other changes in the climate system" and it is well known that CO_2 or more in general green-house gases anthropogenic emissions have the responsibility for this dangerous and irreversible change (IPCC 2001; Karl and Trenberth 2003). The four times increase of CO_2 emissions in the atmosphere, which has occurred in the last 50 years, largely depends on the use of fossil fuels which, despite a decreasing energy intensity of the economies, still today represent one of the most important factors of production and the main object of the climate mitigation actions.

In order to cope with the climate change, an interdisciplinary approach is needed involving natural scientists, engineers and social scientists, which have to respectively study the effects on the climate of increasing CO_2 concentration in the atmosphere, technical solutions to reduce the dependence of economic systems on fossil fuels and policy and economic instruments through which it is possible to efficiently realize a reduction in CO_2 emissions. From this latter perspective, a reduction in green-house gases emissions in order to achieve the Kyoto targets, can be pursued through two different policy instruments: command and control, which is based on the fixing of limits about emissions and controlling that these limits are respected, and the economic instruments (Pigouvian taxes, incentives, tradable permits) which are based on the market mechanisms. Compared to command and control, which implies high administrative costs of implementation, the economic instruments feature the advantage of being more cost effective. Among all the economic instruments, the carbon tax and the tradable permits have been deeply discussed and widely proposed as an instrument to control the emission of CO_2, although their adoption has often been criticized for the increasing costs of production these instruments determine and the consequent loss of competitiveness for the most energy intensive sectors.

In the present study the Input-Output model has been applied in order to investigate some short-term effects of a carbon tax unilaterally imposed in Italy. The results can be easily extended to the case of a permissions trading scheme, since both the instruments charge industries with additional costs of CO_2 abatement in proportion to their use of fossil fuels.[1] Firstly, the energy-related CO_2 intensities are calculated

[1] A system of tradable permits is equivalent to the environmental tax, since the price of a permit represents an environmental charge for an industry as the tax. Thus from a mere economic point of view both have the capacity to achieve an environmental standard at least costs. However, the system of tradable permits reduce the uncertainty in complying with a certain environmental target, since the authority fixes the number of permits in regard to the admitted level of pollutant emission (for instance CO_2) and subsequently by negotiating those permits their price emerges. While in the case of a carbon tax the authority fixes the tax rate *a priori* therefore the achievement of the environmental target depends on the accuracy of the *a priori* estimation of the tax rate. In this study we chose to refer to the carbon tax since it is easier to find carbon tax rate estimation in literature than the permit's price estimation, however the results can be extended to the case of a system of tradable permits whose prices are equivalent to the applied tax rate.

for the Italian economy; the series expansion of the Leontief inverse allow us to unravel the CO_2 intensities into direct and indirect production ones. Secondly, different carbon tax rates are applied in order to estimate the price effects for each of the 59 Italian economic sectors, according to the classification scheme of the Italian Input-Output table. Lastly, on the basis of the percent price increase and of elasticities of substitution of domestic with imported commodities (used as intermediate inputs), the IO matrix is modified, in order to account for the reduction in the CO_2 emissions due to the increasing import of commodities.

This chapter is organized as follows: the second section provides a description of the carbon tax, focusing on advantages and disadvantages of this economic instrument; the third one discusses the advantages and disadvantages of using the IO model in this field of analysis, the fourth section describes the dataset and the methodological approach used, the fifth shows the results about the price increases calculated through the model. The last section discusses the results and concludes with some remarks and future outlook.

Carbon Tax

The Pigouvian[2] tax takes the name of "carbon tax" when it is imposed on the production or consumption of fossil fuels proportionally to their carbon content (Pearce 1991). The adoption of a carbon tax more often refers to a consumption than a production or extraction tax. The main difference between the consumption and extraction tax consists in who is the recipient of the fiscal revenues deriving from the tax: in the first case the fossil fuels importers and consumers, while in the second case the producers and exporters.

A carbon tax reduces CO_2 emissions operating both through energy conservation and by pursuing the shift toward less carbon intensive fuels or energy sources which, after the imposition of the tax, become more convenient. Indeed, a carbon tax relies more heavily on coal than on oil, or more on the latter than natural gas, because of the different carbon content of the fuels per unit of calorific value. Although a generalized energy tax, which consists in a fixed amount per unit of energy, should induce energy conservation, it would not lead to substitution among fuels (coal with oil or oil with natural gas), since coal, oil and gas would be equally taxed regardless of their different carbon intensity per unit of energy.

The carbon tax allows the polluters to choose the most cost minimizing abatement strategy. Indeed, industries abate CO_2 emissions up to the point where the marginal cost of abatement (the costs of abating one additional unit of CO_2) equals the marginal cost of polluting (the cost of emitting one additional unit of CO_2), since after this point it becomes more convenient to pollute and pay the tax (or to

[2] An environmental tax, which is imposed on a polluting activity in order to internalize its social costs, takes the name of Pigouvian from the well known economist Pigou who proposed this economic instrument for the first time.

buy the permit). This means that the polluters can minimize their abatement costs, according to their own marginal cost of abatement, by choosing either to pay the tax (or to buy permits), in the case of higher abatement costs, or otherwise to invest in cleaner technologies (Baumol and Oates 1988). Thus with a carbon tax, the same CO_2 reduction target is achieved with lower costs than with an energy tax, since a carbon tax operates on two levels (Manne and Richels 1993). It has been estimated that an economic instrument reduces the costs of compliance with a CO_2 reduction target by 50% compared to command and control measures or standard fixation (Tietenberg 1990). Among the advantages of a carbon tax the fiscal revenues it produces should not be neglected; they are generally quite large considering the high dependencies of economies upon fossil fuels and can be used to mitigate the distortional effects of other taxes (labor taxes, income taxes, etc.) or to finance research programs and initiatives in the environmental field.

Among the disadvantages of adopting this economic measure, the effects on international competitiveness are the most concerning (Poterba 1993). The adoption of a carbon tax is always accompanied by criticism concerning the increasing costs of fuels and consequently of production, which can determine a loss of competitiveness especially for firms operating on the international market. These concerns are crucial in the debate about the "Pollution Haven Hypothesis", which argues that firms can be induced to relocate in "haven" countries with weaker environmental legislation (Leonard 1988; Jaffe 1995; Suh et al. 2002). Carbon tax could also determine a carbon leakage. Indeed, differences in global warming legislation by countries, as for instance between Annex I and non-Annex I countries in the Kyoto protocol, is on the basis of another phenomenon which is called "carbon leakage" and consists in the underestimation of the CO_2 domestically emitted because of the exclusion of the CO_2 embodied in imports by countries without any "carbon constraints", which is completely neglected in the national inventory compiled yearly under the United Nations Framework on Climate Change (Italian Ministry for the Environment and the Territory 2002; Wyckoff and Roop 1994; Mongelli et al. 2005).

A carbon tax was introduced in Italy on the 1st of January 1999 (L 448/1998) on the consumption in energy plants of coal, petroleum coke and orimulsion (emulsion composed of 70% of natural bitumen and 30% of water) with a tax rate initially fixed on 1,000 £/t of product (around 0.52 €/t). It was established a progressive increase of the tax rate between the 1999 and the 2004 in order to increase the energy consumption price of 4% and 9.4% respectively for the final consumers and the producers and to obtain an estimated final CO_2 reduction of 12 Mt within the 2005 (one third of the overall Italian reduction target). This fiscal regime has been into force in Italy only during the 1999, since the oil price increase occurred in the same year induced policy makers to froze the tax in order to avoid stronger inflation effects. The fiscal revenues of the carbon tax in 1999 amounted to 240 billions of lira (around 123 million of euros) and they were used to fund research projects aiming to develop low-emission technologies, to co-finance new investments on the basis of the flexible mechanisms of the Kyoto protocol (JI and CDM) and in a larger part to finance local initiatives (regions and provinces). Although discussed, after the

1999 the reintroduction of the carbon tax in Italy has not been seriously considered anymore and at the moment the achievement of the Kyoto targets is pursued through a permission trading scheme adopted in Europe on 2003 (European Union 2003).

The IO Model to Evaluate the Carbon Tax Effects: Advantages and Limits

The IO Model to Evaluate How the Carbon Charge Propagates Throughout the Economy

The effects of a carbon tax, which at the beginning relies more heavily on the most energy/carbon intensive sectors, propagate through the entire economy because of the net of interactions among sectors on which an economic system is based. Indeed, even if a sector does not directly make use of a large amount of fuels, it uses fuels indirectly through its intermediate inputs, which embody energy and carbon. For example, the tax produces its effects on the tertiary sector directly through diesel used for heating and gasoline used for transportation, while indirectly through the computers, furniture and paper it uses as intermediate inputs. Thus, the carbon tax produces its effects both directly and indirectly on each sector. The IO model has been widely recognized as the best economic model to study and evaluate both direct and indirect "interactions" or "interdependences" among sectors at a detailed level. Moreover, through the series expansion of the Leontief inverse it is possible to evaluate how much each level of interaction contributes to the final price increase (Treloar 1997).

This ability to analyze interdependencies among economic sectors is quite well known and the IO model has been applied in several studies to evaluate the price effects of a carbon tax. Symons et al. used the IO model in combination with a demand model to examine the social effects of a carbon tax in the UK, thus the incidence of the tax on different income classes (Symons et al. 1994). Cornwell and Creedy followed the same approach used by Symons et al., based on a complementary use of the IO model and a demand model, to evaluate the distributional implication of a carbon tax imposed in Australia to reduce the emissions of CO_2 by 20% in 2005 compared to those in 1988 (Cornwell and Creedy 1996). Labandeira and Labeaga combined IO analysis with a micro demand model in order to account for environmental and distributional effects of a carbon taxation in Spain, finding that despite a substantial increase in fiscal revenues and the absence of regressivity, the environmental effects in terms of reduction of CO_2 emissions are modest (Labandeira and Labeaga 1999). Since the above cited works combine IO model with a demand model, they can be defined as "behavioral" in the sense that they take into account changes in the consumers' choices induced by the higher price of commodities. Labandeira and Labeaga applied the IO model without taking into account behavioral changes in consumers (Labandeira and Labeaga 2002). In regard to the *who* *pays* question, Morgensten et al. apply the IO model to find the most impacted manufacturing sectors by the costs of a CO_2 mitigation policy in the US. The authors focused on near-term impacts which do not include substitution among fuels and of domestically produced intermediate inputs and imported ones. The authors conclude that only a few manufacturing sectors experience a considerable price increase in the short term, but it is likely to predict that these increases will be completely shifted onto consumers so that the impact on firms' profits could be negligible if not positive (Morgensten et al. 2004).

Limitations of IO Model in Modeling Carbon Tax Effects

In contrast to the advantage of a detailed analysis, which is extended both on direct and indirect effects of the tax, the limitation of the IO model in this field concerns the stylized representation of the economy it provides assuming, for instance, zero elasticity of substitution among inputs, which means that an industry has no possibilities of substitution among inputs, used in fixed proportions (Sadelberg 1973). In other words, in the linear IO model each sector has a fixed technology. This type of production function is said to be the Leontief function. However, an industry chooses the best combination of its inputs according to their relative prices and, of course, to the technological constraints. For example, if an industry can use plastic or paper indifferently in production and a carbon tax modifies the relative prices of these commodities, there will certainly be a shift from the use of one input to the other. The same arguments can be said in regard to fuels, which would be mixed differently with the adoption of a carbon tax, because it changes the relative prices of fuels.

The Computable General Equilibrium (CGE) model is often seen as a better alternative than the IO model, especially for what concerns climate policy application and carbon tax modelling. The equilibrating procedure in the CGE models works on the basis of changes in the relative prices assuming forms of the production function different to the Leontief one (i.e. Cobb-Douglas, Constant Elasticities of Substitution, etc.), so it can evaluate the feedback effects on the economic structure of a carbon tax. However, this clear advantage is counterbalanced by a higher level of inputs aggregation and a lack of empirical foundation (Borges 1986); indeed the IO table represents the empirical core of many CGE applications.

The use of a Leontief function in the present study produces an overestimation of the effects of the tax on the consumers in terms of price increases as main consequence. Indeed, the possibility for an industry to change the input and energy mix moderates the effect of the tax in terms of price increase, or it allows a CO_2 reduction target to be achieved with a lower taxation. This is confirmed by Cornwell and Creedy (Cornwell and Creedy 1996), who points out that the tax rate necessary to achieve the Toronto target for Australia is less then half if some hypothetical changes in technology, occurring in a time frame of 10–20 years, are considered. Therefore the results of this study have to be considered as an upper bound estimation or pessimistic prevision. Moreover, due to the assumption of fixed technology, the results are restricted to a short-run time horizon, which means before any substantial adjustments of technology are possible. Another limitation of the IO model consists in the assumption of a perfect competitive market and constant return to scale which implies an increase of the prices directly proportional to the tax. This assumption underlies even most of the CGE applications in this field, since it avoids complexities in dealing with an imperfect competitive market (Zhang and Folmer 1998).

Methodology and Dataset

Methodology

The Input-Output model describes the interactions among economic sectors by means of a set of simultaneous linear equations, each one representing the identity between the total output produced by each economic sector and the output purchased and consumed by all the other sectors of the system plus the final demand (households, exports, investments, public administration) (Leontief 1966). The Leontief IO model is commonly used in the field of environmental policy analysis, which requires an extension of the traditional IO model in order to consider the interactions between the economic system and the environment. One possible environmental extension of the IO model consists in pre-multiplying the Leontief inverse by an environmental matrix, whose coefficients indicate, for example, the direct emission of a pollutant in order to obtain "total pollution intensity" for each sector (Miller and Blair 1985). In this study the main equation used to account for the CO_2 intensities by sectors is, in matrix notation, the following:

$$m = e'B(I - A)^{-1} \tag{18.1}$$

where m is a 59×1 vector showing the CO_2 intensity for each sector, e is a 11×1 vector including the coefficient used to convert the energy use into CO_2 emissions (the superscript apostrophe means the transposition of the vector), B is a 11×59 matrix showing the direct use of 11 different energy sources[3] by the 59 Italian economic

[3] The energy sources included in the model are the following: Methane, Fuel oil (HS), Fuel oil (LS), Gasoline (unleaded), Gasoline, Diesel, LPG, Petroleum coke, Coal, Metallurgical coke, Refinery gas. The electricity consumption has been considered and included in the model, but it has been expressed in terms of primary energy sources consumed to produce that amount of electricity, according to the Italian energy mix.

sectors and $(I - A)^{-1}$ is the well known Leontief inverse. The post-multiplication of the m vector by a final demand vector results in the total CO_2 emission following that final demand.

The price increase effect of a carbon tax is obtained through the scalar product of the tax rate r by the vector m:

$$\Delta p = rm \tag{18.2}$$

Firstly the energy related CO_2 intensities for each of the 59 sectors of the Italian IO table have been accounted for (Equation (18.1)) and secondly these CO_2 intensities have been multiplied by a tax rate in order to evaluate the percent price increases for each sector (Equation (18.2)).

Dataset

The present analysis is based on a dataset composed by the following information:

- The last published Italian Input-Output tables of the Italian economy in 2000 (domestic and at basic prices) (ISTAT 2004)
- An energy database showing the consumption of 11 energy sources, classified on the basis of the Input-Output classification scheme (59 sectors)

The energy database is based on the three following sources:

- National Energy Balance, 1999 (Ministero dell'industria e delle Attività Produttive 1999)
- Consumption of energy in the Italian industry in 1999 (ENEA-ISTAT 2000)
- Consumption of energy in the Italian services sector in 1999 (ENEA-ISTAT 2000)

The CO_2 emissions by sectors are easily calculated by multiplying the amount of fossil fuels consumed by each sector by the factors provided by IPCC following the Tier 1 approach (Houghton et al. 1996). Therefore, in the present study only the emission of CO_2 due to energy consumption is considered for each sector.

The last revision of the system of national accounts took place with the System of National Accounts 1993 (SNA93) and it has been introduced in Europe as the new European System of Accounts 95 (ESA95) with the Council Regulation (EC) n.2223/96 of June 25. The main purpose of this revision is the international harmonization of the concepts, definitions and nomenclatures, schemes and methodology for the national accounts. An innovation introduced with the ESA95 regards the scheme for the IO table, which from now on must be based on the supply-use types of tables. The supply and use tables (SUT) represent the starting point from which a Symmetric Input-Output Table (SIOT) is derived by applying a particular mathematical algorithm working on certain assumptions regarding how the different products, by-products and scraps are produced (commodity technology assumption, industry technology assumption). According to the ESA95 each Member States have to yearly compile and communicate to Eurostat the supply and use tables, while five yearly the square input-output tables. Although many countries have been compiling supply and use tables for decades, the Italian system of accounts has always been based on a directly compiled SIOT and recently SUT have been introduced. On December 2003 the Italian National Institute of Statistics published and provided Eurostat a dataset including SUT for the years from 1995 to 2000 and SIOT only for the years 1995 and 2000 with the dimension of 60×60. This dimension corresponds to the minimum required by the ESA95 and compared to the previous tables, which refer to the Italian economy in 1992 and whose dimension is 92×92, some important manufacturing sectors have been aggregated, while the tertiary sectors substantially keep the same level of detail of the previous IO table. A relevant aggregation concerns the sector “Chemicals and artificial fibers”, which resulted from the aggregation of four different sectors: “Basic chemicals”, “Fine chemicals”, “Pharmaceutical products” and “Artificial and synthetic fibers”; as well as the sector “Rubber and plastic products” which was previously subdivided in the two different sectors: “Rubber products” and “Plastic products”. Aggregations for the tertiary sectors mainly regard the trade and the transportation sectors, which have been both reduced from a number of five to three sectors. Although a lower dimension of the IO tables does not certainly represent an improvement, what really reduces the usefulness of the new Italian IO tables, especially in the field of Industrial Ecology, is the aggregation of important manufacturing sectors, which represent the core of the Italian industry. The SIOT provided for the years 1995 and 2000 are available as based on “domestic” or “imported” intermediate inputs. In the first case the interindustry flows of commodities only refer to the domestically produced ones, while in the second case they only refer to the imported intermediate inputs. The consistent industries and products classification codes used are the NaceRev. 1 for the former and Statistical Classification of Products by Activity in the EC (CPA) for the latter. In order to comply with the ESA95 requirements, Italy has also provided another table that relates the SUT to the other national aggregated accounts. This first experience with SUT is not based on new surveyed data but on already existing estimations of National Accounts for 1992, which were mostly obtained with a survey about the company costs structure involving 30,682 large and medium enterprises (with more than 20 employees) and 21,121 small enterprises (with less than 20 employees) and only the agricultural and energy sectors were compiled on the basis of a survey which was conducted respectively by the Agricultural Accounting Information Network and the Ministry for Industry and Productive Activities.

Box 18.1 Taxes in IOT

In IOTs, taxes fall within the category of "primary resources" together with capital, labor, depreciation, etc. Taxes and subsidies, together with the transport and trade margins, explain differences between producer's, purchaser's and basic prices in a IOT. Therefore they are fundamental for the calibration procedure necessary to build an IO model.

Different types of prices relate each other according to the following equations:

Producer's price = Purchaser's price + Trade and Transport margins

Purchaser's price – Taxes + Subsidies = Basic price

For reason of homogeneity (margins, taxes and subsidies may have different incidence across sectors) it is recommended to use IOTs at basic price. The same argument is valid for import matrix and export vector, which may be altered by import or export duties.

In a standard IO table, taxes are included as a part of primary inputs, which embraces:

- Taxes on products
- Value added tax
- Taxes and duties on imports
- Similar categories for subsidies
- Taxes less subsides

The IO model is widely used to evaluate fiscal policy with a macroeconomic perspective. Fiscal revenue collected by the government according to certain taxation by sector and following an exogenous change in the output produced (as for example in the case of project of public expense) or taxation level may be evaluated with an IO model. IO model may be combined with micro demand model in order to perform evaluation of tax shocks on income distribution among different household income classes.

However, the level of detail often is not high enough to allow all the types of fiscal studies to be performed. As for other sectors the new IO classification adopted in Europe according to the ESA95 implies an aggregation of primary resources classification. For what concerns taxes and subsidies it is reported only the net tax imposition (subsidies less taxes for each sectors), which is for example used by Wood and Lenzen in order to account for fiscal revenue related to different diets in Australia (see Chapter 15 of this handbook).

A general approach for fiscal Value Added Tax (VAT) evaluation through IO analysis is based on the price Leontief type of model, which relates prices to value added via technological coefficient matrix. The Leontief price model allow an analyst to estimate how values increases at various stages in the production chain and thus to evaluate the extent to which the tax paid by consumers on the final transaction, is accumulating at each stage. This type of model is extensively described and applied in Chapter 27 of this handbook by Nakamura and Kondo in order to evaluate Life Cycle Costs in the Waste IO model.

Results

The Percent Price Increase

In Table 18.1 the results of Equation (18.1) are shown. The figures represent the energy-related CO_2 emission (in kg) due to the production of 1€ by each Italian economic sector. The total CO_2 intensities, which are listed in the first column, are unraveled in order to single out the direct and indirect contribution, which are listed respectively in the second and third column.

The most energy/carbon intensive sectors are in this order: “Terrestrial transportation” (0.90 kg CO_2/€), “Non metallic mineral mining” (0.74 kg CO_2/€) “Electricity, gas distribution and steam” (0.73 kg CO_2/€), “Metals and alloys” (0.51 kg CO_2/€), “Fishing and other related services” (0.39 kg CO_2/€), “Paper and paper products” (0.31 kg CO_2/€), “Water collection and distribution” (0.29 kg CO_2/€), “Coke and refining petroleum products” (0.24 kg CO_2/€), “Chemicals and artificial fibers” (0.20 kg CO_2/€). The indirect contribution to the total intensity range from a minimum of 7% for the “Terrestrial transportation” sector to a maximum of 95% for “Radio-TV apparatus”. The tertiary sectors are generally characterized by the highest indirect contribution (“Professional activities” 92%, “Insurance and pension (social security not included)” 90%, “Research and development” 90%, “Transportation auxiliary activities and travel agency” 88%, “Machineries rental” 86%, etc.) and nearly half of the sectors have an indirect contribution between 60% and 80% of the total intensity. While the most energy/carbon intensive sectors feature the lowest indirect contribution (“Terrestrial transportation” 7%, “Fishing and other related services” 9%, “Coke and refining petroleum products” 12%, “Electricity, gas and steam” 17%, “Metals and alloys” 19%, “Chemicals and artificial fibers” 32%, “Paper and paper products” 39%).

In order to calculate the effects of a carbon tax, the energy-related CO_2 intensities listed in Table 18.1 are multiplied by a scalar, which represents the carbon tax rate (Equation (18.2)). tax rates applied are the following: 20, 73 and 146 €/t of CO_2 and are taken from literature. The first of the applied tax rates has been estimated as the one which would permit Italy to achieve the Kyoto target (Macchi et al. 2003). The result of Equation (18.2) is an *ad valorem* tax, which can also be interpreted as the percent price increase for each sector.

The percent price increases following the application of the three tax rates are listed in Table 18.2.

Obviously, the price increases keep the same pattern of the carbon intensities listed in Table 18.1. Figure 18.1 provides a general picture of the effect of the three considered carbon tax rates of 20 €/t CO_2, 73 €/t CO_2 and 146 €/t CO_2 on prices displaying the distribution of the price increases across the economic sectors.

The skewed distribution displayed in the first graph of Fig. 18.1, which refers to the tax rate of 20 €/t, indicates that nearly 30% of the Italian sectors would experience a price increase which is within 0.2%, and that the price increase of nearly 90% of the sectors is less than 0.6%. While less than 10% of the sectors would

Table 18.1 Energy-Related CO_2 Intensities of the Italian Economic Sectors (kg CO_2/€)

Input-output sectors	$e'B(I-A)^{-1}$	$e'B$	$e'B(A+A^2+A^3+\cdots+A^n)$
Agriculture, hunting and other related services	0.203	0.155	0.048
Forestry and other related services	0.011	0.000	0.011
Fishing and other related services	0.391	0.356	0.036
Coal	0.001	0.000	0.001
Oil, natural gas and mining services	0.001	0.000	0.001
Uranium and thorium	0.000	0.000	0.000
Iron ores mining	0.141	0.141	0.000
Other products of mining industries	0.263	0.141	0.122
Food and drinks	0.184	0.068	0.115
Tobacco industry	0.032	0.001	0.031
Textile products	0.146	0.068	0.078
Clothes and furs	0.095	0.020	0.075
Leather products	0.098	0.026	0.073
Wood, wood products and cork (furniture not included)	0.116	0.040	0.076
Paper and paper products	0.308	0.189	0.119
Printing and editing industry	0.118	0.036	0.082
Coke and refining petroleum products	0.241	0.212	0.029
Chemicals and artificial fibres	0.204	0.138	0.066
Rubber and plastic products	0.146	0.053	0.093
Non metallic mineral mining	0.739	0.537	0.202
Metals and alloys	0.511	0.411	0.099
Metal products (machineries and equipments not included)	0.202	0.059	0.143
Mechanical machineries and equipments	0.123	0.029	0.093
Computers and office equipments	0.015	0.002	0.012
Electrical apparatus n.e.c	0.129	0.031	0.098
Radio–T V apparatus	0.061	0.004	0.058
Medical apparatus, of precision, optical instruments and watches	0.058	0.008	0.050
Vehicles	0.107	0.023	0.084
Other transportation equipments	0.079	0.024	0.055
Furniture and other manufacturing products	0.135	0.028	0.108
Recycled materials	0.138	0.028	0.109
Electricity, gas and steam	0.731	0.607	0.125
Water collection and distribution	0.292	0.080	0.212
Buildings	0.197	0.030	0.167
Trade, maintenance services and vehicles repairing	0.056	0.009	0.047
Wholesale trade (car and motorcycle not included)	0.050	0.008	0.042
Retail trade (car and motorcycle not included)	0.055	0.012	0.043

(continued)

Table 18.1 (continued)

Input-output sectors	$e'B(I-A)^{-1}$	$e'B$	$e'B(A+A^2+A^3+\cdots+A^n)$
Hotels and restaurants	0.171	0.087	0.084
Terrestrial transportation	0.900	0.833	0.067
Water transportations	0.077	0.037	0.040
Air transportation	0.058	0.020	0.038
Transportation auxiliary activities and travel agency	0.086	0.010	0.076
Postal service and telecommunication	0.062	0.010	0.052
Financial intermediation, (insurance and pension not included)	0.028	0.007	0.021
Insurance and pension (social security not included)	0.039	0.004	0.035
Auxiliary services of financial and monetary intermediation	0.030	0.010	0.020
Real estate, activities	0.020	0.005	0.015
Machineries rental	0.058	0.008	0.050
Computer and related services	0.029	0.004	0.025
Research and development	0.029	0.003.	0.026
Professional activities	0.036	0.003	0.033
Public administration and defence; social security	0.052	0.017	0.035
Education	0.037	0.014	0.023
Social and health care	0.083	0.026	0.058
Waste treatment, sludge and similar services	0.115	0.025	0.090
Associative organization	0.033	0.013	0.020
Sport and culture activities	0.058	0.019	0.039
Other services	0.133	0.101	0.032
Household services	0.000	0.000	0.000

experience an increase in price greater than 1%. The second graph of Fig. 18.1, referring to the carbon tax of shows a rather different distribution with the price effects up to effects up to the maximum increase of 6.6%. In this second case less than 10% of the sectors would experience a price increase up to 0.2%, while less than 50% of the sectors would be up 0.6%. The third considered tax rate of 146 €/t would have have more intense price effects, as indicated by the price increase distribution displayed in the third graph. In this last case slightly more than 5% of the sectors would have a price increase up to 0.2%, while less than 25% of the sectors would experience a price increase of 0.6%. The results listed in Table 18.2 and shown in Fig. 18.1 indicate that the price increases determined by the three considered tax rates are rather small for the first one, while are remarkable for the other two analyzed cases.

Table 18.2 Percent Price Increase for Each Sector

Input-output sectors	€/t CO_2		
	20 (%)	73 (%)	146 (%)
Agriculture, hunting and other related services	0.4	1.5	3.0
Forestry and other related services	0.0	0.1	0.2
Fishing and other related services	0.8	2.9	5.7
Coal	0.0	0.0	0.0
Oil, natural gas and mining services	0.0	0.0	0.0
Uranium and thorium	0.0	0.0	0.0
Iron ores mining	0.3	1.0	2.1
Other products of mining industries	0.5	1.9	3.8
Food and drinks	0.4	1.3	2.7
Tobacco industry	0.1	0.2	0.5
Textile products	0.3	1.1	2.1
Clothes and furs	0.2	0.7	1.4
Leather products	0.2	0.7	1.4
Wood, wood products and cork (furniture not included)	0.2	0.8	1.7
Paper and paper products	0.6	2.3	4.5
Printing and editing industry	0.2	0.9	1.7
Coke and refining petroleum products	0.5	1.8	3.5
Chemicals and artificial fibres	0.4	1.5	3.0
Rubber and plastic products	0.3	1.1	2.1
Non metallic mineral mining	1.5	5.4	10.8
Metals and alloys	1.0	3.7	7.5
Metal products (machineries and equipments not included)	0.4	1.5	3.0
Mechanical machineries and equipments	0.2	0.9	1.8
Computers and office equipments	0.0	0.1	0.2
Electrical apparatus n.e.c	0.3	0.9	1.9
Radio–TV apparatus	0.1	0.4	0.9
Medical apparatus, of precision, optical instruments and watches	0.1	0.4	0.8
Vehicles	0.2	0.8	1.6
Other transportation equipments	0.2	0.6	1.2
Furniture and other manufacturing products	0.3	1.0	2.0
Recycled materials	0.3	1.0	2.0
Electricity, gas and steam	1.5	5.3	10.7
Water collection and distribution	0.6	2.1	4.3
Buildings	0.4	1.4	2.9
Trade, maintenance services and vehicles repairing	0.1	0.4	0.8
Wholesale trade (car and motorcycle not included)	0.1	0.4	0.7
Retail trade (car and motorcycle not included)	0.1	0.4	0.8
Hotels and restaurants	0.3	1.2	2.5
Terrestrial transportation	1.8	6.6	13.1
Water transportation	0.2	0.6	1.1
Air transportation	0.1	0.4	0.8

(continued)

Table 18.2 (continued)

Input-output sectors	€/t CO_2		
	20 (%)	73 (%)	146 (%)
Transportation auxiliary activities and travel agency	0.2	0.6	1.3
Postal service and telecommunication	0.1	0.5	0.9
Financial intermediation, (insurance and pension not included)	0.1	0.2	0.4
Insurance and pension (social security not included)	0.1	0.3	0.6
Auxiliary services of financial and monetary intermediation	0.1	0.2	0.4
Real estate activities	0.0	0.1	0.3
Machineries rental	0.1	0.4	0.8
Computer and related services	0.1	0.2	0.4
Research and development	0.1	0.2	0.4
Professional activities	0.1	0.3	0.5
Public administration and defence; social security	0.1	0.4	0.8
Education	0.1	0.3	0.5
Social and health care	0.2	0.6	1.2
Waste treatment, sludge and similar services	0.2	0.8	1.7
Associative organization	0.1	0.2	0.5
Sport and culture activities	0.1	0.4	0.8
Other services	0.3	1.0	1.9
Household services	0.0	0.0	0.0

Substitution Effects of Domestic Goods with Imported Ones

The results discussed in the previous section are obtained by means of a Leontief function of production with zero elasticity of substitution, thus the technological and non-technological changes induced by the tax (substitution of the energy and non energy inputs, substitution of domestic intermediate inputs with imported ones) are neglected. For this reason, the results listed in Table 18.2 refer to a short-term horizon and they have also to be considered as a pessimistic evaluation. However, it is likely to predict that the Italian industries in the short-term will, at least, tend to increase the use of imported intermediate inputs, whose prices remain unaffected by the tax. In turn, this mitigates the increase of the prices and it lowers the domestic emission of CO_2, since a certain amount of CO_2 is now embodied in imported goods and it is emitted in the exporting countries.

The linear IO model imposes a fixed composition of imported and domestic intermediate inputs, thus in order to estimate the extent to which the adoption of a carbon tax would determine this phenomenon, the input-output matrix is changed on the basis of elasticities of substitution between domestic and imported goods (Armington 1969). The elasticities used in this study are those applied in the GTAP model (Hertel 1997) and are listed in Table 18.3.

The modification of the input-output matrix on the basis of the price increase and of the elasticities of substitution listed in Table 18.3 allow us to estimate how much

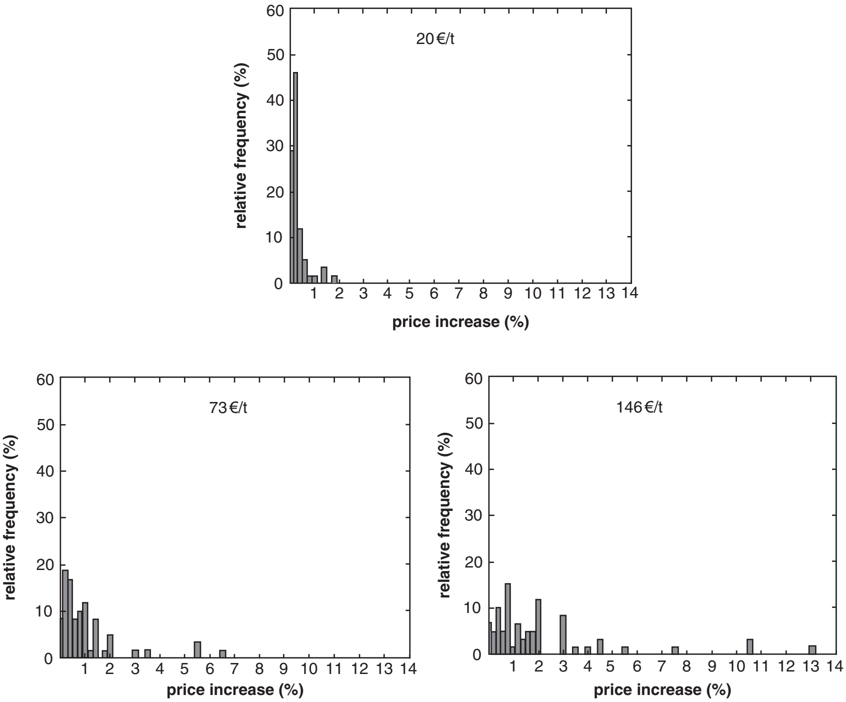

Fig. 18.1 Percent Price Increases Distribution After the Imposition of the Three Different Carbon Tax Rates: 20, 73 and 146 €/t CO_2

Table 18.3 Armington Elasticities of Substitution Between Domestic and Imported Goods

Sectors	Armington elasticities
Coal	2.80
Crude oil	10.0
Gas	2.80
Petroleum and coal products	1.90
Electricity	2.80
Ferrous metal	2.80
Chemical, rubber, plastic products	1.90
Other manufacturing, trade, transport	2.59
Agriculture, forestry and fishery	2.47
Commercial/public services, dwellings	1.91

the three applied tax rates mitigate the price increase and determine a reduction of the domestically emitted CO_2 through the substitution of the domestic intermediate inputs with the imported ones.

The substitution of domestic intermediate inputs with imported ones lowers the price increase produced by the tax. In particular, the substitution induced by the tax rates of 20 and 73 € reduces the average price increase respectively from 0.29%

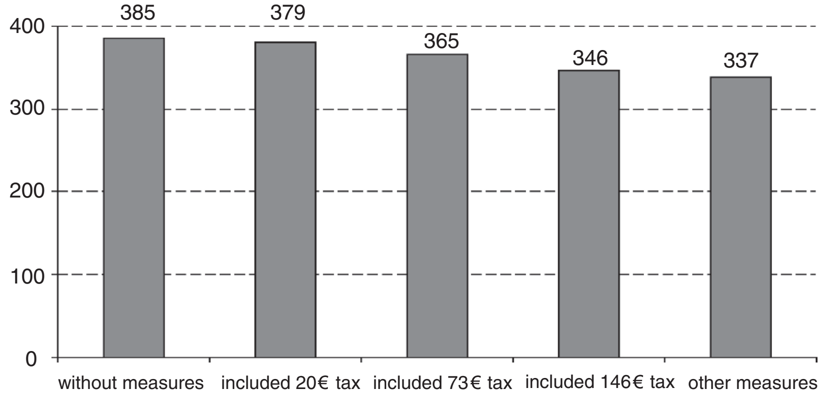

Fig. 18.2 Reduction of the Emitted CO_2 Obtained Through the Substitution Between Domestic and Imported Goods After Three Different Rates of Carbon Tax

to 0.28% and from 1.05% to 1.00%. While stronger effects are produced by the third applied tax rate of 146 €, which lowers the average price increase from 2.11% to 1.89%.

The reductions in the total emission of CO_2 obtained through the substitution of domestic with imported intermediate inputs are displayed in Fig. 18.2. These reductions are then compared with the total CO_2 emission in 2000 calculated by the product of the *m* vector (Equation (18.1)) and the vector of the total output as reported in the Italian IO table. The resulting emissions are about 385 Mt CO_2.[4]

With a carbon tax of 20 €/t, the reduction in the domestic emission of CO_2 gained thanks to the substitution of domestic goods with those imported is equal to 5.7 Mt which represents a reduction of 1.5% compared to the emission linked to the total output in 2000. As expected, the reduction is greater with the other tax rates. In particular a tax rate of 73 €/t determines a reduction of 19.8 Mt which is 5.1% of the emissions in the year 2000, while a carbon tax of 146 €/t CO_2 implies a reduction of 38.8 Mt of CO_2 which represents slightly more than 10.0% of the 2,000 emissions. Nearly half of the reduction in the domestic emissions of CO_2 is obtained through greater imports of commodities produced by the sectors listed in Table 18.4.

Despite the higher relevance of the manufacturing sectors listed in Table 18.4, an interesting result concerns the significant reduction indirectly gained through sectors whose production is not traded and for whom no substitution between domestic

[4] According to the Third National Communication Under the UNFCCC, the total CO_2 emissions occurred in Italy in 2000 amount to 463 Mt and the energy-related ones amount to 434 Mt. In the present study a total energy related CO_2 emission of 385 Mt has been estimated and the difference between the two estimations is due to different data sources and methodology used. We chose to refer to the model estimation since we consider that the comparison of all the model estimations for the reduction in CO_2 emissions with the total CO_2 burden calculated in the same way is more accurate.

Table 18.4 Most Contributing Input-Output Sectors to the Reduction Obtained Through the Substitution of the Domestically Produced Intermediates Inputs with the Imported Ones

Input-output Sectors	Contribution to the reduction (%)
Food and drinks	7.1
Mechanical machineries and equipments	6.7
Metal products (machineries and equipments not included)	6.0
Electricity, gas and steam	5.2
Chemicals and artificial fibres	3.8
Metals and alloys	3.8
Non metallic mineral mining	3.7
Vehicles	3.7
Textile products	2.7
Furniture and other manufacturing products	2.5
Total	**45.2**

and foreign production has been assumed. The indirect reduction amounts to 14.2% of the total reduction and it is mainly due to the following sectors: "Buildings" 6.7%, "Professional activities" 2.8%, "Public administration and defense; social security" 1.8%; the remaining 2.9% of indirect reduction is due to "Education" 0.9%, "Real estate activities" 0.9%, "Waste treatment, sludge and similar services" 0.6%, "Other services" 0.3%, "Research and development" 0.1% and "Associative organization" 0.1%.

Conclusions

In the present chapter the IO model has been proposed as a tool to estimate the short-term effects of a carbon tax in Italy. The short-term effects considered are the increase of prices and the increase in the import of commodities or intermediate inputs to substitute less competitive domestic ones. The analysis only focuses on carbon tax effects, but it can be extended to tradable permits, which will come into force in the UE in 2005 (European Union 2003); the two economic measures are totally equivalent, since they charge industries with additional costs of abatement.

The application of a linear IO model in this field presents advantages and limitations. Among the former the high level of detail and the possibility of considering both direct and indirect effects of the tax. Among the latter the linearity of the model which does not reflect the feedback effects on the economic structure of a carbon tax and which restricts the results to a short-term horizon. Due to the assumption underlying the linear IO model, these results have to be considered as an upper bound estimation.

The results of the present analysis demonstrate that a carbon tax of 20 €/t CO_2, which is considered enough for Italy to achieve the Kyoto target, would produce, in the short-term, a small increase in the prices of commodities, which is higher for some sectors. Nearly 30% of the Italian sectors would experience a price increase lower than 0.2% and for nearly 90% of the sectors the increase is lower than 0.6%. The price effects of the other two considered tax rates are more 73 €/t CO_2 less than 10% would than 10% would experience a price increase which is up to 0.2%, while less than 50% of the sectors would increase their price up to 0.6%. In the third case slightly more than 5% of the sectors would have a price increase up to 0.2% and less than 25% up to 0.6%.

The most hit industries by the three tax rates are the following: "Terrestrial transportation" (1.8%, 6.6%, 13.1%), "Electricity, gas distribution and steam" (1.5%, 5.3%, 10.7%), "Non metallic mineral mining" (1.5%, 5.4%, 10.8%), "Metals and alloys" (1.0%, 3.7%, 7.5%), "Paper and paper products" (0.6%, 2.3%, 4.5%) and "Coke and refining petroleum products" (0.5%, 1.8%, 3.5%). The modest effects on prices, determined by a tax of 20 €/t, would not lead to a relevant substitution of domestic intermediate inputs with imported ones and consequently to higher CO_2 emissions in other countries. In terms of embodied CO_2, the greater imports would amount to 5.7 Mt of CO_2, which represent only 1.5% of the Italian emission in 2000. The scenarios are rather different if the other applied (73 €/t CO_2, 146 €/t CO_2). In these cases the effects on prices are heavier prices are heavier and the substitution between domestic and imported intermediate inputs would lead to greater imports, which are equal to 19.8 and 38.8 Mt as embodied CO_2 (5.1% and 10.0% of the 2000 CO_2 emissions). Nearly half of this reduction is gained through greater imports of the manufacturing products listed in Table 18.4. An interesting result concerns 14.2% of this reduction indirectly gained through those sectors whose products are not traded on the international market and for whom no substitution between domestic and foreign production has been assumed. This result underlines the importance of the indirect effects of a carbon tax implementation, which are easily captured by the use of an IO model.

The present study is not "behavioral", in the sense that the change in the consumers' choice, induced by higher prices, is not taken into account. Therefore a natural development of this study is the use of these results in combination with a micro demand model, which allows us to evaluate how the increase of prices affects the consumers' choices and consequently the CO_2 emissions.

Another aspect that would deserve investigation is the use of non-linear function of production in the IO model, which would allow the substitution among intermediate inputs and fuels thus permitting a long-term analysis.

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Chapter 19
Comparing the Environmental Effects of Production and Consumption in a Region – A Tool for Policy

Harry C. Wilting and Jan P.M. Ros

Introduction

National environmental policies, in general, are directed to environmental quality, emission reduction and spatial planning of nature areas, all within the borders of a country. Despite the growth in GDP in the Netherlands in the past decades, Dutch environmental policy has led to a substantial decrease in the emissions of several substances (RIVM 2004a). However, nowadays, policy makers realize that there are still several persistent global environmental issues, such as climate change, the loss of biodiversity and the depletion of natural resources that cannot be tackled on a national scale (VROM 2001). Attempts to deal with these issues require an understanding of the relations between economy and the environment, both within and between countries.

For policy makers to develop policies that have an effect on the cross-border environment, they have to be provided with relevant information on economic activities and their ecological effects. Data on environmental pressure across national borders can be assigned in several ways to both production and consumption activities in a country and international trade. It is up to scientists to use the necessary cross-sections from this data to provide policy makers with the right information. Input-output (IO) analysis in combination with industrial ecology offers tools and methodologies for presenting the same data in different ways directed at specific policy questions concerning national or cross-border issues.

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This chapter investigates the environmental impact of a country or region using two approaches to gain a clear understanding of the producer–consumer relation and the shift of environmental pressure to other countries. In the first approach, the environmental pressure of production and consumption within the country's geographical borders is investigated, while in the second, the pressure of the country's inhabitants and related to their consumption patterns is explored. In an open economy such as the Netherlands, there will be a difference in outcome between the two approaches. This is due to high import and export quotes compared to less open economies. Dutch sectors deliver goods and services, both for domestic and foreign markets. On the other hand, the Netherlands imports goods and services for its own inhabitants. So, environmental pressure is partly due to production of goods for consumption abroad. On the other hand, consumption by Dutch households leads to environmental pressure abroad. For a larger region than the Netherlands, e.g. the European Union (EU), the role of imports and exports is less important. This can be shown in similar calculations carried out for a region roughly corresponding with the EU.

The environmental impacts for both approaches were calculated at sector level using an IO model. The model, described for the Netherlands in Chapter 16 (Nijdam et al.) in more detail, is based on the relationships between production and consumption in a region, and related imports and exports. Taking these activities as a starting-point, the model describes the use of natural resources and emissions to the environment in a region and abroad. Since climate change, as mentioned above, is one of the persisting environmental issues not tackled yet, the model is illustrated by calculating greenhouse gas emissions in the Netherlands and abroad for both approaches. For the EU region, calculations are carried out for CO_2 emissions. The discussion goes into the differences between the two approaches and the relevance these differences have for policy.

Background

The shift to other locations, e.g. countries, qualifies as one of the four types of environmental pressure shifting, as listed below (Bade et al. 2001):

- To other locations, both inside and outside a region or country
- To other environmental themes or compartments
- To other sustainability domains, viz. economy and social and
- To other, viz. future, generations

In the past decades, there was a growing interest in Dutch national policy documents for these types of shifting. The third National Environmental Policy Plan (VROM 1998) showed the trade-offs between environmental themes and compartments (air, soil and water), i.e. shifts that also played a role in product-oriented environmental policies (see Chapter 16 by Nijdam et al.). The document, Environment and Economy (in Dutch) (EZ 1997) focused on the area of tension between economic and environmental interests. Globalization of environmental issues has also occurred recently in Dutch policy. The fourth National Environmental Policy Plan (VROM 2001) pushed climate change, the prevention of damage to the global biodiversity and the exhaustion of natural resources onto the political environmental agenda, thereby directing attention in policy-making to the environmental impact of a nation's consumption on other countries. This policy plan introduced an integrated environmental policy, in which solutions for one problem would not lead to an increase of other problems, and in which the solutions of today would not be the problems of tomorrow.

Nowadays, the Dutch government is seeking sustainable economic development, in other words an absolute decoupling of economic growth and environmental pressure in the Netherlands. Such sustainable economic development should take place on condition that shifting environmental problems somewhere else or into the future is prevented (NSDO 2002; VROM 2004). Combining these implies a decoupling of what we might call the ecological footprint (based on the idea of Wackernagel and Rees 1996) and the socio-economic handshake (Ros and Poolman 2004), the last one especially with reference to developing countries. This form of decoupling is the leading concept of the international part of the action plan for sustainable development in the Netherlands.

Sustainable production and consumption patterns may help to tackle the persistent environmental issues previously mentioned. As already indicated, policy options are generally directed to the environmental pressure inside the borders of a country (first approach). In such a country approach, both the environmental pressures of exports and domestic final demand are influenced. However, national policies directed only to reducing environmental pressure in a country might not be optimal. For example, the worldwide reduction of greenhouse gas emissions, which is regulated under the Kyoto Protocol, departs from such a country approach. At a country level, policy options are mainly concerned with efficiency improvements by stimulating new technologies. Furthermore, the existence of some energy-intensive activities may be limited, which, for example, can lead to a shift to more imports of electricity from other countries. It is imaginable that production will be moved to other countries with less-efficient technologies, resulting in higher overall emissions (carbon leakage; see references in Hoekstra and Jansen 2002). This shift can be analyzed using IO analysis.

One option for the Netherlands is to contribute to emission reduction in other countries via the Kyoto mechanisms, Joint Implementation and the Clean Development Mechanism. This new type of trade or investment allows one to buy negative emissions. Of course, the emissions trading programme will be an important policy instrument in the coming years. Moreover, initiatives like 'trees for travel' fit in with the idea that a country might have an impact elsewhere. We will be the first to take these impacts into account if they are positive. However, policies directed at more sustainable consumption patterns (according to the second approach), including volume limitations, have been less often applied. These options not only influence a part of the environmental pressure inside a country, but also affect the environmental pressure abroad (although they do not influence production technologies in other countries).

There is a need for more transparency in production chains and the impact of consumption to facilitate policy making on sustainable production and consumption. Insights into production processes have provided conditions for a dialogue between stakeholders and market parties on the requirements for sustainable production and consumption (VROM 2004). The SER has underlined the importance of transparency in production chains for sustainable consumption too (SER 2003).

This type of analysis points to the question of responsibility. Pollution occurs in all stages of the life chain of products. Who is responsible for the emissions related to the production and distribution of a certain product? Is it the producer, who actually produces the emissions or is it the user/consumer, who purchases a good or service? The responsibility question comes up both at the national level in a country (producers versus consumers) and at the regional level (the shift between nations). The resulting question is who should pay for the pollution: the polluter or the user? The 'polluter pays' principle is based on direct emissions or pollution. In cases where the user has to pay, pollution during the whole life chain of products has to be considered. Steenge suggests a combination; both polluter and user have to pay a part (Steenge 1999). The policy measures taken should depend on who is responsible (Hoekstra and Jansen 2002).

There are different answers (depending on one's values) to the question of what country is responsible for the environmental pressure in other countries (RIVM 2004c). From a market-oriented perceptive the choice between the economy and the environment is the responsibility of the exporting country. Trade is the consequence of a search for the most efficient production chains; and trade stimulates developing countries in their development. From the point of view of international solidarity it can be said that trade due to stiff competition has a negative consequence for nature and environment in developing countries. Rich countries should take their responsibility for this in the form of trade agreements, technology transfer, investments and development assistance. In this way, rich countries (partly) pay for reducing pollution in poor countries (Steenge 1999).

There are several scientific approaches in existence to support policy making on the issues mentioned above. A well-known approach concerning the environmental shift of one country to other countries is the ecological footprint concept (Wackernagel and Rees 1996). The ecological footprint approach is directed primarily to the shifting of land use on to other countries. However, the approach has also been used for investigating other environmental effects related to consumption (see Chapter 16 by Nijdam et al.). Related studies concern the calculation of the environmental impacts of imports as, for example, carried out for six OECD countries (Wyckoff and Roop 1994), and the USA (Suh et al. 2002). Some studies have been extended to allow comparison of the emissions related to imports and exports, resulting in an environmental balance of trade for a country. Such studies were carried out, for instance, for Japan and China (Gerilla et al. 2002), Poland (Przybylinski 2002) and the Netherlands (De Haan 2004). The two-system approach, which is discussed in this chapter, was applied by Wilting (1996), who compared energy use and CO_2 emissions in the Netherlands to energy use and emissions related to Dutch consumption. Ros and Wilting (2000) extended this approach to include acidification and land use. All studies, except that of Wackernagel and Rees, were carried out using IO methods.

Two Systems: A Region Versus the Inhabitants of the Region

The two approaches – distinguished in this chapter and defined below – have different system boundaries.

- System 1: the production-consumption system in a country or region. The physical borders of the country mark the first system, which concerns all production and consumption in the country. Environmental policies of national governments are directed mainly to the activities in the system, including all production in the country, both for domestic demand and exports. Furthermore, the system consists of all consumption-related activities in a country, including the activities of foreigners visiting the country. A part of the environmental pressure in a region can be seen as a shift of other regions to the region under consideration.
- System 2: consumption of the inhabitants of a country or region. Consumption patterns mark the second system directed to all production related to the consumption of the inhabitants of a certain country or region. These patterns include the indirect part of the production chain (partly abroad) and the activities of the inhabitants abroad (on holidays, for example). Collective services and public consumption are also included. So, System 2 concerns the shift of the region on to other regions. System 2 is related to a production chain approach such as the ecological footprint.

The two-systems approach does not include environmental pressure related to import required for exports. Figure 19.1 shows, as an example, the two-system approach for the Netherlands.

The overlap of Systems 1 and 2 consists of the economic activities within the region directly and indirectly related to the consumption of the inhabitants of that region. In the case of a small country like the Netherlands, different results can be expected per system because of the open character of the economy. The differences between the two systems show the environmental relevance of imports and exports. Differences show that the Dutch population (shortly referred to as the Dutch) has a 'footprint' abroad, but others as well have part of their 'footprint' in the Netherlands.

Methodology

IO analysis was used for the calculation of the environmental pressure for both systems. Although insights into total pressure per sector for System 1 can be obtained from monitoring data, IO analysis is required for dividing pressure over domestic

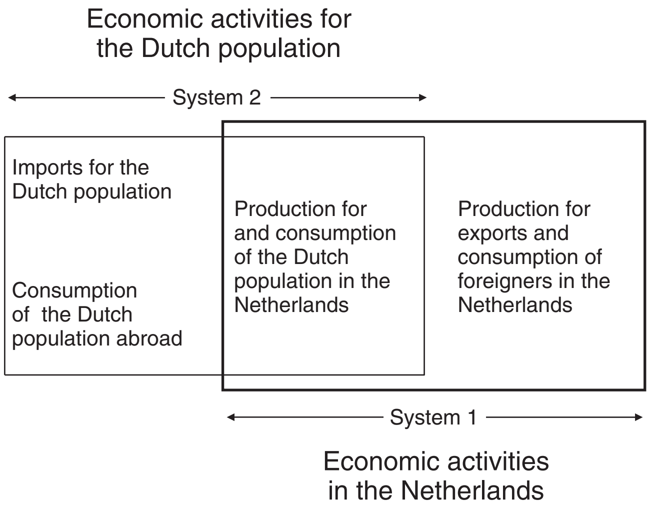

Fig. 19.1 Two Systems for Studying the Environmental Pressure Related to the Netherlands in the Netherlands and for the Dutch Population

demand and exports. The calculation follows a similar scheme for both systems. Starting-point is the determination of the final demand under consideration in the relevant system, such as household consumption or exports. After that, the required production per sector and region is calculated for the relevant final demand with the Leontief inverse matrix. Combining this production (also called production by origin) with direct environmental intensities results in the total environmental pressure per sector required for final demand. The calculation scheme for both systems is explained in more detail on the basis of the calculations concerning greenhouse gases for the Dutch situation.

System 1

System 1 concerns the production in the Netherlands divided over exports and domestic final demand. In order to assign all final demand in the Netherlands to one of the two final demand categories, investments were allocated to these categories on the basis of the production by origin per sector. So, consumption of the Dutch does not only consist of private consumption, but also of public consumption (e.g. government consumption, education and defense) and part of the new investments. Static Leontief inverse was used for both consumption and exports in order to calculate the production in Dutch sectors for these final deliveries. The calculation was carried out with a direct requirements matrix for the Dutch economy, excluding imports.

The calculated production by origin for both types of final demand was combined with intensities per sector for greenhouse gas emissions per unit of production. Some of the emissions from Dutch transport companies and fisheries occur abroad. Since these emissions do not belong to System 1, marked by the borders of the Netherlands, these emissions were excluded from the calculations (for System 1).

Direct emissions caused by consumption were added to complete the calculation of the greenhouse gas emissions in System 1. The direct environmental pressure of consumption concerns activities which take place in households, such as CO_2 emissions of combusting natural gas for heating and combusting fuels in passenger cars. Methane emissions of household waste at landfills were added too.

System 2

System 2 concerns the environmental pressure related to the consumption patterns of the inhabitants of the Netherlands. Direct pressure together with indirect environmental pressure (calculated by means of an IO analysis as described above) builds up total environmental pressure of Dutch consumption in the Netherlands. The data from the environmental pressure that takes place in the Netherlands is already calculated in System 1. In order to determine total environmental pressure of the Dutch, the part that takes place abroad has to be added.

The greenhouse gas emissions related to Dutch consumption are caused by a large amount of production processes in maybe all countries of the world. A pragmatic way to handle this, which is often applied, assumes that all imports are produced with technologies similar to those in the Netherlands. In general, however, production technologies differ across countries. To account for the differences in production technologies across countries, technologies were categorized into three world regions. So, in total, the model consists of four regions, the Netherlands, OECD-Europe, the other OECD countries and the non-OECD countries. Each foreign region produces directly or indirectly (via the Dutch production system) for Dutch consumption.

The requirements of imports for Dutch consumption were determined on the basis of the tables of competitive and non-competitive imports for the Netherlands. These imports consist of imports that are directly consumed by the Dutch population and those that are used in the Dutch production sectors for Dutch consumption. With the use of import statistics, total imports per sector were assigned to one of the three foreign regions as the place of origin. In this way, the deliveries for the Dutch production and consumption system were determined per region. Final demand of a foreign region concerns the exports to the Netherlands, both for production and consumption, and a small part of the investments; this allows maintenance of the production capacity for the Dutch. Finally, production by origin for the three regions was calculated. The Leontief inverse matrices for the three regions were derived from IO tables for the three regions at a 30-sector level. Total production by origin per region was combined with greenhouse gas intensities per sector and region in order to determine the greenhouse gas emissions related to Dutch consumption in other countries.

In fact, the method described is a simplification, since the trade flows between the three regions were not taken into account. The imports of a region were assumed to be produced in that region with the technology installed in that region. Since, for each region, imports are relatively small compared to total production, the errors that were introduced will be small too. The part of the model functioning outside the borders of the Netherlands does not cover the whole world (excluding the Netherlands), but only consists of the production in foreign countries that is ultimately, i.e. directly or indirectly, meant for the consumption by the Dutch.

Application of the Two-System Approach

The two-system approach was applied to two cases: (1) greenhouse gas emissions related to the Netherlands, and (2) CO_2 emissions related to the EU. The CO_2 emissions in the Netherlands taken over a time period were considered too.

Data

The cases required both economic data, especially IO tables, and data on emissions. For the Netherlands (NL) case, the technological matrix was derived from an IO table for the Netherlands geared to 105 sectors (CBS 1998). The IO data for the foreign regions and the EU were constructed by aggregating detailed economic data of individual countries and sub-regions from the GTAP database (McDougall et al. 1998).

For the NL case, the amount of imports was derived from national import statistics (Statistics Netherlands 1998). For the EU case, imports were derived from the GTAP database.

The intensities for Dutch industries were derived from both production per industry and total emissions per industry. The latter were obtained from the Dutch national emission inventory system (VROM 1997). Direct emissions of Dutch consumers were obtained from the same system (see also Chapter 16 of this handbook by Nijdam and Wilting). For the three foreign regions, data for greenhouse gas emissions per sector were collected from the EDGAR database (Olivier et al. 1996).

The NL Case

The first case concerns greenhouse gas emissions related to the Netherlands for the year 1995. This section presents both the outcomes of the calculations and a comparison of the outcomes. To illustrate the relevance of the economic structure

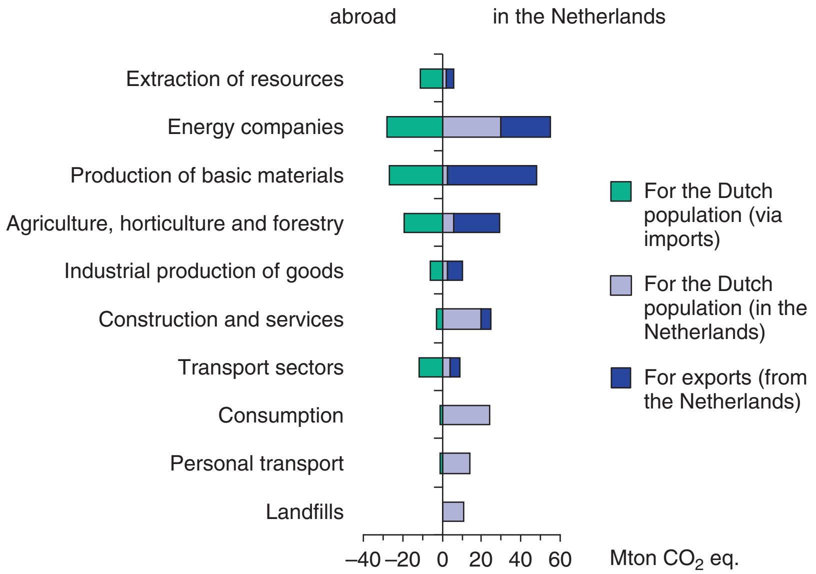

Fig. 19.2 Greenhouse Gas Emissions in the Netherlands (Both for the Dutch Population and Exports) and Abroad for the Dutch Population, 1995 (Extraction of Resources Includes Oil and Natural Gas; Energy Companies Include Refineries and Power Stations)

in the Netherlands for the environmental pressure in the country, the production-consumption chain was broken up into ten main parts. Figure 19.2 shows the greenhouse gas emissions for the two systems assigned to the ten parts of the production–consumption system. The greenhouse gases considered are CO_2, CH_4, N_2O and HCFCs. The amounts of all gases were expressed in CO_2 equivalents, using the so-called Global Warming Potentials, which describe the relative contribution of a gas to the greenhouse effect.

The right-hand side of the figure shows the greenhouse gas emissions in the Netherlands divided over exports (from the Netherlands) and domestic demand. Almost 50% of the greenhouse gas emissions in the Netherlands occur as a result of the exports of goods and services. Especially the energy-intensive sectors at the beginning of production chains, such as agriculture and horticulture, the energy sectors and the basic industries (chemicals, metals and paper), are responsible for a fair amount of greenhouse gas emissions related to the exports. An important explanation is the availability of cheap natural gas that led to a rapid expansion of basic industries in the Netherlands in the early 1970s.

Greenhouse gas emissions directly related to consumption occur mainly in the Netherlands. These emissions appear, for example, during the combustion of natural gas for heating or fuels for personal transport. The greenhouse gas emissions at landfills concern methane mainly. These emissions are assigned to all the inhabitants of the Netherlands, since by far the largest part of these emissions concerns waste from households. The left-hand side of Fig. 19.2 depicts the greenhouse gas emis-

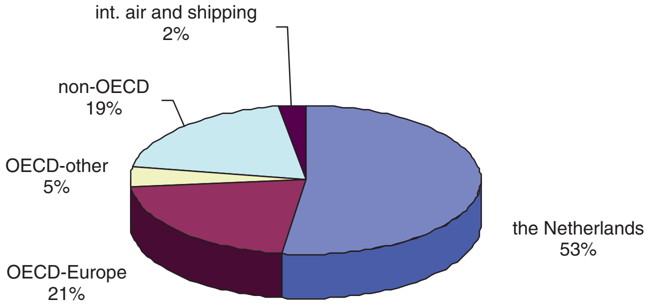

Fig. 19.3 Greenhouse Gas Emissions for the Dutch Population per Region, 1995

sions that occur to the advantage of the Dutch outside the borders of the Netherlands. They add up to 47% of the total greenhouse gas emissions related to the Dutch. The left-hand side of the figure also includes emissions from international shipping and air transport, which occur along the borders of the Netherlands but cannot be assigned to other countries either.

Figure 19.3 shows the emissions of greenhouse gases as related to the consumption of the Dutch population divided over the regions considered in the model. Most of the foreign emissions occur in OECD-Europe and the non-OECD countries. About 70% of the greenhouse gas emissions for the Dutch in foreign countries are regulated in the Kyoto Protocol. This protocol has the character of an agreement; there are no sanctions if the protocol is violated. So, 30% of the greenhouse gas emissions for the Dutch population are not included in the agreement. These emissions occur in countries that have not ratified the agreement, such as the USA, or in countries that have not signed the Kyoto agreements. Furthermore, these emissions concern activities that are not part of the climate agreement, like international air and sea transport (2% of the emissions related to Dutch consumption).

The IO calculations as described for System 2 depict the environmental pressure of the Dutch per sector and per region. Chapter 16 (Nijdam et al.) shows the environmental pressure of consumption at the level of consumption categories, an interesting illustration from the viewpoint of consumption patterns.

The EU Case

Since the Netherlands is characterized by high imports and exports compared to production in the country, the difference between the system approaches is substantial. This may be different for larger nations or regions with less international trade. A comparison for the world as a whole only shows the effects of international transport of which the emissions are not assigned to countries. In order to show how the two-system approach worked for a larger region, it was applied to a region consisting of the EU-15 extended with some Eastern-European countries. This newly

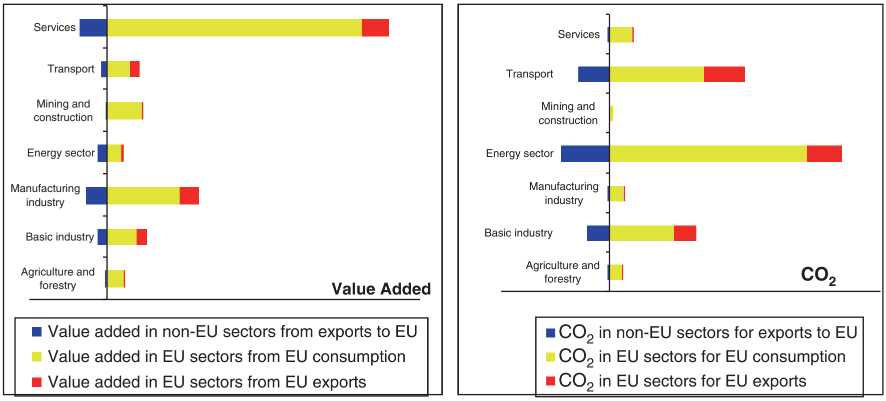

Fig. 19.4 CO_2 Emissions and Value Added for the Two Approaches in and for the EU, 1995

created region covers approximately the area occupied by the EU-25. Calculations were carried out for both CO_2 emissions and for value added.

Figure 19.4 shows a fairly closed EU; most of value added is generated in the EU for the EU. The same holds for CO_2 emissions. About 55% and 20% of value added are created in the service and manufacturing industries, respectively. These sectors contribute less than 10% to regional CO_2 emissions. However, they generate emissions related to transport and energy use in other sectors. The figures show that sectoral emissions take place mainly at the beginning of production chains and that value added is gained mainly at the end of production chains.

The EU's contribution to total global environmental pressure is decreasing, but the interaction with other parts of the world is increasing, for example, due to the lowering of trade barriers. Increasing trade has changed the distribution of pressures on the environment among countries and regions of the world. In the past 20 years, goods in which manufacturing exerts intensive pressure on the environment have been increasingly imported from newly industrial or developing countries. The share of imported resources in the total material requirement of the EU has increased (Schütz et al. 2004).

The NL Case Again

Considering the fourth National Environmental Policy Plan (VROM 2001), developments in the Netherlands should take place under the condition that total emissions for Dutch consumption do not increase. Figure 19.5 shows the developments in CO_2 emissions for both approaches for the 1990–2010 period. Total CO_2 emissions in the Netherlands were derived from monitoring data, but the division in domestic demand and exports was based on IO calculations for 1990, 1995 and 2000, and interpolation for 2010.

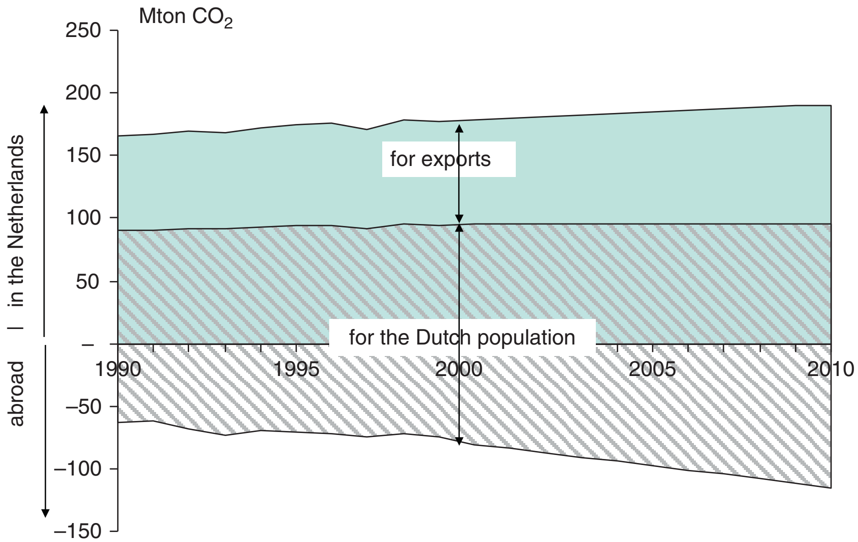

Fig. 19.5 CO_2 Emissions in The Netherlands and Abroad for the Dutch Population

Figure 19.5 shows an increase of 8% in CO_2 emissions in the Netherlands in the 1990–2000 period. In the first 5 years the increase was stronger than in the second 5 years. The weaker increase in the second 5 years is the result of an increase in the imports of electricity (Van den Wijngaart and Ybema 2002). The Netherlands Bureau for Economic Policy Analysis (CPB 2002) formulated two economic scenarios for 2000–2010: (1) a cautious and (2) an optimistic economic scenario. Van den Wijngaart and Ybema (2002) constructed the development in CO_2 emissions for the optimistic economic scenario for 2001–2010. According to the optimistic economic scenario, production for exports will increase faster than the production for domestic demand in the period up to 2010. The CO_2 emissions in the Netherlands for domestic consumption will stay at the same level.

From consumption models, CO_2 emissions related to consumption of the Dutch were derived that would increase further in the 2000–2010 period as a result of growing consumption. This increase in volume cannot be compensated by efficiency improvements in production and consumption. Since the possibilities for production for consumption in the Netherlands are limited, shift in production for Dutch consumption from the Netherlands to abroad will increase. And so CO_2 emissions abroad for Dutch consumption will increase too.

Summarizing, CO_2 emissions related to exports will increase in the Netherlands in the period up to 2010, but the emissions abroad for the Dutch consumption will increase even faster in the same period.

Discussion

This chapter has focused on the calculation of environmental pressure using IO analysis for a country or region seen from two perspectives. The advantage of using an IO analysis is the insight it provides into the spatial relationships between producers and consumers, and environmental pressure, which may help policy makers in their considerations on the responsibility issue, for example.

The figures used in this chapter had been presented previously in reports destined for the use by Dutch government departments and policy makers. The figures concerning the Dutch case were included in several documents meant for the Dutch government departments, Parliament and policy makers. They have been presented in the fifth Environmental Outlook (RIVM 2000). In fact, the fourth National Environmental Policy Plan (VROM 2001) reacted to this information by designating the problem. However, quantified policy goals for reducing the impact of consumption have not been set, although the figures were also used in the Environmental Balance 2002 (RIVM 2002). The EU figure was taken up in the EU environmental balance (RIVM 2004b). Dutch government has taken note that on the basis of the study presented in Chapter 16 of this handbook by Nijdam and Wilting most environmental pressure related to Dutch consumption takes place abroad. However, the government claims this pressure to be, in most cases, beyond the reach of environmental legislation and agreements with industries (Tweede Kamer 2004).

The environmental pressure related to exports has, to date, not received much attention in Dutch policy documents. Reduction of this environmental pressure forms part of the policy aimed at sectors for reduction of emissions. However, taking environmental pressure exerted by exports out of the total pressure 'picture' in the Netherlands will allow us to build up an ecological balance. How do environmental pressure of imports and exports relate to each other? And how do these pressures relate to the value flows of imports and exports?

This chapter has shown different ways to present the relations between domestic production, imports, exports, consumption, etc. by using the two-system approach. Both systems aim at the quantification of the environmental pressure of a country. From an equity perspective, in which each world citizen has the same claims on prosperity, the System 2 approach seems fairer. This approach enables a comparison between inhabitants of different countries or regions and their environmental profiles. In this connection, the approach can be used for revealing possible disproportionate pressure on the environment of the inhabitants of certain countries. Furthermore, System 2 also portrays emissions that are not included in the System 1 approach, such as the emissions of fisheries, and international shipping and aviation. The emissions related to international transport occur outside the borders of countries and are not included in national emission statistics. As a consequence, they are not included in national environmental policies either. Since climate policy includes several new forms of trade, it is a challenge to include them in IO analysis.

Country borders are based on historical events and are arbitrarily chosen from an environmental perspective. It is quite reasonable to expect differences between the systems per country or region. Considering the large international trade flows there will be no countries for which the systems completely overlap; in other words, no country is completely self-supporting. For historical reasons, and considering the size of the Netherlands and the open character of the economy, we can see that differences between the two systems do exist. The calculations show the total emissions of greenhouse gases in System 1 to be at the same level as those in System 2. However, the overlap between the two systems, i.e. the emissions for the Dutch population in the Netherlands, only accounts for about 50% of total emissions. This implies an enormous shift of greenhouse gas emissions from the Netherlands to abroad and vice versa. The second case study showed the difference between the two systems for the EU to be far lower than in the Dutch case. Although in the EU situation the two systems match far better than for the Netherlands, the question remaining is who should pay for the pollution.

In the Netherlands, CO_2 emissions for other countries are at about at the same level as CO_2 emissions in other countries caused by the Netherlands. However, there are differences in technologies and efficiencies per country and region. In some other countries, production is less efficient than in the Netherlands. However, the state of technologies and knowledge about technologies only partially explain the differences. Climate characteristics, soil properties, the available mix of energy carriers, population density and spatial relations are country-specific and have an impact on production efficiencies too. The multi-regional character of the IO model allowed us to estimate the differences as well. If other countries were to apply Dutch production technologies, the CO_2 emissions in other countries caused by Dutch consumption would drop by about 30%. Therefore, in the eyes of many stakeholders, the presence of large energy-intensive industries in the Netherlands is justified by the fact that some of the Dutch companies are among the best in the world and support technological optimization. As for Dutch companies not being on the top, policy goals have been set to get them there. The concept of benchmarking has been developed to stimulate economic sectors in such a way as to allow them to compete with sectors abroad for their efficiencies. Benchmarking is now one of the leading approaches in Dutch policy on industrial energy use.

One drawback of the aggregation over European countries in the EU case is that aggregation hides the differences in technologies and efficiencies between countries. So for sectors with a high environmental pressure, optimization on a European level may take place inside that sector. Agreements will have to be made at this level.

The cases dealing with the calculation of the environmental pressure in the two systems concerned climate change (CO_2 and greenhouse gas emissions). Of course, the methodology is applicable to other substances and environmental themes as well. Ros and Wilting (2000) calculated environmental pressure for both approaches related to acidification and land use. The model outcomes for intensities of environmental pressure, for example, can be used as inputs for other models. These translate the use of natural resources and emissions of substances related to the Dutch population into loss of biodiversity and public health. A further step may be the application to economic (e.g. value added in the EU case) and social aspects. In this way, the two-system approach can be used for sustainability assessments.

The differences and insights obtained from the chain approach of System 2 may be useful for optimizing production–consumption chains over country borders. A global optimization across countries might lead to more optimal results in environmental policy. Such an optimization, which requires an international approach, may involve a shift of foreign production to the Netherlands (and produce more efficiently), or may actively improve technology elsewhere. However, optimization has to be carried out with care, since optimization for greenhouse gases may lead to less optimal outcomes for other environmental themes, like acidification, land use or pesticides. These themes are specific for certain regions, unlike climate change, which is a global problem. And in some cases the use of land may have the same efficiency across countries, but the damage to nature may vary per country. From an ecological perspective, a shift to other countries may be justified if the production efficiencies in other countries are at least at the same level as in one's own country, so that overall environmental pressure and damage to nature will not increase. So, from an ecological perspective, for most cases, a shift to developing countries, with a high biodiversity, would not be preferable. Furthermore, optimizing on ecological aspects alone is too narrow from a sustainability perspective. Therefore economic and social aspects have also to be considered when optimizing across countries.

The case of the greenhouse gas emissions showed large differences in the efforts to deliver calculations for both the systems. The emissions in System 1 were obtained from environmental statistics based on emission monitoring. Only the division over exports and domestic demand required an IO analysis for the Netherlands. Determining the emissions in System 2 was much more labor-intensive. Besides the IO analysis of the Netherlands, this calculation required a large amount of data on trade flows and production technologies in other countries and regions. The fact that these calculations are based on more assumptions implies that the uncertainties in the outcomes for System 2 are higher.

Conclusions

IO economics offers opportunities to show the relations between production, consumption, international trade and environmental pressure in different ways. Different cross-sections of environmental pressure and economic activities may help policy makers in pursuing new policies.

This chapter has discussed two approaches using IO analysis for determining the environmental pressure of a country or region. The calculations have provided insights into the differences between the two approaches. Determining the environmental pressure in a country (System 1) is far easier and outcomes are less uncertain than for determining the environmental pressure of the inhabitants of a country (System 2). However, policies directed to reduce the environmental pressure related to the inhabitants of a country (System 2) seems to be fairer. Since both approaches have their specific pros and cons, they may complement each other. Especially the outcomes of the System 2 approach deserve more attention in environmental policies.

The results show greenhouse gas emissions in the Netherlands to be in contrast with those related to the inhabitants of the Netherlands. The Dutch show a shift to other countries and vice versa, a shift that will increase in the next decade. Optimization across countries may be useful to reduce the shift in greenhouse gas emissions. However, in optimizing, other environmental themes, and social and economic aspects have to be considered too.

The two system approach does not provide policy solutions for the problem of shifting environmental pressure to other locations. However, it does show where and to what extent shifting takes place. The two system approach can prove to be a useful instrument for dealing with choices and examining the most optimal solutions, and so may serve as a tool for weighing up policy options.

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Chapter 20
Prioritizing Within the Product-Oriented Environmental Policy – The Danish Perspectives

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Background

As a supplement to the site, substance and media specific environmental policies, Denmark has had, since 1998, a product-oriented environmental policy (at the European level known as "Integrated Product Policy"). The policy has been organized as prioritized activities in selected sectors and/or product areas. This prioritization was informed by the results from the project "Environmental prioritization of industrial products" (Hansen 1995). Other previous studies with similar objectives, i.e. to identify the most important product groups from an environmental perspective, include Dall et al. (2002) for Denmark, Finnveden et al. (2001) for Sweden, Nijdam and Wilting (2003) for the Netherlands, Nemry et al. (2002) for Belgium, and Labouze et al. (2003) for the EU. The Swedish and Dutch study use the same general methodology as our study, namely environmentally extended IO-analysis (Miller and Blair 1985), while the remaining studies use a bottom-up process based analysis.

Due to the environmental indicators used (energy consumption and resource loss) the product groups that are ranked high by Hansen (1995) are those with either large energy consumption or which are destroyed or dissipated during use. This includes the main energy carriers, transport activities (represented by the vehicles including their use phases), fertilizers, animal feeds, meat and dairy products, building materials, detergents, newspaper, beer and furniture.

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Dall et al. (2002) have a consumption perspective and include only private consumption. The study focuses mainly on energy consumption and concludes that food, car driving, and housing are the most important product groups. Also clothing and personal hygiene appear high in energy consumption.

The product groups that are ranked high by Finnveden et al. (2001) for the emissions of CO_2, SO_2 and NOx, are electricity and heat, food, dwellings, transport activities, and hotels and restaurants. The fact that retail trade and public services, such as waste handling and recreational activities, also come out high in the Swedish study is probably due to the specific infrastructure of the Swedish economy. Finnveden et al. (2001) also rank the product groups according to emission intensity, and here we find transport by ship at the top of the list. Also construction materials, fish & seafood, metals, agricultural products, and pulp and paper are ranked high on impact intensity. When considering the ranking by CO_2 and SO_2, it is also not surprising to find electricity and heat among the important products.

Nijdam and Wilting (2003) use a number of environmental indicators, including global warming, acidification, nutrient enrichment and photochemical ozone. For global warming they find the most important consumption groups to be food (30%), followed by leisure (22%, mainly due to transport for holidays), and housing (17%; mainly for heating and electricity).

Nemry et al. (2002) and Labouze et al. (2003) find dwellings and transport to be the most important product areas. Nemry et al. (2002) do not include food products in their ranking, while Labouze et al. find food products to be the largest source of eutrophication (due to fertilizer application) and a large source of global warming and photochemical oxidation (due to enteric fermentation and manure management). Nemry et al. (2002) furthermore point to packaging and electrical appliances as important products, while Labouze et al. (2003) find textiles among the largest sources of acidification and photochemical oxidation.

At the European level, the Commission has initiated in 2003 a project "Evaluation of environmental impact of products" (EIPRO), which includes a review of the above-mentioned studies and aims at identifying the products with the largest environmental improvement potentials (Tukker et al. 2004).

As a Danish contribution to this, the Danish Environmental Protection Agency commissioned an updated and more detailed method, to provide a well-documented decision basis for planning and selecting products for future product-oriented activities. The method is based on a combination of environmental statistics and the Danish national accounts, also known as environmentally extended IO-analysis (Miller and Blair 1985).

The method has been applied to provide prioritized lists of those product groups and industries where Danish environmental measures will give the largest environmental improvement, both for the products currently produced in Denmark (for domestic consumption or for export) and the products currently consumed in Denmark (domestically produced as well as imported). The result of this prioritization is presented in this paper, along with some considerations on the importance of applying different perspectives on the data.

Method

This section provides a short presentation of our methodology for prioritizing product groups. This is to be seen mainly as background information, since the main focus of this paper is on policy implications, not on methodology (see Miller and Blair 1985, and Weidema et al. 2004 for details).

The project takes its starting point in the Danish national accounts of the economic flows between Danish enterprises and institutions, i.e. their mutual purchases and sales, imports and exports, and supply to final consumption. This is also known as national input-output tables or short: IO-tables. These are then combined with data from different environmental statistics, starting with the Danish NAMEA (Danmarks Statistik 2003), which are adjusted to the same level of detail as the industries and product groups of the national accounts.

The assessment has been performed for the year 1999, since at the start of the project this was the most recent year for which comprehensive data were available. It has been checked and confirmed that 1999 was not an atypical year for any specific product group, so that the conclusions from the project will also be valid more generally. Obviously, trends in production and consumption change over time, so we would recommend the study to be repeated every 5 year to keep the policy information relevant. With the applied method, and given the current availability of data, such updating is not complicated.

The study includes all substances that contribute significantly to the eight environmental impacts that are normally included in product life cycle assessments, i.e. global warming, ozone depletion, acidification, nutrient enrichment, photochemical ozone formation, ecotoxicity, human toxicity and nature occupation.

Results are calculated for each impact category separately, using characterization factors expressing the contribution of each emitted substance to each impact category, as given by Hauschild and Wenzel (1998) and later updates (Olsen 2003, see also Weidema et al. 2004). An overall score for environmental impact is constructed by normalizing the results for each of the eight impact categories to the total impact from Danish production and consumption, and then adding these normalized results. Thus, the eight environmental impact categories all participate with equal weight in the overall score.

By taking the economic flows between all enterprises as a starting point, the chosen method ensures a high degree of completeness – avoiding the omission of processes with small contributions to many products, e.g. transport processes.

Nevertheless, to use IO-tables or NAMEAs as a basis for environmental analysis involves a number of limitations, some which are inherent to the methodology, and some have to do with data availability. Most of these limitations have been satisfactorily overcome by adjusting and expanding the NAMEA.

In terms of data availability, the main limitation of the official Danish NAMEA is the coverage of environmental exchanges, which is limited to specific air emissions. We have added more environmental exchanges, aiming for the same degree of completeness as in the normalization reference for Denmark provided by the Danish "EDIP" life cycle assessment methodology (Hauschild and Wenzel 1998).

The life-cycles of each product group have generally been constructed by linking the upstream processes proportionally to the monetary value of the flows between the processes, as is traditionally done in economic input-output analysis and product life cycle assessment. This implies the assumption that a change in demand for a product will lead to a proportional change in production volume in the entire supply chain. To take into account that not all industries can change their production volume in response to a change in demand (for example, because of the European quotas on milk production, a change in the output of milk from the dairies will not be able to influence the amount of milk produced in agriculture, and therefore not the environmental impacts from agriculture either), we analyzed all industries systematically for long-term production constraints, i.e. constraints that influence investment decisions, like the one mentioned for dairy farms. For the most important constrained industries we have divided the industry into a constrained and a non-constrained part, transferred the constrained supplies to the alternative non-constrained industry and added the constrained outputs as separate products in new final consumption group, typically named "industry name (constrained)". Since a constrained production is still relevant for non-market-based environmental measures, a constrained product takes part in the same way as any other product in the prioritization in the supply perspective.

An important limitation of IO-tables is the implicit assumption of homogeneity of the industries, i.e. that all products from an industry are assigned the same environmental impact per monetary unit. The higher the level of aggregation of industries, and the more diverse the industry in question, the more erroneous this assumption will be. Based on an uncertainty analysis, we subdivided the most important of such inhomogeneous industries, using hybrid techniques (see e.g. Joshi 2000; Suh et al. 2004; Suh et al. (2004).

Some of the accounting conventions applied in the national accounts are also less appropriate for environmental IO-analysis, and have therefore been corrected (classifying previously unclassified imports, including tourism expenditures, redistributing investments to the industries supplying the investment goods, and redistributing financial intermediation services to the financial industries supplying the loans).

An important assumption of traditional IO-analysis is that imported products are produced in the same way as the similar domestic products, although it is well-known that emission factors (e.g. CO_2/DKK) can vary significantly from country to country due to differences in geographic and administrative conditions, industries composition, applied technology, management systems and sizes of production units. This assumption was applied in an initial analysis, and showed that the imports to Denmark resulted in an average environmental impact of a size approximately one third of the environmental impact from the Danish production and use stages. As Denmark has very little raw material extraction and primary processing, it is to be expected that applying Danish emission factors to foreign production will result in an underestimation of the actual environmental impact. This expectation was confirmed in a later analysis, where emission factors from the USA were used for the foreign industries. This resulted in an average environmental impact of a simi-

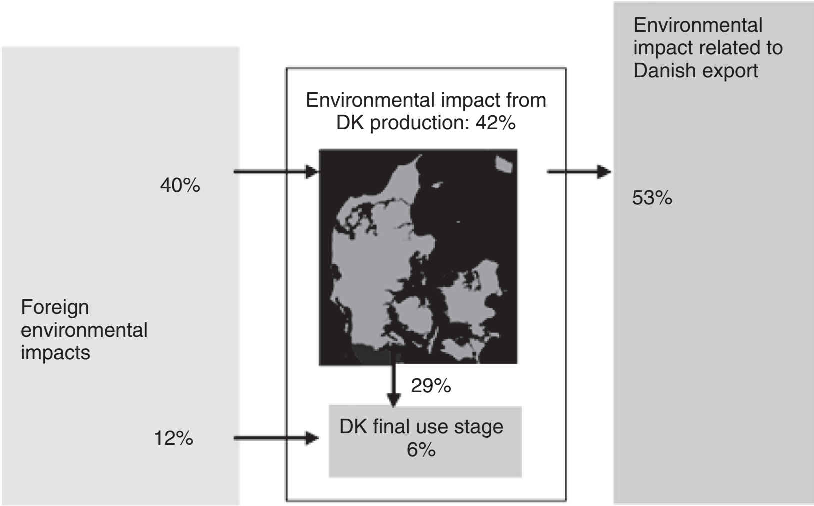

Fig. 20.1 The Environmental Impact Potential Related to Danish Production and Consumption, in Percentage of the Total Environmental Impact, Expressed as an Average of Eight Environmental Impact Categories, Which All Participate with Equal Weight. From a Supply Perspective, the Total Environmental Impact (100%) can be Divided in the Part That is Related to Danish Industry (40% for the Products Used by Danish Industries and 42% from Danish Production) While the Remaining 18% are Environmental Impacts Abroad Related to the Products Imported to Denmark for Direct Consumption (12%) and from the Final Use Stage (6%). From a Consumption Perspective, the Same 100% Can Be Divided in the Part Related to Danish Final Consumption (12% + 29% + 6% = 47%) and the 53% Related to the Exported Products Consumed Abroad

lar size as the environmental impact from the Danish production and use stages (see Fig. 20.1), i.e. three times the original result. It was decided to use the US-American data after an initial analysis of available NAMEA data. Contributing to this decision was the relatively low level of aggregation of the US table (493 industries), the high number of emissions available (more than in the Danish NAMEA) and the relatively high completeness of the US-American economy in terms of industries covered (due to the size of the country, practically all kind of industries are found within the country). We compared the emission factors from the US data (as provided by Suh 2003) to the emission factors from the closest corresponding Danish industries. In general, we found the original US data to provide a reasonable proxy for imports to Denmark, while in some instances we found it necessary to make adjustments to the US data.

Finally, using monetary IO-tables to represent physical flows of commodities between industries implies an assumption of proportionality of monetary and physical flows. Only for energy related air emissions, does the Danish NAMEA relate to physical flows of specific fuels based on the Danish energy matrices, which are provided in both economic and physical units. In connection to the above-described subdivision of industries, we have sought to minimize this problem by isolating physical product flows related to specific emissions, such as ozone depleting substances from refrigeration.

The Importance of Different Perspectives

When asking for which product groups the Danish product-oriented environmental policy would give the largest environmental improvement, the system boundaries must be drawn from a life-cycle perspective, i.e. for each product group including all upstream processes from the "cradle", i.e. material extraction from nature, and downstream to the "grave", i.e. waste treatment. Furthermore, it is necessary to look both at the products produced in Denmark (as the policy could influence the Danish industries directly) and at the products consumed in Denmark (as the policy could influence foreign producers through supplier requirements and influence the Danish consumers directly).

This provides the two basic perspectives applied in this study[1]:

The *supply* or *net production* perspective looking at the total environmental impacts caused by the supply of products *from Danish industries* going either *to final consumption or export*, i.e. equivalent to the net production of Danish industries.[2] To avoid double-counting, production for internal use in Danish industries is only included as upstream processes for the net production. This is a "cradle to gate" perspective, where the gate is the point where the product leaves the Danish industry. It includes the foreign products imported for use internally in Danish industry. Compared to the consumption perspective (see below) it excludes products imported to Denmark directly for final consumption (i.e. outside of Danish industries) and the final use, but includes production for export from Denmark.

The *consumption* perspective, looking at the total environmental impacts caused by the products *from foreign or Danish industries* going *to final consumption in Denmark*, both private and public. It is a complete "cradle to grave" perspective on these products. This implies that the use stage is included, unless specifically excluded. Compared to the supply perspective, the consumption perspective excludes products exported from Denmark (and their upstream processes), but includes products imported to Denmark directly for final consumption.

A third perspective combines the supply and consumption perspectives. This is:

The *process* perspective, looking at the environmental impacts, separately from each single process within both *foreign and Danish industries and Danish households*, caused by the products going *to final consumption in Denmark or export*. This is a "gate to gate" perspective of each process, scaled to the size determined by *Danish production and consumption*. It thus includes all products imported to Denmark, also those for direct consumption,[3] and all products produced in Denmark, also those exported. It also specifically includes products that are solely produced for use internally in Danish industries and therefore not separately reported by either of the two perspectives, because they are neither going to final

[1] The exact mathematical expressions for the applied perspectives are provided in Appendix.

[2] Net production of Danish industries is the products supplied by Danish industry for domestic final consumption or for export, as opposed to the gross production that includes also the products supplied for internal use in Danish industry.

[3] Products for re-export are not included in any of the perspectives applied.

consumption nor export. Like the supply perspective, it also includes constrained processes. Like the consumption perspective, it includes environmental impact from the use stage.

Thus, the three perspectives differ mainly in their system delimitation, as shown in Table 20.1. The data used are the same for all three perspectives, see also

Table 20.1 Three Perspectives on the Influence-Spheres of Danish Product-Oriented Environmental Policy and Their Corresponding System Delimitations

	Supply perspective	Consumption perspective	Process perspective
Life-cycle perspective	"Cradle to gate"	"Cradle to grave"	"Gate to gate"
Policy objective	Reducing life-cycle impacts from Danish industries and their products	Reducing life-cycle impacts from Danish consumption	Reducing impacts from processes contributing most to Danish production and consumption
Sub-division of product groups	According to Danish producing industries	According to consumption groups (need groups/product functions)	According to producing industries and use stage processes according to consumption groups
Captures/includes impacts related to:	• Danish production for Danish final consumption and upstream imports to this • Exported products • Constrained production	• Danish production for Danish final consumption and upstream imports to this • Imports directly to Danish final consumption • The use stages • Consumption of Danes traveling abroad	• All processes in the supply or consumption perspectives • Danish production for use in Danish production, as separate products (also included in the other perspectives, but not separately)
Ignores/excludes impacts related to:	• Imports directly to Danish final consumption • The use stages • Consumption of Danes traveling abroad	• Exported products • Constrained production	

Appendix. However, the differences between the perspectives influence their results in terms of prioritized product groups (see Table 20.2) as well as their policy relevance (as shown in Table 20.4).

The supply perspective results in identification of product groups where Danish industry has a large output volume, for example transport by ship and pork products, disregarding that these products are mainly exported. For an export-oriented economy, like the Danish, the supply perspective is essential for catching that part of the environmental impacts (and improvement options), which are related to the export industry. Also, due to its inclusion of the export products, the supply perspective will identify product groups that are not going to final consumption, i.e. intermediate products used in foreign industries, e.g. transport by ship and wholesale trade. The environmental impact from these intermediate service products contributes to the environmental impact of many different final consumer products, and therefore does not become visible unless these intermediates are regarded as products in their own right. Interestingly, wholesale trade does not appear in the top-ten of the process perspective, since the environmental impacts are not due to the trade process itself, but due to the impacts from its supplying processes, mainly transport and packaging and to a lesser extent advertising and buildings. On the other hand, the process perspective identifies basic ferrous metals as a process with an important product, which reflects this product takes part as an intermediate in many other products. This product does not appear in the supply perspective because it is not produced to any significant extent in Danish industries. Also, the supply perspective does not capture environmentally important products that are imported directly to final use in Denmark (such as textiles, detergents and automobiles), products with important use phase emissions (car driving, heating in dwellings), and consumption of Danes traveling abroad, which are only captured by the consumption perspective.

These examples all show the importance of being able – as in this project – to analyze the environmental impacts from different perspectives.

The total environmental impact of a product group depends partly on its environmental impact intensity (i.e. the impact per monetary unit), partly on the size of the product group in economic terms. When prioritizing product groups according to total environmental impact, it is unavoidable that the result is influenced by how the product groups are defined, and especially their level of aggregation. A highly aggregated product group is more likely to show up among the top ten, and by disaggregating it into a number of smaller product groups, it can be made to disappear from the top ten. For example, in our study, the product group "education and research" only reaches the top-ten of environmental impact (see Table 20.2) because it is a highly aggregated product group. In itself, education has very low environmental impact intensity and would not have reached the top ten if it had been divided into primary, secondary and higher education, and adult education etc.

To counter this inherent arbitrariness in the ranking, it is relevant also to look at the prioritization when impact intensity alone is used as the ranking principle (see Table 20.2), i.e. ignoring the size of the product group. A product with a large impact per economic value will then appear on the top of the prioritization also when disaggregated. In this approach, the only way an important product can disappear

Table 20.2 Top Ten Most Important Product Groups Depending on Perspective and Ranking Principle

System delimitation: Ranking principle	Supply perspective	Consumption perspective	Process perspective
Total impacts (impact intensity * production volume)	• Transport by ship (out of which 99% is for export) • Pork and pork products (out of which 80% is for export) • Cattle and dairy products (constrained) • Electricity and heat (constrained) • Beef and beef products (out of which 71% is for export) • Dwellings (entirely for domestic consumption) • Industrial cooling equipment (entirely for export) • Wholesale trade (out of which 61% is for export) • Restaurants and other catering (out of which 4% is for export) • Defence, justice, public security etc. (entirely for domestic consumption)	• Car purchase and driving in DK, private consumption • Dwellings and heating in DK, private consumption • Meat purchase in DK, private consumption • Tourist expenditures by Danes traveling abroad, private consumption • General public services, public order and safety affairs • Clothing purchase and washing in DK, private consumption • Catering, DK private consumption • Personal hygiene in DK, private consumption • Education and research, DK public consumption • Bread and cereals purchase in DK, private consumption	• Transport by ship, DK and ROW (Rest-Of-World) • Pig farms, DK • Meat animal farms and meat industry, ROW • Dairy farms (constrained), DK • Basic non-ferrous metals industry, ROW • Industrial cooling equipment industry, DK • Electricity production (constrained), DK • Car driving in DK, private • Refining of petroleum products etc., ROW • Detergents and other chemical industries, ROW

(continued)

Table 20.2 (continued)

System delimitation: Ranking principle	Supply perspective	Consumption perspective	Process perspective
Impact intensity alone	• Industrial cooling equipment • Meat and meat products, incl. fish and seafood • Agricultural products in general • Basic non-ferrous metals • Transport by ship • Motor vehicles, parts, trailers, etc. • Tobacco products • Basic plastics • Fertilizers • Cement, bricks, tiles, etc.	• Fireworks, private cons. • Meat purchase, private • Eggs, imported, private • Car driving for holiday abroad, private • Detergents prepared for use, imported, private • Potatoes etc., private • Bread and cereals in DK, imported, private cons. • Pet food, imported, private consumption • Non-durable household goods n.e.c. (includes labels, polishes, minor textile items, wrapping paper, brooms and brushes, carbon dioxide cartridges and pesticides) • Vegetable oils, imported, private consumption	• Not applied

from the top of the prioritization is if it is aggregated with another product with a low environmental impact. This means that it is still possible that very inhomogeneous product groups (in terms of impact intensity) can conceal products with large impact intensities. However, this problem can be solved by appropriate disaggregation.

Thus, arbitrariness in the ranking is reduced partly by studying impact intensity alone, partly by ensuring that the product groups are defined so that producing industries are as homogeneous as possible and so that consumption groups are based on what needs the different products fulfill. In this functional approach to defining consumption groups, the entire consumption is broken down from top down, so that important product groups are not "concealed" and products that functionally belong together (such as car purchase and car driving) are not separated.

Key Results

To be relevant for product-oriented environmental policy, a product group must have both high total impact and high impact intensity. Surprisingly, this is the case for most of the top-ten product groups in Table 20.2. Notable exceptions are "Education and research" which, as already mentioned, has a high level of aggregation that places it high in total impacts in spite of a low impact intensity (and thus with an inherently low relevance for specific policy interventions) and tobacco products and fireworks that have high environmental impact intensity, but a low volume that make them less relevant for a policy intervention. That the last two product groups appear on the top-ten nevertheless points to them as being under-priced compared to their environmental externalities (which are not even completely covered by the impact categories applied in this study, which does not include noise and passive smoking).

In Table 20.2 and Fig. 20.1, environmental impact is expressed as an average of eight impact categories (global warming, ozone depletion, acidification, nutrient enrichment, photochemical ozone formation, ecotoxicity, human toxicity and nature occupation), which all participate with equal weight. For results per impact category, see Weidema et al. (2004). As an example of the information that can be found here, Table 20.3 shows the results for the consumption perspective for the impact category human toxicity.

The top-ten product groups in Table 20.2 account for a surprisingly large share of the total environmental impacts from Danish production and consumption. In the supply perspective, ranked according to total impacts, the top-ten products groups (out of a total of 138) account for 45% of the total environmental impact from Danish production and consumption. In the consumption perspective, ranked according to total impacts, the top-ten products groups (out of a total of 98) account for 57% of the total environmental impact from Danish consumption, and 25% of the total impact from Danish production and consumption.

This implies that the product-oriented environmental policy may result in large improvements by focussing specifically on these product groups. However, it is still necessary to be cautious that any specific measures do not lead to problem-shifting.

For those product groups that have been identified as most important, significant improvement options have been identified and ongoing activities have been reviewed (see Weidema et al. 2004).

A quantitative uncertainty assessment has been performed in order to provide the prioritization results with confidence intervals (see Table 20.3). Generally, the difference between the product groups are so large that their overall position in the prioritization (among the 10 most important, among the 20 most important etc.) is very stable, even for product groups where the environmental impact is determined

Table 20.3 Product Groups Within Danish Consumption with the Largest Human Toxicity Potential (HTP), in Person-Equivalents (PE) and % of Total HTP from Danish Production and Consumption

	HTP (in PE)	In % of total	Accumulated %
Dwellings and heating in DK incl. maint. and repair, private	4.3E + 05 ± 18%	8.0	8
Car purchase and driving in DK, private consumption	3.3E + 05 ± 27%	6.2	14
Tourist expenditures abroad, private, except car driving	1.1E + 05 ± 39%	2.1	16
General public services, public order and safety affairs in DK	1.1E + 05 ± 11%	2.0	18
Economic affairs and services, DK public consumption	9.3E + 04 ± 14%	1.8	20
Education and research, DK public consumption	8.5E + 04 ± 12%	1.6	22
Television, computer etc. in DK, incl. use, private consumption	7.3E + 04 ± 40%	1.4	23
Personal hygiene in DK, private consumption	6.9E + 04 ± 17%	1.3	24
Hospital services in DK, public consumption	6.5E + 04 ± 23%	1.2	26
Catering, DK private consumption	6.5E + 04 ± 14%	1.2	27
Furniture & furnishing in DK, private consumption	6.5E + 04 ± 16%	1.2	28
Transport services in DK, private consumption	6.1E + 04 ± 14%	1.2	29
Clothing purchase in DK, private consumption	5.8E + 04 ± 41%	1.1	30
Toys, DK private consumption	5.8E + 04 ± 105%	1.1	31
Meat purchase in DK, private consumption	5.7E + 04 ± 17%	1.1	32
Telecommunication and postal services in DK, private cons.	4.6E + 04 ± 37%	0.9	33
Retirement homes, day-care etc. in DK, public consumption	4.6E + 04 ± 30%	0.9	34
Recreational services in DK, private consumption	4.3E + 04 ± 22%	0.8	35

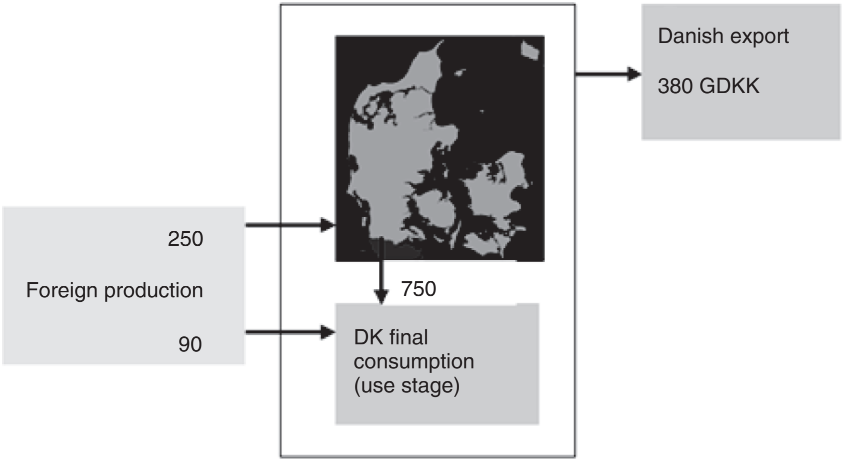

Fig. 20.2 The Flows of Products Related to Danish Production and Consumption, in Monetary Terms. Data Based on the National Accounting Matrices for Year 1999. Danish Consumption Amounted to 840 GDKK (Without Product-Related Taxes). Out of this 90 GDKK Were Products Imported Directly for Final Consumption, While 750 GDKK was from Danish Production. Danish Production also had an Import Totaling 250 GDKK (Without Re-export), but also an Export at a Value of 380 GDKK

with relatively large uncertainty. The main source of uncertainty is the aggregation level of data for the industries.

Danish exports are responsible for approximately half of the environmental impacts caused by Danish industry (see Fig. 20.1), in spite of this export contributing only half as much economic value as the Danes' own consumption (see Fig. 20.2). Thus, the export is relatively environmentally intensive. In other words, both imported products and products produced for export in general cause more environmental impact than products produced in Denmark for the Danish market. Especially noticeable is the export of meat and ship transport.

Figures similar to Figs. 20.1 and 20.2 can be made for each single product group and each single impact category, thus providing information on how environmental impacts are related to the import and export of that commodity. This could be useful e.g. when discussing how emission quota can best be designed and administered at the national level.

As it may be seen from Table 20.2, high environmental impact intensity is often linked to primary products, i.e. un-processed bulk products like fish, agricultural products directly from the farm, basic metals and plastics etc. Not presented in Table 20.2, but in the detailed project report (Weidema et al. 2004), low impact intensity is primarily linked to products with a relatively high proportion of labor, which does not contribute with environmental impact. This is also the explanation behind public consumption having much smaller environmental impact intensity than private consumption. Depending on the impact category, one DKK used by public authorities has an environmental impact between 13% and 64% of that of one DKK used by a private Dane.

Comparison with Results of Previous Similar Studies

In general, our results confirm those of the previous studies mentioned in the section “Background.” However, the different perspectives and especially aggregation levels used by the different studies make exact comparisons difficult. For example, we regard electricity and heating as products to be ranked, while Hansen (1995) ranks the *energy carriers* including their use phase and Nemry et al. (2002) rank the *electrical appliances* including their use phase. Similarly, Nemry et al. (2002) point to packaging as an important product group, while packaging is not included as a product group on its own in our study, but contributes to explaining our high ranking of wholesale trade.

Other differences between studies may be explained by differences in the environmental indicators used. For example, Hansen (1995) apply the indicator “resource use”, which implies that products that are destroyed or dissipated during use, such as detergents, newspaper, beer and furniture, receives a high ranking. Our study focus less on resource use and therefore such products appear less important in our prioritization.

Differences between countries in terms of the structural composition of industries are the reason for other differences in results. For example, Swedish pulp and paper industry has high impact intensity, while the corresponding Danish industry has a completely different product composition (more finished products), explaining its lower impact intensity.

Differences in scope may also explain some differences between studies. For example, tourist expenditures and car driving (private fuel use) do not appear in the Swedish ranking, since these product groups were not included in the Swedish data. Similarly, Nemry et al. (2002) do not include food products in their ranking.

It is interesting to note that dwellings and transport appear as important product areas in all studies, in spite of completely different methodological approaches (IO-analysis and bottom-up process analysis). This points to these two product areas as being of such size that they are likely to appear in any priority list, despite differences in methodology and data basis to derive these lists.

Implications for Policy

The relative importance of imports and exports illustrated by Figs. 20.1 and 20.2 naturally leads to a recommendation that the Danish product-oriented policy must include – and even focus on – both foreign producers and foreign markets. The importance of the supply perspective to identify important exported products, and the consumption perspective to capture important imported products, has already been mentioned.

Also in other ways, it appears that the different perspectives supplement each other. In Table 20.4, the policy relevance of the different perspectives is summarized.

Table 20.4 Policy Relevance of the Three Perspectives Depending on the Applied Ranking Principle

System delimitation: Ranking principle:	Supply perspective	Consumption perspective	Process perspective
Total impacts (impact intensity * production volume)	Suggests what product groups to target with policy elements that: • Address the producing industries directly • Create markets for environmentally improved products • Address the export markets	Suggests what product groups to target with policy elements that: • Address the level of consumption • Address consumer choices and behavior • Create labelling initiatives that include imported products • Address public consumption	Suggests which processes to target with policy elements that address process optimizations directly
Impact intensity alone	Suggests what product groups to target with policy elements that • Seek to substitute low priced, high-impact material inputs or techniques with high-quality, low impact labor/ service inputs, materials or techniques	Suggests what product groups to target with policy elements that: • Seek better correspondence between product price and environmental impact • Address consumer choices and behavior, taking into account substitutions as a result of price differences (re-bound effects)	Suggests which processes to target with policy elements that • Address process eco-efficiency (better correspondence between net value added and environmental impact)

While the supply perspective leads to a focus on industries' options for producing the same product in alternative ways, reducing impacts and/or reducing inputs (costs), the consumption perspective leads to a focus on options for substituting between products fulfilling the same need – or even substituting between needs. The process perspective supplements this by focussing attention on those processes where improvements would contribute significantly to many product groups.

The additional ranking according to impact intensity highlights important aspects of sustainable consumption, namely:

- That as long as the total consumption in monetary terms remains the same, reducing the level of consumption of one specific product may not have a positive impact on the environment – a change will only happen when substituting with products with a lower impact intensity.
- That overall environmental impact is best reduced by a strategy that combines impact reduction with measures that can increase the sales price, either by increasing the labor/service content and/or quality of the products, or through environmental product taxes that internalize the environmental impacts into the product prices.

Products with low environmental impact intensity are particularly services, e.g. bookkeeping and auditing, insurance, social security, financial and legal services, education and research, kindergartens and crèches, home and day care services and retirement homes. It is obvious that the products with high environmental impact intensities, such as food and transport, cannot be directly substituted by these low impact intensity services, since they do not fulfill the same needs. However, the information on impact intensities can be used to point out the products for which it would be highly desirable to search for satisfactory substitutes, which may go beyond the mere substitution of products with identical properties. For example, the general consumer welfare would not necessarily be affected by a non-compensated reduction in the amount of (high-impact-intensity) meat consumed. This could point to possible, desirable changes in the general consumption pattern.

Applying impact intensity alone as a ranking principle in the process perspective is equivalent to ranking according to process eco-efficiency (impact per net value added). As can be seen in Table 20.2, we have not applied this principle, since for prioritization of product groups we find it more relevant to look at product eco-efficiency (impact per product price), particularly when the use stage is included, as in the consumption perspective. However, this does not mean that process eco-efficiency may not be relevant in a product-related context as, for example, demonstrated by the application of the E2-vector by Goedkoop et al. (1998), identifying eco-efficiency based options for substituting processes within a product life cycle.

Conclusion

It has been demonstrated that available data and methods are sufficient to identify, within the Danish economy, the most important product groups from the perspective of environmental policy.

The system delimitation and the ranking principles have decisive influence on the results, as well as on the policy implications, which leads to the recommendation to apply several complementary system delimitations, notably both a supply and a consumption perspective, and a ranking according to both impact intensity and total impact. By combining these perspectives and principles, it is possible to gain an in-depth understanding of the policy options.

The most important cause of uncertainty in the results stems from the rather high data aggregation level. Thus, the most important improvement on the study results would be achieved by a further disaggregation of the 138 industries and 98 consumption groups applied in this study using hybrid techniques.

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Appendix: Mathematical Expression of the Three Perspectives Applied

Based on the data for environmental exchanges (emissions, etc.), the magnitude of environmental impacts can be calculated using life cycle impact assessment methodology (e.g. Hauschild and Wenzel 1998). Let b_{ij} denote the amount of environmental exchange i by the process or industry producing product j. Let c_{ki} denote the characterization factor for the contribution of an environmental emission i to the impact category k, and n_k and w_k respectively the normalization reference (in this study the total impact for Danish production and consumption) and the weighting factor (=1, in this study), for impact category k. Then the weighted total direct environmental impact m of product j is calculated by

$$m_j = \sum_k \left(w_k \frac{\sum_i c_{ki} b_{ij}}{n_k} \right) \tag{20.1}$$

which in matrix notation becomes,

$$\mathbf{m} = \mathbf{w}\hat{\mathbf{n}}^{-1}\mathbf{CB} \tag{20.2}$$

The *supply perspective* takes the environmental intervention generated *by the Danish industries and their upstream imports* to satisfy the *Danish final demands and exports*. Let $\mathbf{B}^{\mathrm{Dk}}$ denote the environmental intervention per unit monetary production by process (industry) matrix for the industries in Denmark and $\mathbf{B}^{\mathrm{RoW}}$ the same for the rest of the world. Similarly, let $\mathbf{A}^{\mathrm{Dk}}$ and $\mathbf{A}^{\mathrm{RoW}}$ denote direct requirement coefficients matrices for Denmark and the rest of the world, respectively. Let $\mathbf{T}^{\mathrm{DR}}$ and $\mathbf{T}^{\mathrm{RD}}$ denote domestic (Danish) industry by foreign (rest of the world) industry and foreign industry by domestic industry matrix, respectively, both showing the international trade flows between the domestic and foreign industries. I.e., $\mathbf{T}^{\mathrm{DR}}$ shows inter-industry exports from Denmark to the rest of the world and $\mathbf{T}^{\mathrm{RD}}$ does that of the opposite direction. The amount of environmental impacts caused by Danish production processes throughout both domestic and foreign supply-chain is calculated by

$$\mathbf{m}^{*} = \mathbf{w}\hat{\mathbf{n}}^{-1}\mathbf{C}\left[\mathbf{B}^{\mathrm{Dk}}\ \mathbf{B}^{\mathrm{RoW}}\right]\left[\mathbf{I}-\begin{pmatrix}\mathbf{A}^{\mathrm{Dk}} & \mathbf{T}^{\mathrm{DR}}\\ \mathbf{T}^{\mathrm{RD}} & \mathbf{A}^{\mathrm{RoW}}\end{pmatrix}\right]^{-1}\begin{bmatrix}\mathrm{diag}(\mathbf{y}^{\mathrm{DDK}}+\mathbf{y}^{\mathrm{EDK}})\\ \mathbf{0}\end{bmatrix} \tag{20.3}$$

Where $\mathbf{y}^{\mathrm{DDK}}$ and $\mathbf{y}^{\mathrm{EDK}}$ denote the total final consumption of domestically produced products by Danish households and exports, respectively, and diag($\mathbf{x}$) generates a diagonal matrix out of the vector $\mathbf{x}$.

The *consumption perspective* covers the environmental interventions generated from the *domestic and foreign production processes* to satisfy the *Danish domestic final consumption* on both domestically produced and directly imported products and the environmental emission *directly generated by Danish households*. Let $\mathbf{Y}^{\mathrm{DDK}}$ denote the product by consumption category matrix for domestically produced products consumed by Danish final consumers and $\mathbf{Y}^{\mathrm{IDK}}$ that for the imports directly consumed by Danish final consumers. Let $\mathbf{E}^{\mathrm{Dk}}$ be the environmental intervention by consumption activity matrix for the direct emissions generated directly by final consumption activities in Denmark. Overall, the environmental impacts per consumption activity including direct emissions from the final consumers and considering the entire supply-chain throughout both the domestic and the foreign supply-chain is calculated by

$$\mathbf{m}^{**} = \mathbf{w}\hat{\mathbf{n}}^{-1}\mathbf{C}\left\{\left[\mathbf{B}^{\mathrm{Dk}}\ \mathbf{B}^{\mathrm{RoW}}\right]\left[\mathbf{I}-\begin{pmatrix}\mathbf{A}^{\mathrm{Dk}} & \mathbf{T}^{\mathrm{DR}}\\ \mathbf{T}^{\mathrm{RD}} & \mathbf{A}^{\mathrm{RoW}}\end{pmatrix}\right]^{-1}\begin{bmatrix}\mathbf{Y}^{\mathrm{DDK}}\\ \mathbf{Y}^{\mathrm{IDK}}\end{bmatrix}+\left[\mathbf{E}^{\mathrm{Dk}}\ \mathbf{0}\right]\right\} \tag{20.4}$$

The process perspective covers the environmental interventions generated by domestic and foreign production processes and Danish households to satisfy both Danish consumption on domestically produced and directly imported products as well as Danish exports. More importantly, now the total amount of environmental interventions generated is not attributed to the end products, but is attributed on-site to the production or final use processes that generate the environmental intervention. This is calculated by

$$\mathbf{m}^{***} = \mathrm{diag}\left(\mathbf{w}\hat{\mathbf{n}}^{-1}\mathbf{C}\left[\mathbf{B}^{\mathrm{Dk}}\ \mathbf{B}^{\mathrm{RoW}}\ \mathbf{E}^{\mathrm{Dk}}\right]\right)\left[\mathbf{I}-\begin{pmatrix}\mathbf{A}^{\mathrm{Dk}} & \mathbf{T}^{\mathrm{DR}} & \mathbf{0}\\ \mathbf{T}^{\mathrm{RD}} & \mathbf{A}^{\mathrm{RoW}} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\end{pmatrix}\right]^{-1}\begin{bmatrix}\mathbf{y}^{\mathrm{DDK}}+\mathbf{y}^{\mathrm{EDK}}\\ \mathbf{y}^{\mathrm{IDK}}\\ \mathbf{I}\end{bmatrix} \tag{20.5}$$

Chapter 21
Input-Output Equations Embedded Within Climate and Energy Policy Analysis Models

Donald A. Hanson and John A. "Skip" Laitner

In this paper we show how IO equations for sector outputs and prices are used as part of a larger policy analysis modeling system for energy and climate-related studies. The IO framework is particularly useful because it can accommodate the analysis of both price and direct program expenditure impacts. We briefly discuss the advantages of including non-price programs in any serious climate policy or sustainable energy strategy. Further, we contend that the impacts on the economy from a set of price and program expenditure polices can be seen by comparing constructed IO tables for a future year, such as 2030, with and without these polices. We present the All Modular Industry Growth Assessment (AMIGA) modeling system which has the capability to forecast future IO table values.

Introduction

Transitioning from current business-as-usual growth patterns to sustainable development paths need not imply lower standards of living. Rather, it may imply greater use of alternative resources and more efficient energy technologies. Embedded within a computable general equilibrium economic model, an input-output (IO) framework can provide the basis for analyzing the economic effects of greenhouse gas reduction policies and energy transitions. This chapter provides an overview of the methodology used to enable the use of the IO model for these applications.

The IO model can be viewed as the core of the system, providing both an accounting structure and benchmark factor intensity data. These input intensities are used in calculating the goods and services demanded and the production cost, or

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competitive price, for each sector. However, we undertake additional disaggregation of the conventional IO model in order to better represent physical energy flows and prices, energy conversion, emissions of greenhouse gases (GHG), and opportunities for end-use substitution of capital for energy and capital for direct reduction of some GHG emissions. We examine specific energy-intensive services and the technology embedded in specific capital stocks. The energy and specific capital stock modules can be thought of as providing additional underlying structure to the data normally reported in an IO table.

As we have applied the IO accounts embedded in a general equilibrium model, the future state of the economy can be represented by constructing consistent input-output tables for future years. Toward that end we have benchmarked the model to 2004 input-output accounts, energy production and consumption data, and sector GHG emissions. The economic effects of price and other policy signals are then represented by the difference between constructed future IO tables for the base and policy cases. Here in this chapter, we present some general results for energy price change impacts on sector output prices. Another paper provides scenario results as part of the Stanford University Energy Modeling Forum (Hanson and Laitner 2006). In that special issue of the *Energy Journal*, about 20 climate policy assessment models are reviewed. In this paper we use the Argonne National Laboratory's AMIGA Modeling System for illustration.

Overview of the Climate and Energy Policy Model System

Figure 21.1 shows the IO model as the centerpiece of an integrated climate and energy policy analysis model as it is applied within the AMIGA Modeling System. The IO model of the economy is the demand driver for the set of physical energy supply models. The energy conversion modules represent conventional power generation, petroleum refining, combined heat and power (CHP) or cogeneration systems, other waste heat recovery and renewable energy technologies, and hydrogen production systems. This includes the operating and variable costs for existing capacity and optimal technology choice for capacity expansion. For example, the market shares for new base-load, shoulder-load, peaking, and intermittent renewable technologies need to be selected on a least cost basis. This yields marginal and average costs to produce a kilowatt-hour (kWh) of electricity and the electric rate schedule is provided to electricity customers.

Electricity generation and production of petroleum products are major sources of GHG and other emissions. More efficient CHP and polygeneration technologies – i.e., systems which produce multiple outputs such as mechanical power or chemical feedstocks in addition to heat and power production – can reduce emissions and primary energy consumption. Petroleum refineries, for example, are major players in CHP utilization and are potential test beds for advanced polygeneration technologies that would increase overall energy conversion efficiencies. To extend the usual IO models to evaluate these technologies, the AMIGA system includes the Macro

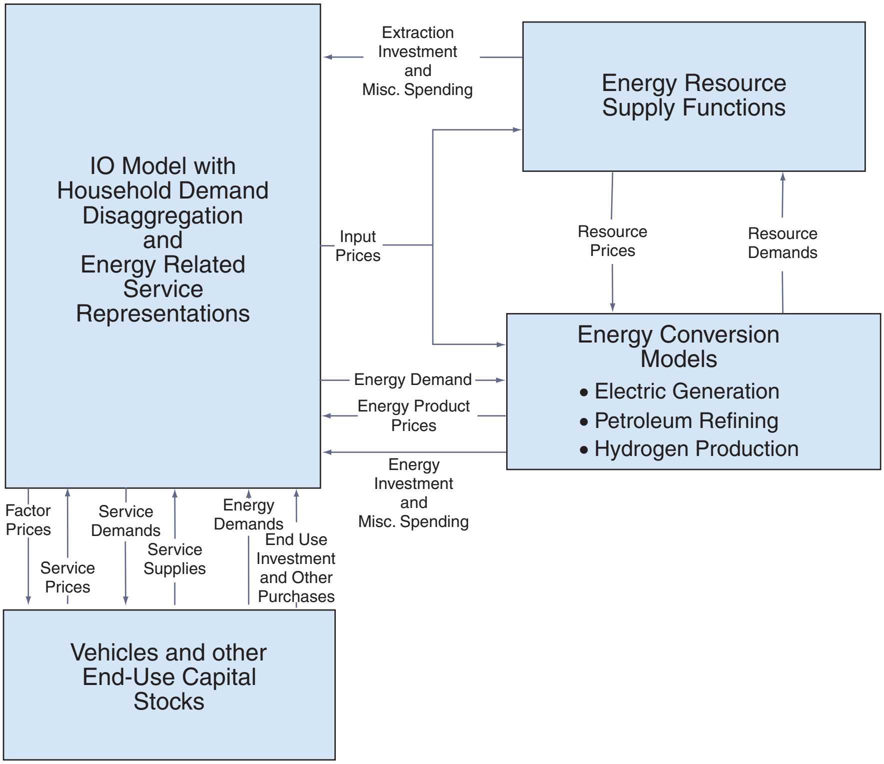

Fig. 21.1 Block Diagram of the Climate and Energy Policy Analysis System

Analysis of Refining Systems (MARS) model which provides energy investments and variable operating costs to the IO framework. Labor requirements are also provided to the IO model (Marano 2005).

Resource supply functions include natural gas and natural gas liquids; light, medium, heavy, and very heavy crude oils (by sulfur content), and coal. Natural gas and light, low sulfur crude oil sell at a premium relative to heavier, dirtier resources. The heavy, high sulfur oils also have significant cost, energy and carbon emission penalties associated with their use as refinery feedstock. The resource price gap estimated among these resource grades is based the differential costs and product yields using the profit maximization criterion.

Natural gas supply functions are central to the simulation results of the model. Gas is a premium, relatively clean fuel with many applications including use as a chemical feedstock for items ranging from plastics to fertilizers. Hence, steep gas supply functions imply rapidly rising gas prices as gas demand increases. Under a regime of higher energy prices (and/or new programs of incentives and technical assistance) other resources including energy efficiency and renewable sources are likely to substitute for natural gas. Natural gas is then allocated to its highest value use. The model currently uses simple linear gas supply functions, one for

US domestic production and one for gas imports. To represent both technological progress under normal autonomous trends, or under a regime of higher natural gas prices, AMIGA will shift these supply functions to the right over time, mainly reflecting improved offshore deep water drilling technology and unconventional gas extraction in low permeability formations. In the IO model, it is conventional to combine oil and gas drilling and extraction into a single economic sector. Again, the resource extraction investment and variable operating cost expenditures feed back into the IO model.

The full AMIGA Modeling System uses a 180-sector representation of the economy. The full model is based on the 1997 benchmark IO tables published by the Bureau of Economic Analysis (BEA 2005). A more current version has been updated using the 2004 Annual IO Tables (which are based on the 1997 benchmark table updated with more recent commodity demands and NAICS sector outputs). For this example, we aggregated the 65 sector Annual IO data to 45 sectors and split the "utilities" sector Annual IO rows and columns into electricity and natural gas.

We use six representative household consumer groups based on income and propensity to adopt new, innovative technology (market leaders and followers). Prices for purchased goods are derived by adding retail trade markups into purchased household prices. Each representative consumer has a set of demand functions for goods and services which are consistent with utility maximization under a budget constraint. We adopt the Lancaster theory of the consumer which is based on demand for household services rather than direct energy and associated durable goods purchases (Lancaster 1971). This is the household production function concept. Households purchase houses, cars, refrigerators, gasoline, home heating oil, and electricity and produce associated services such as personal transportation and comfortable houses. The advantage of implementing the Lancaster demand functions is that explicit household production functions are estimated. In this case, technological progress in a household production function, such as producing home heating comfort, can be achieved through a more efficient furnace and less natural gas consumption, but still delivering the same level of lifestyle comfort. In the AMIGA model, the incremental capital for an efficient furnace (substituting for natural gas) is considered to be a separate, specific of capital. The energy efficiencies of newly installed end-use technologies are stored in the computer to calculate annual energy consumption over the lifetime of that equipment.

Passenger vehicles and other light-duty vehicles are major consumers of petroleum products, but with great potential for improvement in energy efficiency. Characteristics of advanced vehicles and their market share elasticities are derived from Greene, Duleep, and McManus (Greene et al. 2004).

The household production functions are represented as constant elasticity of substitution (CES) functional forms. The extent to which capital substitutes for energy depends on the price of the energy carrier, such as natural gas, and the discount rate applied by that consumer group. Service prices are represented by the marginal cost to the consumer of increasing the quantity of service, and this service price is passed to the consumer demand module of the IO model, as shown in Fig. 21.1 above. In summary, energy-related services are derived from disaggregated capital stocks for vehicles and other end-use equipment by vintage. These disaggregated end-use capital stocks are an important augmentation of the IO model to construct a full climate and energy policy analysis model on the energy demand side. The resulting energy demand is passed back to the IO model. Investments in these end-use technologies (including the incremental investments to reduce energy use) are also passed back to the IO investment module.

Similarly the industry and commercial business sectors of the IO model demand energy-related services, not energy consumption for its own sake. Each IO model sector has a set of CES production functions representing the production of a variety of energy-related services (e.g. space cooling, lighting, or refrigeration). There is a great opportunity in industry to substitute cost-effective capital for energy (Ross et al. 1993; Steinmeyer 1998).

A table of commercial energy services is shown in Table 21.1. It shows a typical sensitivity analysis for the response of factor intensities to the factor price ratio. In this case, we examine the effect of a 50% price increase on the change in energy intensity for selected end-use service demands.

In this table, the *sigma* parameter governs the ease with which we might expect more energy-efficient capital to substitute for energy use. For instance, if there is a desire to provide additional space cooling, the commercial building owner might dial down the thermostat, install a more energy efficient building shell, or upgrade the efficiency of an air conditioner. The last two items provide opportunities to substitute capital for energy. These two levels are represented as a hierarchy where the output air conditioning is an input to a CES function which substitutes either building shell or air conditioning capital. Current capital-energy tradeoff isoquants are based on characterizations of existing technologies. In the case of space cooling, the technologies for air conditioning suggest an elasticity of substitution (or sigma) of

Table 21.1 Sensitivity to a 50% Increase in Relative Price Ratios with Current Technology[a]

End use demand	Sigma parameter	Percent reduction in energy intensity[a]
Commercial electricity use		
Space cooling	0.67	6.3
Lighting	0.88	15.9
Refrigeration	0.78	10.7
Other	0.94	19.3
Commercial gas use		
Space heating	0.69	8.6
Other	0.66	7.5
Commercial building shell	0.87	15.6
Light industry electricity	0.93	18.7
Light industry gas	0.76	11.5

[a]Generally, technological advance would increase the percentage reduction in energy while learning or experience would reduce the amount of capital needed to achieve a given level of energy savings.

0.67. This means that a 50% increase in the relative price ratios would be expected to reduce energy intensity by 6.3%. Under current energy prices, a $120 incremental expenditure on greater efficiency of a room air conditioner might save $17 per year. Simple payback would be about 7 years; perhaps not enough to induce the improved efficiency. But if prices rose by 50%, the payback would fall to about 4.7 years which might be enough for some building managers to make the purchase.

The CES function is shown in Appendix 1. In the literature on endogenous technical progress, the factor scaling parameters, *alpha* and *beta*, are used to represent factor biased or factor augmenting technological change (Acemoglu 2002). However, we find that technological progress for energy technology often also changes the curvature of the CES function isoquants toward a higher elasticity of substitution, *sigma*. That is, the result of technological progress is the potential to move to lower energy intensity without sharply rising capital costs (Laitner and Hanson 2006). These parameter changes can adjust endogenously over time in the AMIGA model driven by cumulative production of a new technology (learning by doing) or by higher relative energy prices, or directed R&D programs. The shifted capital-energy isoquants that represent the success of developing advanced technologies are based on extrapolating the performance of existing technologies, such as extrapolating hybrid vehicle technology performance and cost.

In the CES function, if *alpha* and *beta* are used to represent technological progress, they can be set to 1.0 in the base year. Then the *theta* and *phi* parameters can be used for base year calibration. For example, in the main value added function, which is a CES function in main capital and labor, the *theta* and *phi* can be chosen to replicate factor shares in the base year. Figure 21.3 shows a typical hierarchy of CES production functions for the AMIGA model. Table 21.2 provides parameter data based on a review of the literature (Ballard et al. 1985; Kemfert 1998).

Table 21.2 Value Added Elasticities of Substitution for Selected Sector Groups

Sector	Sigma	Rho
Agriculture	0.68	0.48
Mining	0.61	0.64
Utility services	0.41	1.44
Construction	0.52	0.92
Food processing	0.71	0.40
Clothing and apparel	0.90	0.11
Paper products	0.90	0.11
Petro chemicals	0.83	0.20
Heavy manufacturing	0.74	0.36
Light manufacturing	0.91	0.10
Transportation equipment	0.92	0.08
Transportation services	0.77	0.30
Business services	0.57	0.75
Personal services	0.51	0.96
Government	0.42	1.38

The IO Model Equations and the General Equilibrium Solution

For a given set of prices, household demands for goods and services are calculated, and least-cost factor intensities are chosen by the model for the set of CES functions, electricity generation, and other decision modes. For the CES functions, the calculated factor demands per unit output yield factor intensity coefficients. Once calculated as functions of prices, these represent input-output coefficients.

Quantities for each good and service in the model are calculated in the usual IO form for each sector that uses that commodity. That is, demand for commodity i by sector j is $a_{ij} * X_j$, where X_j is a specific sector output.

Final demands are added to intermediate demands (Table 21.5). Total demand must equal total supply from domestic sector outputs or imports. When the AMIGA model is run for the US economy alone, most traded goods and services in the model are treated as "Armington" goods (Armington 1969). That is, there is differentiation and imperfect substitution between a US produced good and a foreign produced good classified in the same sector. However, when climate policy analysis models are run in a global assessment mode, supply and demand for each commodity balances across all countries. A condition is imposed on the US to slowly move toward a sustainable current account trade deficit.

In summary, the supply and demand balance for each good is determined from a row calculation in the IO table.

The same input-output coefficients and derived factor intensities can be used to calculate the prices of goods and services produced. The price calculations are the "dual" of the quantity calculations.

$$P_j = \sum_i P_i a_{ij} + VA_j \tag{21.1}$$

where VA_j is value added given by a CES function. This price equation can be viewed as summing over the column of an IO table.

The coefficients in the model are calibrated to base year 2004 data. The final demand table in 2004 is shown in Appendix 2. These are shown as columns by convention. We also show some important production input data in Table 21.6. For each sector, this table shows the base year expenditures on electricity, natural gas, and petroleum products. It also shows total material input to each production sector and value added from labor and capital for the year 2004. These inputs to production sectors are conventionally represented as rows, but for convenience, we show them in Table 21.6 in column format.

The solution strategy for the overall model, including both the IO equations and the physical energy and specific capital stock equations, is the Gauss–Seidel method of iterative convergence. It is well known in the field of numerical methods that the Gauss–Seidel method solves faster than alternative methods for large systems problems like the type of model described here (Press and Vetterling 1992). In the neighborhood of the solution, nonlinear functions can be approximated as being linear based on the Taylor series expansion. At this point as the global solution is

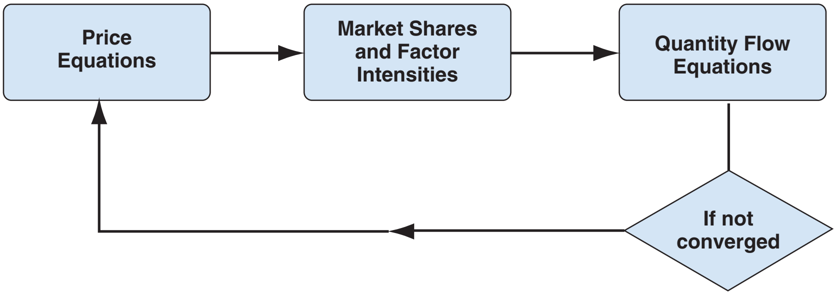

Fig. 21.2 Flow Chart of the Convergence Method

approached, the entire problem looks like a large-scale linear system which allows the algorithm to solve very quickly.

The model can be closed in different ways, but most climate policy assessments are based on smooth transitions to sustainable paths maintaining full employment. However, in an economy going through an adjustment process and not maintaining full employment, the IO model can be used to examine the economic and job creation benefits of domestic expenditures on sustainable development technologies.

The household demands are translated into purchases of goods and services to construct the consumption final demand vector. Similarly the individual types of investments with their characteristic components of equipment and construction activities are summed to construct the overall investment vector.

Figure 21.2 shows the iterative solution strategy – first solving the price equations, then the factor intensity equations, and thirdly, the supply and demand quantity equations. This loop is repeated until the entire system collapses to the general equilibrium solution.

Interpretation of Results

Here we present an experimental climate analysis in which there are both price induced effects and direct program efforts and related expenditures, such as rebates on energy efficient equipment and Energy Star standards on manufactures of energy-intensive equipment (EPA 2003). The IO model is ideally capable of analyzing both price and expenditure related policies. For these runs, government spending and exports are assumed to grow at exogenous rates. These variables are tuned to the *Annual Energy Outlook* 2006 published by the U.S. Department of Energy's Energy Information Administration (EIA 2005).

The carbon charge is assumed to begin in year 2010 so the model predicts its cumulative effects by year 2030. The carbon charge is phased-in over this period, reaching $100 per ton of carbon by year 2030. (To provide a benchmark, it takes about 400 gallons of gasoline to generate 1 t of carbon emitted into the atmosphere. Hence, if gasoline prices reflected the value of carbon at $100 per ton, the price of gasoline would be about 25 cents higher than in the reference case.)

There are a number of reasons to use non-price methods, in combination with a modest carbon charge, to induce a transition to sustainable economic development paths. High energy prices, resulting from a large carbon charge, would have negative effects on international competitiveness, inflation, income transfers and income distribution. And as we show in Hanson and Laitner (Hanson and Laitner 2004), a mix of cost-effective energy-related programs can reduce the required price signal necessary to bring about a desired emissions reduction. In effect, the programs are complementary to the market price signal.

The CES disaggregated production structure has significant effects on model behavior, compared with a conventional approach. In the conventional approach, factors are combined first. So all capital is combined into an aggregate capital index, and similarly labor, energy, and materials are combined into single aggregate factors. Then in the conventional aggregate production function approach, elasticities of substitution are specified between aggregate factors. However, the ability to reduce energy with incremental investments in specific capital (e.g., more efficient lighting systems) is much easier than substituting aggregated capital in the economy for energy reductions. Our approach of building macroeconomic results from a disaggregated production structure results in more substitution of capital for energy in specific uses, lower investment requirements to improve energy efficiency, and less sector output price impacts of a carbon tax or energy Btu tax. Specific capital substitutes directly to reduce energy use without needing as much structural adjustments in the non-energy portion of the economy.

Table 21.3 shows the effect of a $100 carbon charge on the resulting electricity, natural gas and petroleum product prices. These numbers are percentage change from the reference case prices in year 2030. Yet these fairly large percentage changes in energy prices that firms pay under a $100 carbon charge, are attenuated when passed on as increased product costs and prices. This is shown by the small percentage changes in sector output prices shown in the last column of Table 21.3. One reason for this is that the energy intensity of a sector decreases when faced with persistent higher energy costs and other non-price GHG reduction programs. This leads to only a relatively small expenditure increase on energy in these production sectors by year 2030.

Note that these price impacts are the result of a complete solution to the set of IO price equations. That is, a change in cost in one sector will propagate cost changes into all other sectors which use the first sector as an input.

Table 21.4 illustrates this point by showing energy expenditure cost shares for each sector as changes from the reference case in year 2030. By 2030, there has been 20 years to implement energy efficiency measures, with a carbon charge that was first initiated in year 2010. Due to substituting away from purchased electricity and natural gas, for most sectors the cost shares for electricity and gas decrease, but for industrial petroleum use, cost shares increase. For example, the cost share of petroleum in trucking increases notably. It is relatively difficult to substantially reduce freight-related energy consumption. Almost all sectors use freight deliveries as an input to production. So an increase in freight costs will cause some increase in sector product prices in all sectors.

Table 21.3 Price Changes from Reference (%)

Year 2030	Price electricity	Price NGas	Price oil	Product price
Farms	19.52	11.47	17.49	0.67
Forestry & related	19.52	11.47	17.49	0.23
Oil and gas	21.51	11.67	17.15	0.2
Mining, other	21.51	11.67	17.15	0.69
Mining support	21.51	11.67	17.15	0.97
Construction	19.8	11.38	16.64	0.36
Food & beverage	25.15	14.16	17.42	0.42
Apparel & mills	25.15	14.16	17.42	0.36
Paper products	25.64	14.73	19.17	0.61
Chemicals & plastic	25.64	14.73	19.17	0.67
Mineral products	25.15	14.16	17.42	0.43
Primary metals	25.64	14.73	19.17	0.51
Fabricated machines	25.15	14.16	17.42	0.28
Computer, electrical	23.67	13.86	16.95	0.19
Vehicles & parts	23.67	13.86	16.95	0.25
Other transport eq	23.67	13.86	16.95	0.23
Misc & wood	23.67	13.86	16.95	0.24
Wholesale trade	17.54	11.47	17.63	0.11
Retail trade	17.54	11.47	17.63	0.14
Air transportation	17.39	11.57	18.53	1.82
Rail transportation	17.39	11.57	18.53	0.51
Water transportation	17.39	11.57	18.53	0.62
Truck transportation	17.39	11.57	18.53	1.08
Passenger transp	17.39	11.57	18.53	0.82
Pipeline transport	17.39	11.57	18.53	1.81
Warehousing & sup	17.54	11.47	17.63	0.5
Information services	16.66	11.09	16.21	0.1
Finance & insur	16.66	11.09	16.21	0.04
Real estate	16.66	11.09	16.21	0.08
Rental and leasing	17.54	11.47	17.63	0.14
Professional service	16.66	11.09	16.21	0.09
Management	16.66	11.09	16.21	0.13
Waste management	16.66	11.09	16.21	1.19
Educational services	16.66	11.09	16.21	0.1
Health care	16.66	11.09	16.21	0.13
Recreation	16.66	11.09	16.21	0.1
Food & lodging	16.66	11.09	16.21	0.2
Other services	16.66	11.09	16.21	0.16
Federal enterprises	16.66	11.09	16.21	0.35
Federal government	16.66	11.09	16.21	0.17
State local enterp	16.66	11.09	16.21	0.72
State & local govt	16.66	11.09	16.21	0.42

Table 21.4 Expenditure Shares: Change from Reference

Year 2030	Expend electricity	Expend gas	Expend oil
Cost shares			
Farms	−0.04	0	0.23
Forestry & related	0	0	0.05
Oil and gas	0	0	0.04
Mining, other	−0.01	0	0.26
Mining support	−0.01	−0.01	0.49
Construction	0	0	0.13
Food & beverage	0.02	−0.01	0.02
Apparel & mills	0.02	0	0.01
Paper products	0.03	0	0.11
Chemicals & plastic	0.02	0	0.2
Mineral products	0.03	0	0.02
Primary metals	0.03	0	0.07
Fabricated machines	0.02	−0.01	0.03
Computer, electrical	0	0	0.01
Vehicles & parts	0.01	0	0.01
Other transport eq	0	0	0.02
Misc & wood	0.01	0	0.01
Wholesale trade	−0.01	−0.01	0.03
Retail trade	−0.04	0	0.04
Air transportation	−0.01	0	1.09
Rail transportation	−0.01	0	0.26
Water transportation	0	0	0.3
Truck transportation	−0.01	−0.01	0.54
Passenger transp	−0.01	0	0.44
Pipeline transport	−0.03	−0.02	1.04
Warehousing & sup	−0.03	−0.01	0.26
Information services	−0.01	0	0
Finance & insur	0	0	0
Real estate	−0.07	−0.01	0.01
Rental and leasing	−0.01	−0.01	0.03
Professional service	−0.02	0	0.01
Management	−0.02	−0.01	0.03
Waste management	−0.06	−0.03	0.54
Educational services	−0.02	0	0.01
Health care	−0.02	−0.01	0.01
Recreation	−0.06	0	0.01
Food & lodging	−0.08	−0.01	0.02
Other services	−0.03	−0.01	0.03
Federal enterprises	−0.01	−0.01	0.15
Federal government	−0.02	−0.01	0.04
State local enterp	−0.09	−0.04	0.28
State & local govt	−0.06	−0.02	0.17

We find that over 90% of the carbon reduction comes from energy efficiency measures (both price and program induced) and less than 10% come from structure change in the economy's mix of non-energy sector outputs. (Of course, energy production and imports can be reduced as a result of the energy efficiency measures.) Non-energy sector structural change is a result of sector product prices reflecting the total carbon embedded in the product (taking into account cost-effective energy efficiency measures). That is, the carbon charge externality price is filtered through the IO structure of the economy to capture the full embedded cost of carbon in each good and service produced in the economy. This leads to economic efficiency for a given carbon reduction (Baumol and Oates 1988).

Conclusions

In this paper we show how IO equations for sector outputs and prices are used as part of a larger policy analysis modeling system for energy and climate-related studies. The IO framework is particularly useful because it can accommodate the analysis of both price and direct program expenditure impacts. We have briefly discussed the advantages of including non-price programs in any serious climate policy or sustainable energy strategy. Further, we contend that the impacts on the economy from a set of price and program expenditure polices can be seen by comparing constructed IO tables for a future year, such as 2030, with and without polices.

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Appendix 1: CES Production Structure

The Constant Elasticity of Substitution (CES) production function can be written in the form:

$$Q = A(\theta(K/\alpha)^{-\rho} + \phi(E/\beta)^{-\rho})^{-1/\rho} \tag{A1.1}$$

where the elasticity of substitution, sigma, is expressed in terms of *rho* as:

$$\sigma = 1/(1 + \rho) \tag{A1.2}$$

Given factor prices p_K and p_E, the cost of factor inputs, K and E, is given by

$$costs = p_K K + p_E E \tag{A1.3}$$

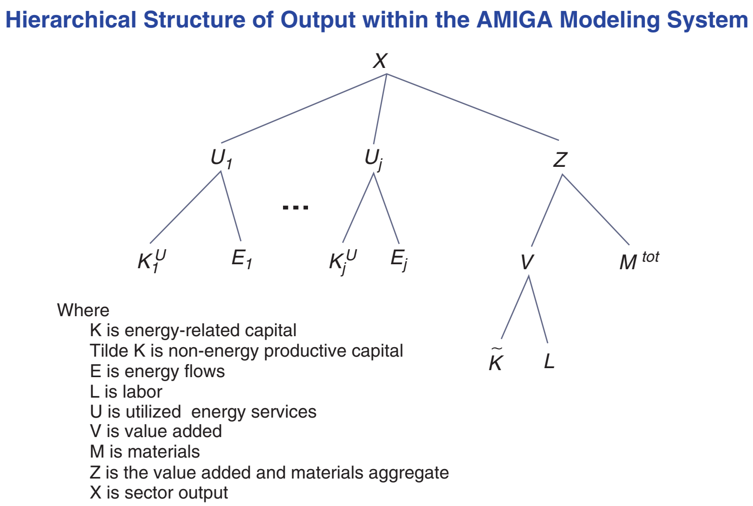

Fig. 21.3 Typical Hierarchy in CES Production Structure

K and E are chosen to minimize costs for a given output, Q, and given parameters A, θ, ϕ, α, and β. A closed form solution exists for the factor demand equations:

$$E = \beta^{1-\sigma}(\phi/p_E)^{\sigma} D^{1/\rho} Q/A \tag{A1.4}$$

$$K = \alpha^{1-\sigma}(\theta/p_K)^{\sigma} D^{1/\rho} Q/A \tag{A1.5}$$

where we define the function D as

$$D = \theta^{\sigma}(\alpha p_K)^{1-\sigma} + \phi^{\sigma}(\beta p_E)^{1-\sigma} \tag{A1.6}$$

We use parameters θ and ϕ for base-year calibration and parameters α and β to capture technological change time trends. Isoquants are defined as the graph of K versus E for a given output Q. Isoquants may be constructed using the factor demand equations for different factor price ratios (Varian and Yohe 1992).

Appendix 2: Base Year 2004 IO Data Tables

Table 21.5 Final Demands and Total Intermediate Demands by Sector, 2004

AIO Data Millions 2004$	TotInterm	Consump	Invest	Govt	Exports	Imports	Total_FD
Farms	20,1242	41,965	0	−1,830	24,010	16,169	48,989
Forestry	70,256	6,962	0	0	4,192	11,844	−506
Oil and gas	331,620	0	0	1,204	2,352	165,458	−158,509
Mining, other	49,056	113	39	0	3,544	994	5,543
Mining suppt.	5,113	0	56,455	0	0	0	56,515
Electric util.	171,860	136,225	0	0	544	1,438	138,207
Gas util.	63,338	69,011	0	0	510	0	69,521
Construction	133,140	0	806,138	227,452	69	0	1,033,659
Food & bev.	239,421	415,419	0	1,232	29,028	51,005	399,901
Apprl. & mills	62,474	162,595	3,828	34	14,944	132,800	51,486
Paper prod	142,664	19,072	0	0	13,290	22,144	12,755
Petrlm. prod	222,067	124,608	0	0	14,540	42,503	102,501
Chem. & plstc.	534,830	215,860	1,680	172	102,776	157,368	176,222
Mineral prod	103,884	6,002	0	0	5,386	18,581	−5,306
Prim metals	202,910	855	0	0	14,617	55,483	−28,181
Fabrctd. mach	366,525	18,306	161,389	11,497	92,412	126,672	171,555
Comp, elect	312,120	91,308	191,696	32,532	127,464	273,762	176,948
Vehicls & pts	218,501	231,434	160,532	15,278	66,932	208,418	269,438
Othr. Trans eq.	67,289	17,203	31,699	28,942	56,292	30,094	106,049
Misc & wood	203,675	123,458	68,699	9,184	26,936	118,918	117,161
Wholesle. Trd.	483,743	318,111	87,658	9,908	77,943	−23,265	528,238
Retail trade	133,597	959,430	45,868	0	1	0	1,005,299
Air trans	55,096	66,841	1,453	215	27,483	23,380	72,711
Rail trans	33,059	6,162	1,654	39	5,412	248	14,226
Water trans	5,509	9,562	14	−3	8,708	−8,334	26,746
Truck trans	154,216	45,822	9,487	760	18,458	2,485	74,251

(continued)

Table 21.5 (continued)

AIO Data Millions 2004$	TotInterm	Consump	Invest	Govt	Exports	Imports	Total_FD
Pass trans	18,249	19,587	0	0	0	0	19,587
Pipeline trans	30,890	689	0	0	838	0	2,089
Warehs. &sup	132,291	5,938	0	0	9,454	−4,616	20,008
Info services	634,619	297,533	57,648	7,917	27,775	6,522	386,969
Financ. & insur.	826,414	652,692	0	0	36,864	30,129	659,426
Real estate	547,587	1,160,512	98,021	0	834	0	1,259,367
Rent & lease	187,804	57,233	0	0	54,530	227	111,536
Prof service	1,063,696	134,251	36,298	0	17,754	8,927	179,375
Management	838,026	32,166	131,149	25,173	54,010	2,227	240,271
Waste mgmt	52,015	12,500	0	0	47	25	12,522
Edu. services	35,420	195,937	0	0	755	377	196,315
Health care	27,680	1,414,700	0	0	27	23	1,414,704
Recreation	52,814	161,408	0	0	217	167	161,458
Food & lodge	137,221	498,834	0	0	588	0	499,421
Othr. services	216,992	420,966	0	0	182	2,067	419,126
Fed enterp.	61,979	10,316	0	0	256	0	10,573
Federal govt.	0	0	0	727,351	0	0	727,351
St. & Lcl. entrp.	12,793	42,944	0	0	0	0	42,944
St. & Lcl. Govt.	0	0	0	1,119,572	0	0	1,119,572
Ncmpr. impts.	133,990	60,219	−308	0	0	193,901	−133,990
Scrap, used	34,133	48,118	−78,454	266	10,483	7,865	−23,230
Rest wrld. adj.	0	−98,570	0	−976	99,616	70	0
Inven. val. adj.	0	0	0	0	0	0	−53,650
Total inputs	9,611,761	8,214,296	1,872,643	2,215,919	1,052,072	1,676,077	11,734,285

Table 21.6 Total Industry Output, Materials Input, Energy Use, and Value Added by Sector, 2004

AIO Data Millions 2004$	Elect. use	NGas	Petroleum	Materials	VA	TIO
Farms	5,085	455	7,739	132,496	112,230	258,005
Forestry	55	83	447	30,887	29,647	61,118
Oil and gas	1,178	22	1,080	71,889	115,510	189,679
Mining, other	954	31	1,978	21,626	30,910	55,499
Mining suppt.	277	153	4,098	30,896	25,725	61,149
Electric util.	53	72	1,768	65,014	184,446	251,353
Gas util.	44	2	269	63,979	39,344	103,638
Construction	2,446	842	21,315	557,083	585,113	1,166,800
Food & bev.	4,460	4,363	1,376	458,197	170,573	638,969
Apprl. & mills	1,158	634	204	73,835	40,431	116,261
Paper prod.	1,986	2,147	1,927	102,612	48,678	157,351
Petrlm. prod.	1,487	2,327	30,022	250,734	37,130	321,700
Chem. & plstc.	6,902	3,892	15,193	411,354	249,386	686,728
Mineral prod	1,186	1,531	350	46,473	49,230	98,770
Prim metals	2,273	1,151	1,355	113,470	53,276	171,526
Fabrctd. mach.	3,660	1,615	1,875	318,514	213,923	539,587
Comp., elect.	2,588	656	521	309,595	172,494	485,853
Vehicls. & pts.	1,373	594	545	372,812	118,939	494,262
Othr. trans. eq.	678	230	616	106,512	66,323	174,359

(continued)

Table 21.6 (continued)

AIO Data Millions 2004$	Elect. use	NGas	Petroleum	Materials	VA	TIO
Misc. & wood	1,880	719	765	186,501	136,842	326,708
Wholesle. trd.	4,559	1,837	3,970	287,859	713,677	1,011,902
Retail trade	12,708	1,830	6,230	352,659	760,852	1,134,279
Air trans.	167	14	15,926	52,903	53,257	122,267
Rail trans.	30	1	1,395	17,984	26,618	46,028
Water trans.	41	17	1,134	22,828	7,897	31,917
Truck trans.	310	196	14,343	106,411	104,616	225,876
Pass trans.	51	9	1,484	9,704	16,705	27,952
Pipeline trans.	226	333	4,058	15,103	13,259	32,979
Warehs. & sup.	1,424	462	5,074	35,253	112,204	154,418
Info. services	4,285	1,423	1,323	593,490	558,218	1,158,738
Financ. & insur.	2,848	261	567	602,706	901,151	1,507,533
Real estate	31,150	7,410	1,954	378,138	1,370,100	1,788,753
Rent & lease	1,248	237	1,083	120,547	145,339	268,454
Prof. service	5,256	1,290	1,074	441,647	645,409	1,094,676
Management	6,761	1,954	4,600	346,681	707,034	1,067,029
Waste mgmt.	903.4	655.6	4,815	24,230	30,247	59,292
Edu. services	599	343	376	58,834	983,48	158,500
Health care	7,847	2,519	3,321	479,217	791,155	1,284,059
Recreation	2,626	382	332	67,539	118,429	189,308
Food & lodge	11,178	3,571	1,740	286,571	310,390	613,450
Othr. services	5,352	2,213	2,346	274,432	348,557	634,458
Fed enterp.	100	359	1,948	−28,622	67,703	88,456
Federal govt.	4,044	1,114	5,364	320,546	405,768	731,677
St & Lcl. entrp.	4,500	2,640	7,913	101,689	75,942	185,544
St & Lcl. govt.	23,923	10,748	36,253	461,723	924,910	1,422,886
Totals	171,860	63,338	222,067	9,154,496	11,734,285	21,399,746

Part VI
Energy and Climate Change

Chapter 22
Application of the IO Methodology to the Energy and Environmental Analysis of a Regional Context

Fulvio Ardent, Marco Beccali, and Maurizio Cellura

Introduction

Aims of the Study

Performing an energy and environmental analysis, researchers have to face many problems regarding the data quality and availability. Data are often out-of-date, not representative and consistent or, frequently, referred to faraway geographic and productive contexts. The Input-Output (IO) model, due to its simplicity, allows to acquire information regarding the energy and environmental performances of productive sectors.

The present paper describes an application of the energy and environmental IO based model to a regional context: the case study of Sicily (Italy). The main aims of the study are:

- *To investigate the advantage/disadvantages of IO approach*
- *To evaluate the possibility of employing the IO model as a tool to support regional strategies*
- *To employ the results as a basis for further environmental analysis (i.e. as support to regional studies of Life Cycle Assessment - LCA)*

The study also focused the attention on the limits of such approach and the problems arisen in the showed application. A sensitivity analysis of the method and of available data has been performed.

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

The IO approach can be employed to continuously monitor the environmental evolution of productive sectors and to assess if and how an economy is moving towards a trend of sustainability. Following the Kyoto protocol agreements, Italy should decrease its CO_2 emissions of about 6% till 2012. An IO based environmental model can support stakeholders to individuate the sectors with the higher margin of environmental improvement, to monitor their emission trends and to evaluate the efficacy of energy and environmental policies.

Input-Output Model

The economic IO analysis, developed by W.W. Leontief, studies the relations between economic sectors (Leontief 1941, 1966). Since Leontief's first publications, hundreds of books and papers on IO analysis have been published. A state-of-the-art overview is given by Miller and Blair (1985), Sohn (1986), Rose and Miernyk (1989).

The IO method assumes that the economy structure of a country can be represented by the following economic subjects:

- Industries or sectors that produce goods and services
- Household sector that demands private consumer goods
- Government sector that demands public consumer goods
- Foreign trade sector that demands exports and supplies imports

The sum of the above demands represents the sector of the final demand. Outputs of an industry may be employed by that industry itself, to be sold to other industries, which uses those as inputs for the production process, or to the final demand sector.

The input-output table is the starting point of an IO analysis. Such table is a description, in terms of monetary exchanges, of the flows of goods and services through the sectors of the examined economy. Usually it refers to a 1-year period (Wilting 1996). As known, the IO table is necessarily square and consists of three major sections (Camagni 1993; Schachter 1988):

- The core of the table is the matrix of intermediate flows. It describes the selling (by rows) and the purchasing (by columns) flows among the n productive sectors.
- In the second section, a series of columns represent the industry deliveries to the final demand (private and public consumptions, investments, supplies and exports).
- The third section completes the matrix with the rows that represent the payments to the productive factors (value added), the imports and the taxes, interpreted as purchasing.

The generic element X_{ij} of intermediate flows represents the quantity of input of sector i needed to produce the output of sector j. In monetary term, it is possible to evaluate by row in monetary term, the quantity of output that sector i sells to itself, to other industries j and to the final demand. It is also possible to evaluate by column the quantity of input that sector j purchases by other sectors, including productive factors (land, labor, capital) to manufacture the final output.

If the IO table is balanced the total input will equal the total output for production sectors. That represents the general constraint of the IO table where the sum per column has to equal the sum per row.

The main equation of the IO method is the following:

$$X = (I - A)^{-1} \cdot y \tag{22.1}$$

where A is the technology matrix, I is the unit matrix, y is the vector of final demand and X is the vector of total outputs. The matrix $(\mathrm{I} - \mathrm{A})^{-1}$ is generally known as Leontief inverse matrix.

The assumptions of IO framework involve many limitations. These are briefly described in the following (OECD 1998):

(a) *Input-output analysis assumes constant returns to scale*. The model assumes that the same relative mix of inputs will be used by an industry to create output, regardless to the quantity produced. It implies that:

    1. *Technical coefficients are assumed to be constant*. The amount of input necessary to produce one unit of certain output is assumed to be constant. Hence, the amount of input purchased by a sector is exclusively based on the level of output desired; no consideration regarding the price effects, changes in technology or economies of scale is developed.
    2. *Input-output analysis assumes linear production functions*. The input-output process assumes that if the output level of an industry changes, the input requirements will change in a proportional way.

(b) *It is supposed that each sector produces only one product.*
(c) *There are not resource's constrains*. Supply is assumed infinite and perfectly elastic.
(d) *Local resources are efficiently employed*. There is no underemployment of resources.
(e) *Actuality of input-output data*. There is a long time lag between the collection of data and the availability of the input-output tables.

Extension of IO Analysis to Energy and Environmental Applications

From the 1970s to nowadays many authors have investigated the extension of the IO model to environmental issues nowadays (Wright 1974; Bullard and Herendeen 1975; Miller and Blair 1985; Wilting 1996; Cruz 2002).

The main aim of the IO energy analysis is the calculation of energy intensities (Wilting 1996). The energy intensity of an economic sector gives the total amount of energy, both direct and indirect, that is needed for one financial unit of production of that sector.

The direct energy use of an economic sector comprises the energy directly used in the production process of that sector. The indirect energy use includes all the energy that is needed for the production and delivery of goods and services that are used in the production process.

The IO analysis applied to the energy system relates the energy flows with the economic flows, assigning to each sector the corresponding quantity of indirect energy consumption induced by its use of goods or services. In order to evaluate the overall energy consumption, all the energy quantities are valued as primary,[1] according also to the methodology usually applied in the redaction of life cycle inventory (ISO 14040 1998).

Worth of note are some "hybrid" models, where the results of the IO analysis are employed to support studies of LCA (Treloar 1996; Lenzen 2001). Such models allow to benefit of advantages of both IO model and traditional process analysis.

The Energy Analysis Model

The energy analysis of an economic system has been performed employing the mathematical relationships introduced by Gay and Proops (1993), Wilting (1996) and Cruz (2002).[2] The resulting model assumes that the used fossil fuel can be split into the energy directly demanded by household consumers (for lighting, heating/cooling, transport, etc.), and the energy (directly and indirectly) demanded by industrial and agricultural producers of goods (Proops 1988). The former is designated as 'direct consumption demand' and the latter (direct plus indirect) as 'production demand' (Cruz 2002).

The energy model assumes that the energy, via the intermediate deliveries, is attributed to the final demand (Wilting 1996).

The total energy consumption is calculated by means of *specific consumption coefficients* that represent the quantity of primary energy used by a generic sector per unit of total output.[3] Being that every fossil fuel has different emission factors, energy sources have to be handled separately. It is possible to use as many *consumption coefficients* as the number of employed energy sources.

Energy intensities are so calculated by means of the Leontief inverse matrix and the primary energy consumption of sectors, as following:

$$E = C \cdot (I - A)^{-1} \tag{22.2}$$

[1] The energy content of energy carriers that have not yet been subjected to any conversion is defined "primary energy" (VDI 1997].

[2] A detailed description of the energy IO model is presented by Cruz in the Chapter "Application of IO Energy Analysis".

[3] Consumption coefficients can be easily obtained dividing the direct energy requirements of a sector by the total sector outputs. Direct energy requirements are generally derived from national energy balances.

where E is the vector of energy intensities, C is the matrix of the consumption coefficients and I and A are the above mentioned matrixes (see Equation (22.1)). The number of rows and columns of matrix C is equal, respectively, to the number of the economic sectors and the considered energy sources.

A critical matter is the management of secondary energy sources. They have to be transformed into primary quantities by means of specific conversion factors that represent the energy necessary to deliver the energy sources to the end-user. In particular, electricity should be express as sum of the energy sources that have produced it, following the national electricity production mix.

Limits and Assumptions of the Energy Model

It has been underlined that one of the basic assumptions of the IO analysis is the price uniformity. It means that all production sectors and the final demand sectors pay the same price for all deliveries from a generic sector. Since, in practice, this is not the case of the energy sector, the deliveries from the energy sectors, in monetary terms, do not correspond to the physical deliveries (Wilting 1996).

To solve this problem some authors have suggested an hybrid IO model in which the deliveries of the energy sectors are given in physical units and the deliveries of the non-energy sectors in monetary units (Bullard and Herendeen 1975; Miller and Blair 1985). However this method requires a detailed IO table with a low aggregation of sectors.

Furthermore, the model allows to calculate an average value of energy intensity of sectors. These data are strongly aggregated and, consequently, they have a low usefulness for a detailed environmental analysis.[4]

The Environmental Analysis Model

Analogously to the energy analysis, the environmental analysis aims to assess the environmental effects due to the production of each sector. In particular, such analysis focuses on the main air pollutants arisen from the use of fossil fuels. The proportionality between production, use of energy sources and released pollutants is assumed by means of specific emission factors.

We point out that the fuel stocks are not entirely burnt for energy production (with consequent release of emissions) but a percentage of them is employed for non-energy uses (as feedstock). These fuel quantities shall be not considered in the emission calculation.

Some limits affect the environmental model. For instance, other emission sources due to production processes should be included (i.e. emissions released during

[4] In fact, following the eco-design approach, more than an average sector indicator it is important the availability of detailed information regarding every component and life cycle step of the product.

processes like cement production, welding, etc.). These contributions are usually neglected because a lack of information about the regional productive system.

Another weak point is revealed when the study aims to estimate the effective emissions related to the domestic demand. In this case the country's emissions related to exports should not be considered as far as the emissions taking place in foreign countries, but resulting from the production of the country's imports, should be added on (Gay and Proops 1993). The study of CO_2 emissions due to imports is very difficult to assess. In fact, the calculation of the energy intensities should include the energy embodied into imports, valued on the basis of the IO tables of the countries from which imports are acquired.

The Case Study: IO Analysis Applied to the Sicilian Regional Context

An energy and environmental balance of the economy system of the Sicily region through the application of the IO analysis is now presented. Energy intensities and specific environmental impacts per unit of economic output have been calculated. Comparing the results of different years it is possible to state the trend of the energy and environmental efficiency of each sector and to assess if the regional economy is moving towards sustainable development or not.

The employed model is that previously described in paragraph 2. Actually, the analysis of a region does not methodologically differ from applications to a wider national context. The peculiarities of such application to the regional context are related to the structure of a regional economy, characterised by a restricted number of dominant sectors and by problems related to data quality as: aged data, aggregated data and discrepancies between energy and economic statistics.

The IO table, referred to the Sicilian regional context, has been performed by Schachter (Schachter et al. 1985). The table has been updated through the RAS (Reiterative Assessment System) methodology.[5] This is a technique frequently used to update the IO table when national income data (such value added and final demand) are available in spite of an absence of information on the processing sector.

The energy data are referred to the "energy regional informative system" performed by the ENEA (Italian National Agency for the Energy and the Environment) (ENEA 1989–1996). Table 22.1 shows the regional energy balance. Energy consumptions grew from 1989 to 1992, returning in 1995, after an economic crisis, to the levels of 1989. It is possible to observe a reduction of the coal use during this time step; renewable energy sources were more than doubled but represented however less than 1% of the overall energy requirement.

[5] The RAS method is an iterative bi-proportional normalisation of rows and columns that spreads the errors between the theoretical and unknown marginal vectors when the structure of flows (the direct requirement coefficient matrix) is available (Schachter 1988). This technique permits to approximate the input output coefficients for an updated IO table by estimating the comparative data of value added and final demand applied to the base year.

Table 22.1 Regional Energy Balance

Year	Energy sources (10^3 TJ)				Total
	Coal	Oil	Gas	Renewable sources	
1989	2.8	541.1	89.5	1.6	635.0
1992	3.5	633.2	81.4	3.8	721.9
1995	2.0	542.2	88.1	5.8	638.0

Economic and energy data have been inserted respectively into the matrix A (the matrix of technical coefficients) and C (the matrix of specific consumption coefficients). In our case study, oil, natural gas, coal and renewable energy sources have been considered.

The IO analysis is a useful tool to state the variations of energy and environmental impacts. Results are as much detailed as more sectors are included. However, the regional economy has been subdivided in 15 sectors contrarily to the initial 17-sectors structure.[6] Analogously, energy sectors have been aggregated into 15 sectors. These modifications have been necessary in order to adapt the dimension of the economic matrix to the energy one.[7] In detail, Table 22.2 shows the correspondence between economic and energy sectors.

Some problems arise with the "energy sector" because, due to the low detail into IO table, it was not possible to state exactly what activities were included. The consequent uncertainty causes a not perfect correspondence between economic flows and their related energy consumption.[8]

The next step is the analysis of primary and secondary energy sources. The energy consumption of each sector has been converted into primary energy by means of conversion factors. We have estimate direct and indirect consumption of each sector. This procedural choice allows to respect the effective consumptions of each sector, congruously to the regional energy balance.[9] We remark that, due to the aggregations of sectors in the IO tables, it was not possible to build a *hybrid* matrix (see paragraph 2.1.1).

[6] In the energy balances, petrochemistry sector is separately managed but there is not an equivalent sector into economic tables. For this reason, petrochemistry industry has been aggregated to the "energy" sector. Furthermore, agriculture and fishing has been jointly managed in the analysis.

[7] In Italy, the National Energy Balance and the IO table are not harmonised. It means that the sectors considered into the energy balance do no fit with sectors included in the economic tables. This circumstance forces the researchers to aggregate sectors in order to respect a correspondence between energy and economic data. This procedure represents a limit of the study, because the aggregation causes an irreversible loss of information.

[8] This uncertainty can affect the reliability of results. A deep sensitivity analysis has been developed to assess the influence of the factors of uncertainty.

[9] An alternative procedure supposes to entirely assign the energy consumption for electricity generation to the "energy" sector. Successively the IO model provides to ascribe the energy consumption to all the other sectors. This alternative has been checked in paragraph 4.2.

Table 22.2 Correspondence Between Economic and Energy Sectors

No	Final denomination	Denomination into regional IO table	Denomination into the energy balance
1	Agriculture and fishing	Agriculture, tobacco	Agriculture Fishing
2	Energy sector	Energy sector	Extractive industry, petrochemistry
3	Metal industries	Metal industries	Metal industries
4	Non metallic mineral industries	Non metallic mineral industries	Glass and ceramic Construction materials
5	Chemical and pharmaceutical industry	Chemical and pharmaceutical industry	Chemical industry
6	Engineering industry	Metal works, machinery, electric materials	Metallurgy
7	Mechanic industry	Motorvehicle, transportation equipment	Mechanic industry
8	Agro-industrial products	Meat, dairy, other foods, beverages	Agro-industrial products
9	Textile products	Textile and clothing, leather	Textile products
10	Paper products	Paper	Paper products
11	Other industries	Wood products, rubber, Other products	Wood products, plastic products, rubber products, Jewels
12	Constructions and public works	Constructions	Constructions and public works
13	Tertiary	Hotel and restaurant, trade Credit and insurance Miscellaneous services	Services
14	Transports	Transports and communications	Transports
15	Local authorities and not saleable services	Government, public health and education, household services	Local authorities

Particular attention needs the electricity production. Figure 22.1 shows the regional energy mix of 1992. The efficiency of electricity production can be calculated as:

$$\eta = \frac{E_{Production}}{E_{Primary}} \tag{22.3}$$

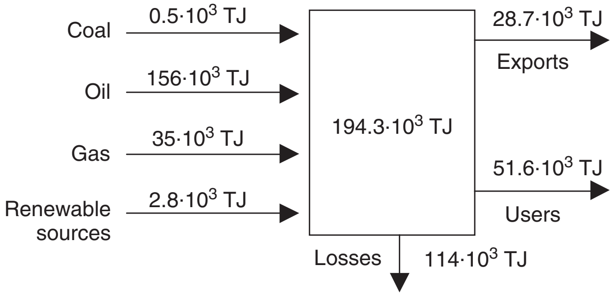

Fig. 22.1 Production of Electricity – Regional Production Mix in 1992

or, analogously:

$$\lambda_{el.} = \frac{1}{\eta} = \frac{E_{Primary}}{E_{Production}} \tag{22.4}$$

where:

- $E_{Production}$ is the total energy production, inclusive of the internal demand and exportations.
- $E_{Primary}$ is the total primary energy consumption.

The term "$\lambda_{el.}$" represents the conversion factor of electricity from "*end*" to "*primary energy*". For example, in the 1992 the two previous indexes resulted: $\eta = 0.41$ and $\lambda_{el.} = 2.42$. It means that the use of 1 MJ of electricity causes the consumption of 2.42 MJ of primary energy.[10] Analogous conversion factors have been calculated for the other energy sources.

The environmental analysis is based on the specific CO_2-emission factor "e_j" (Table 22.3). They have been calculated on the basis of data from IPCC (Intergovernmental Panel on Climate Change) (IPCC 1996). The largest emission factor is related to the coal use, the lowest to the natural gas. Renewable energy sources have not been included in the CO_2 emission calculation. Although these sources have not generally direct CO_2 emissions related to their use,[11] the emissions released during the entire life cycle of the plants should be added. Being the use of renewable sources in our case study very small, their contribution to CO_2 balance is negligible.

[10] We recall that the conversion factors are not constant but yearly change yearly referring to mix of the electricity production.

[11] Actually, the combustion of the biomass causes the production of CO_2. Being that biomasses absorb carbon dioxide from atmosphere when alive, we can consider null the global CO_2 balance throughout the life cycle. However, the combustion of biomasses shall be included into the evaluation of other air pollutants as NO_x, SO_x, particulates, etc.

Table 22.3 Emission Factors ($103\,kgCO_2/TJ$)

Coal	Oil	Gas
94.6	73.3	56.1

The Energy Analysis

The economic and the energy data have been used to fill the matrixes of the IO model. The first step has been the calculation of the energy intensities regarding each economic sector of Table 22.2. The variation of the yearly energy intensities can represent a useful tool to assess the energy trend of economic sectors. In fact, we can assess if the production of one monetary unit would involve a growing or decreasing energy consumption.[12]

Figure 22.2 shows the results referred to the production during the three investigated years. All the quantities are expressed as GJ per thousands of euro. We can observe that:

- The highest energy intensity is related to the "energy sector". It means that energy products involve the highest specific energy consumption. This primacy is not modified during the years. "Transport" and "non metallic mineral" sectors show large specific energy consumptions.
- The analysis points out a general decreasing trend of energy intensities.[13] Highest reductions have interested, "energy sector" (−39%), "non-metallic mineral" (−34.2%) and "local authorities" (−33.5%). An opposite trend characterises other sectors as "agriculture and fishing", "mechanic industry" and "agro-industrial products".
- Extremely variable is the incidence of direct and indirect consumptions. Direct consumption is dominant into "energy", "transports", "metal industries" and "non metallic mineral industries" sectors, with a percentage incidence from 51.8% to 70.5%. On the contrary, "textile products", "constructions" and "paper products" have a direct rate equal to $5 \div 10\%$ of the overall consumption.
- Direct and indirect ratios have small variations during the years.

Results of Fig. 22.2 confirm the trend of regional energy data. In fact, the large reduction of energy intensities can be ascribed to a general improvement of the "energy" sector. The efficiency of the electricity production grew from 39.1% in 1989 to 40.6% in 1995, thanks to economic investments in the sector to gradually substitute solid and liquid fossil fuels with natural gas and renewable sources. Furthermore, due to the increase of the costs of energy products, the "energy" sector raised its economic outputs with a significant decrease of the energy intensity of its products. That decrease had also a positive effect on the reduction of energy intensities of all the other sectors.

[12] Comments are subject to the previously investigated methodological limits.

[13] Variations valued in 1995 respect to 1989.

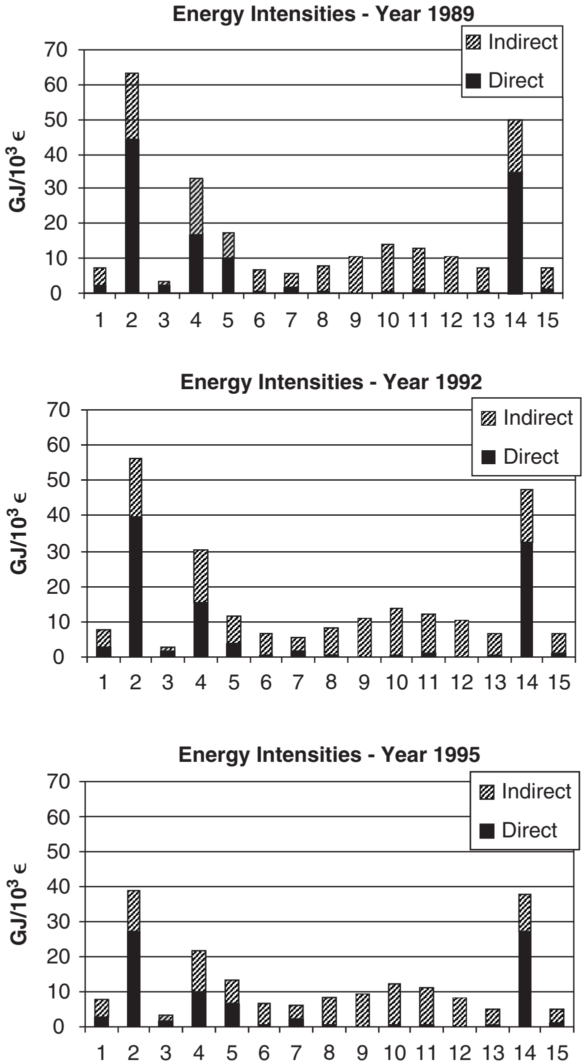

Fig. 22.2 Energy Intensities – Yearly Trend per Sector

A global picture of the regional economy is described by the energy consumptions per sector. Table 22.4 shows that the "energy" and "tertiary" sectors have the largest consumptions; "metal industries", "paper" and "non metallic mineral" industries have a very small incidence into the regional energy balance.

It is also worth noting that the highest yearly energy consumption is related to 1992. In the following period, after an economic crisis, the energy consumption decreased, returning in 1995 to the levels of 1989. The detail about energy sources (Table 22.4) shows that oil is the most important fuel, followed by natural gas; small quantities of solid fuels and renewable sources have been employed. The energy

Table 22.4 Total Energy Consumption of Productive Sectors per Energy Sources (1992)

Sector	Energy source (10^3 T)			
	Coal	Oil	Gas	Renewable
1	–	8.3	0.7	0.03
2	0.3	144.3	24.9	2.0
3	–	0.02	0.03	0.0001
4	0.3	3.9	0.5	0.02
5	–	8.6	5.2	0.04
6	–	15.6	2.3	0.06
7	–	8.1	1.4	0.05
8	–	29.3	3.4	0.12
9	–	25.4	3.02	0.088
10	–	4.1	0.5	0.015
11	–	13.2	1.8	0.05
12	–	51.1	5.8	0.19
13	–	113.2	13.3	0.5
14	–	75.3	2.2	0.08
15	–	75.9	8.9	0.4
Total	0.6	576.4	74.0	3.6

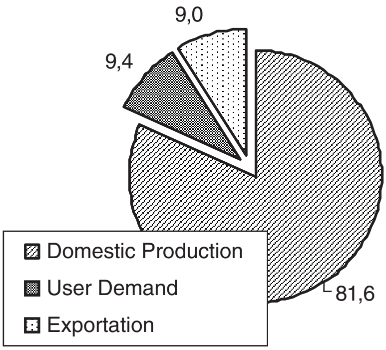

Fig. 22.3 Energy Consumption Detail – 1992

employed by productive sectors has to be added to the energy directly consumed by citizens, mainly as electricity and other secondary energy sources (in 1992 that request amounted 68.2 10^3 TJ).

Further details in the energy analysis can be obtained splitting the total final demand in three segments: consumption for the domestic production, energy necessary to satisfy the user demand and the energy demand for exports. Figure 22.3 shows that, in the 1992, the largest amount of the consumption has been related to the production for the domestic demand (81.6%), while the remaining ratio is subdivided between user demand (9.4%) and the production for the exports (9%). These percentages did not change sensibly during the observed years.

The export demand is particularly significant into the "metal industries" (36.4% of the consumption is employed for exports), "energy sector" (22% for exports) "non metallic mineral" (21.5% for exports) and into the "chemical sector" (16.9% for exports). These results agree with the industrial regional structure, where the exports involve mainly energy and chemical products. The "construction" and "local authorities" sectors do not have exports.

We remark that the estimated energy intensities are average values not totally representative of all the products enclosed into a sector. The structure of the regional IO table is strongly aggregated and, consequently, the low detail of results does not allow their employment for regional studies of LCA. Consequently, it was not possible to apply the "hybrid" energy analysis method (see paragraph 2).

The Environmental Analysis

Starting from the results of the energy analysis, the airborne pollutants released by each sector have been calculated. Figure 22.4 shows the CO_2 emission intensities that represent the total amount of carbon dioxide released by each sector to produce one financial unit (expressed as $10^3\ kg_{CO2}$ per thousands of euro). There is an obvious correlation between energy and emission intensities. However, differences between results of Figs. 22.2 and 22.4 are due to the "non-energy use" of energy sources (feedstock[14]).

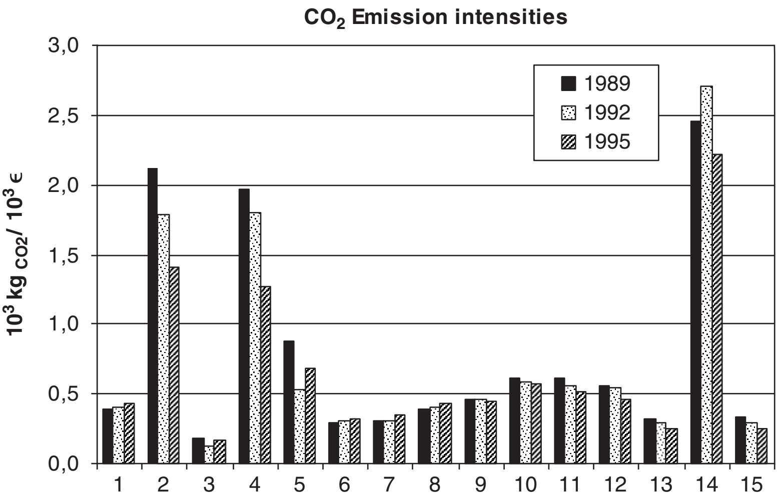

Fig. 22.4 CO_2 Emission Intensities

[14] For further detail about feedstock energy see paragraph 4.2.

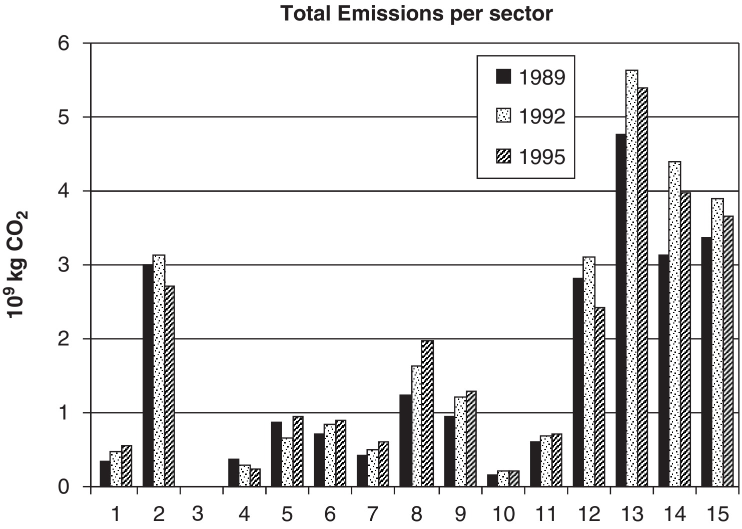

Fig. 22.5 CO_2 Emissions per Sector Due to the Domestic Demand

By this way, it is possible to observe a general decreasing trend of CO_2 intensities through years. From 1989 to 1995, the most remarkable variations have interested the "energy" sector, "non-metallic mineral" and "chemical" industries, showing similar decreasing rates as observed for the energy intensities. Figure 22.5 shows the total CO_2-emissions per sector.

The economic sectors have generally registered an increment of total CO_2 releases in spite of the reduction of the CO_2 intensities. Remarkable increments have interested "agriculture and fishing", "mechanic", "agro-industrial" and "transport" sectors, +61.8%, +58.8%, +44.6% and +27% respectively. More than 60% of the regional CO_2 emissions are ascribable to "tertiary", "transports", "local authorities" and "energy" sectors. Contribution of "metal industries" is negligible.

We point out that in 1992 many sectors had a large increase of CO_2 emissions, but this trend has been successively inverted due to a regional economic crisis.

The yearly carbon dioxide emissions for the domestic demand changed from the amount of $22.7 \times 10^9\,\mathrm{kg_{CO2}}$ in the 1989 to $25.6 \times 10^9\,\mathrm{kg_{CO2}}$ in the 1995. Significant is also the incidence of direct emissions due to the user demands, responsible of $3.4 \times 10^9\,\mathrm{kg_{CO2}}$ in 1989, $3.9 \times 10^9\,\mathrm{kg_{CO2}}$ in 1992 and $4.9 \times 10^9\,\mathrm{kg_{CO2}}$ in 1995. Opposite trend had the emissions due to the production of exports that decreased from $2.5 \times 10^9\,\mathrm{kg_{CO2}}$ in 1989 to $1.7 \times 10^9\,\mathrm{kg_{CO2}}$ in 1995. The total regional emission balance estimates that CO_2 emission grew from $28.8 \times 10^9\,\mathrm{kg_{CO2}}$ in 1989 to $32.2 \times 10^9\,\mathrm{kg_{CO2}}$ in 1995, *with an average increment of 12%.*

This analysis resulted very interesting being possible to monitor the regional trend of greenhouse gas emissions and to individuate the sectors responsible of greatest impacts. Furthermore, in order to comply with the Kyoto agreements, the IO analysis can also be employed to address regional funds and initiatives and to state the efficacy and the efficiency of the regional energy and environmental policies.

Uncertainty and Sensitivity Analysis

The previous paragraphs have shown many problems and limits that arise in the application of IO method. In order to state the precision and reliability of results, it is necessary to perform a sensitivity and uncertainty analysis (Wilting 1996). The sensitivity analysis investigates the influence of variations in the input parameters on the outcomes. The uncertainty analysis investigates the uncertain aspects of the method, the input data and the way they are interpreted, and it studies the effects of these uncertainties on the outcomes of the method itself.

Sensitivity Analysis of IO Parameters

Sensitivity Analysis (SA) aims to manage uncertainties due to elements of the IO table. In particular, SA assess the effects of the variations of "X_{ij}" elements on the Leontief inverse matrix. In the analysis, we have to comply with the general constraint that the total Input equals the total Output for production sector. Consequently it is possible to modify directly only the elements X_{ij} when $i = j$.

Following we demonstrate that energy intensities do not change if an element X_{ii} will be modified (Figs. 22.6 and 22.7).

Let we suppose to have a simplified IO matrix (dimension 2×2) whose elements a_i (i $= 1 \ldots 4$) are the IO coefficients and elements A_j (j $= 1, 2$) are the total sector outputs (Fig. 22.6). Using the previous notation: A is the technology matrix; I is the unit matrix; D is the term $[(A_1 - a_1) \cdot (A_2 - a_4) - a_2 a_3]$; C is the matrix

$$IO = \begin{pmatrix} a_1 & a_2 \\ a_3 & a_4 \end{pmatrix} \qquad A = \begin{pmatrix} \frac{a_1}{A_1} & \frac{a_2}{A_2} \\ \frac{a_3}{A_1} & \frac{a_4}{A_2} \end{pmatrix} \qquad C = \begin{pmatrix} \frac{e_1}{A_1} & \frac{e_2}{A_2} \end{pmatrix}$$

$$(I - A)^{-1} = \begin{pmatrix} \frac{A_1 (A_2 - A_4)}{D} & \frac{a_2 A_1}{D} \\ \frac{A_2 a_3}{D} & \frac{A_2 (A_1 - a_1)}{D} \end{pmatrix}$$

$$E = C \cdot (I - A)^{-1} = \begin{pmatrix} \frac{e_1 (A_2 - a_4) + e_2 a_3}{D} & \frac{e_1 a_2 + e_2 (A_1 - a_1)}{D} \end{pmatrix}$$

Fig. 22.6 Sensitivity Analysis – Calculation of Energy Intensities for an Exemplary IO Matrix (Dimension 2×2)

$$IO' = \begin{bmatrix} a_1 - a & a_2 \\ a_3 & a_4 \end{bmatrix} \qquad A' = \begin{bmatrix} \dfrac{a_1-a}{A_1-a} & \dfrac{a_2}{A_2} \\ \dfrac{a_3}{A_1-a} & \dfrac{a_4}{A_2} \end{bmatrix} \qquad C' = \begin{bmatrix} \dfrac{e_1}{A_1-a} & \dfrac{e_2}{A_2} \end{bmatrix}$$

$$(I-A')^{-1} = \begin{bmatrix} \dfrac{(A_1-a)\,(A_2-A_4)}{D} & \dfrac{a_2\,(A_1-a)}{D} \\ \dfrac{A_2 a_3}{D} & \dfrac{A_2\,(A_1-a_1)}{D} \end{bmatrix}$$

$$E' = C' \cdot (I-A')^{-1} = \begin{bmatrix} \dfrac{e_1\,(A_2-a_4)+e_2 a_3}{D} & \dfrac{e_1\,a_2 + e_2(A_1-a_1)}{D} \end{bmatrix} = E$$

Fig. 22.7 Sensitivity Analysis – Calculation of Energy Intensities for an Exemplary IO Matrix Modifying an Element of the Main Diagonal of the IO Table

constituted by the consumption coefficients, obtained dividing the energy consumption per sector ($e_j : j = 1, 2$) by total sector outputs (see note 3). Figure 22.6 shows the structure of the vector E of energy intensities.

Let we assume to modify an element of the main diagonal (for example, the element a_1 is decreased of an arbitrary quantity $a \leq a_1$). Figure 22.7 shows that this modification does not influence the new vector E' of energy intensities. These results can be extended to any positive or negative variations of the main diagonal elements in a general n-dimension IO matrix. In fact, modifications of IO table and C matrix leave unaltered the E vector.

Although modifies of X_{ii} elements do not affect the total energy intensities, they change the ratio between directs and indirect contributes. For example, increasing of +10% the element $X_{2,2}$ in 1992, the energy intensity of "energy" sector remains 56.3 GJ/€10,000 but the direct contribution moves from 70.5% to 68.6%.

The energy intensities change if we assume to leave unaltered the energy consumption coefficients. The case study of paragraph 3.1 has been repeated supposing to leave unaltered the matrix C and changing the IO coefficients. Table 22.5 shows the variation of energy intensities by changing of ±10% the elements X_{ii} of the main diagonal of the IO table in 1992. We point out that:

- Positive variations of X_{ii} involve an increase of energy intensities. This is due to the increase of outputs that each sector sells to itself. In the same manner, negative variations decrease energy intensities.
- Doubling the variations of the elements of IO table, energy intensities change proportionally.
- Even increasing of 20% the elements X_{ii}, variations of energy intensities are enclosed in the range (2.2% ÷ 5.6%).

Table 22.5 Sensitivity Analysis – Variations of Energy Intensities by Changing of +10% and +20% the Elements of the Main Diagonal of IO Table

No	Sector	+10%	+20%
1	Agriculture and fishing	2.1	4.3
2	Energy sector	2.8	5.6
3	Metal industries	1.1	2.2
4	Non metallic mineral industries	1.8	3.6
5	Chemical industry	1.7	3.4
6	Engineering industry	2.0	4.1
7	Mechanic industry	1.4	2.8
8	Agro-industrial products	2.0	4.1
9	Textile products	2.3	4.5
10	Paper products	2.3	4.6
11	Other industries	2.2	4.5
12	Constructions and public works	1.9	3.8
13	Tertiary	2.2	4.4
14	Transports	1.4	2.8
15	Local authorities	1.9	3.9

- Variations of energy intensities related to the economic sectors are not equal. In particular, largest variations are related to "energy" and "paper" products; "mechanic", "metal industry" and "transport" sectors are less influenced.
- Negative variations of IO table cause symmetric changes of energy intensities.

Another attempt to perform the sensitivity analysis focused on the X_{ij} elements $\forall i \neq j$. These elements cannot be changed without re-balancing the matrix in order to respect the mentioned constraint. A method to face this problem is following described:

- To change the generic X_{ij} element of row i and column j, adding (or subtracting) the generic quantity z.
- The quantity $\frac{-z}{n-1}$ (or $\frac{+z}{n-1}$) is summed to the elements of row i and to the elements of column j.
- The quantity $\frac{z}{(n-1)^2}$ (or $\frac{-z}{(n-1)^2}$) is summed to all the other elements $X_{kh} \forall k \neq i$ and $\forall h \neq j$.

This method allows to respect the matrix constraints and to leave unaltered the sums of elements per rows and the sums per columns. On the other side, this procedure modifies all the elements of the matrix and some items could become negative. To cope with this problem, some alternatives are possible:

- *To set negative elements to zero*. This alternative makes the constraints no more respected. This option is feasible when the sums of elements per rows and the sums per columns do not heavily differ. In this case we have to fix an acceptable percentage of difference.
- *To repeat the same procedure for negative elements* in order to turn them into positive. This alternative could involve an iterative process.

Table 22.6 Sensitivity Analysis – Variations of Energy Intensities by Changing of ±10% the Element $X_{2,14}$ of the IO Table

No	Sector	Without re-balancing the IO table		Rebalancing the IO table	
		$X_{2,14}$ decreased of 10% (%)	$X_{2,14}$ increased of 10% (%)	$X_{2,14}$ decreased of 10% (%)	$X_{2,14}$ increased of 10% (%)
1	Agriculture and fishing	−0.16	0.16	0.62	−0.63
2	Energy sector	–	–	–	–
3	Metal industries	−0.23	0.22	8.9	−8.4
4	Non metallic mineral industries	−0.19	0.18	0.35	−0.37
5	Chemical industry	−0.27	0.26	0.80	−0.81
6	Engineering industry	−0.63	0.61	0.69	−0.68
7	Mechanic industry	−0.43	0.41	1.88	−1.86
8	Agro-industrial products	−0.29	0.28	0.75	−0.76
9	Textile products	−0.47	0.46	0.59	−0.61
10	Paper products	−0.52	0.50	1.2	−1.3
11	Other industries	−0.42	0.40	0.81	−0.83
12	Constructions and public works	−0.45	0.43	0.39	−0.41
13	Tertiary	−0.47	0.46	−0.15	0.14
14	Transports	−1.6	1.5	−1.6	1.6
15	Local authorities	−0.44	0.42	–	–

- *To share the generic quantity z not equally to the elements of rows and columns*, in order to avoid negative elements. It would require higher difficulties to respect the constraints.

For example, we applied this sensitivity analysis to the element $X_{2,14}$ that represents the outputs of "energy" sector to the "transport" sector. The value of $X_{2,14}$ has been modified of ±10% (results in Table 22.6). Initially the analysis has been carried out without rebalancing the IO table and supposing the C matrix constant. Successively the analysis has been repeated proceeding with the suggested rebalancing method and setting negative elements to zero. Variations lower than 1% have not been considered.

Results of Table 22.6 show that, without the rebalancing process, the variations of energy intensities are lower. An increment of $X_{2,14}$ causes the growth of all the energy intensities and, in particular, of the "transport" sector (+1.5%). Analogous results are obtained decreasing the $X_{2,14}$.

The re-balancing process causes higher modifies. Particularly significant is the variation of "metal industries" (−8.4%). This sector is characterised by low values in the IO matrix and, consequently, the method of re-balancing the matrix has involved sensible variations of its values. Regarding all the other sectors, modifying the $X_{2,14}$ of ±10%, the energy intensities have variations enclosed in the range (−1.9%; +1.3%).

As previously discussed, setting to zero negative elements the general IO constraint results to be no more accomplished. However, discrepancies among total Inputs and Outputs are lower than 1%.

The sensitivity analysis showed that the variations of IO elements do not affect significantly the energy intensities. Consequently, large variations into energy intensities detected into paragraph 3 cannot be generally ascribed to the RAS methodology to update IO table.

The previous considerations regarding energy intensities can be analogously extended to CO_2 intensities.

Uncertainty Analysis

Uncertainty analysis has been applied to input data and, in particular, to energy quantities and the way they are interpreted.

We have assumed to increase by 10% the energy consumption of one sector per time, supposing to leave unaltered the energy conversion factors and the elements of the IO table. Table 22.7 shows the variation of energy intensities (variations lower than 1% have been not considered).

For example, increasing of 10% the energy consumption of sector 1 (column 1 in Table 22.7), the energy intensity of agriculture increases of 4.5% while energy intensity of "agro-industrial" sector increases of 2.3%.

Table 22.7 gives a picture of the energy relationships among sectors. We point out that the regional economy is strongly based on a small number of activities that, in accordance with Figs. 22.2 and 22.4, are also the sectors with the higher energy intensities and environmental impacts. In particular, the analysis shows that:

Table 22.7 Sensitivity Analysis of Energy Input Data

		Sector Increased of 10%														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	14
Percentage variation of energy intensities	1	4,5%	4,4%	-	-	-	-	-	-	-	-	-	-	0,1%	0,8%	-
	2	-	9,9%	-	-	-	-	-	-	-	-	-	-	-	0,1%	-
	3	-	3,2%	5,5%	0,1%	-	-	-	-	-	-	-	-	-	1,1%	-
	4	-	2,9%	-	6,1%	-	-	-	-	-	-	-	-	-	0,9%	-
	5	-	4,5%	-	0,4%	3,6%	-	-	-	-	-	-	-	-	1,3%	-
	6	-	5,2%	0,2%	0,4%	-	0,7%	-	-	-	-	-	-	0,2%	3,0%	-
	7	-	3,8%	0,1%	0,3%	-	-	3,3%	-	-	-	-	-	0,2%	2,1%	-
	8	2,3%	4,9%	-	0,2%	-	-	-	0,9%	-	-	-	-	0,1%	1,4%	-
	9	0,3%	6,6%	-	0,1%	0,2%	-	-	-	-	-	-	-	0,3%	2,3%	-
	10	0,1%	6,3%	-	0,2%	0,2%	-	-	-	-	0,5%	-	-	0,2%	2,5%	-
	11	0,1%	5,9%	-	0,4%	0,3%	-	-	-	-	-	0,9%	-	0,2%	2,0%	-
	12	-	4,2%	-	3,1%	-	-	-	-	-	-	-	0,2%	0,1%	2,2%	-
	13	0,1%	6,1%	-	0,1%	-	-	-	-	-	-	-	-	1,3%	2,3%	-
	14	-	2,3%	-	-	-	-	-	-	-	-	-	-	-	7,7%	-
	15	-	5,8%	-	0,2%	-	-	-	-	-	-	-	-	0,1%	2,1%	1,5%

- Energy intensities are generally sensitive to the energy consumption variations.
- Changing the energy consumption of a sector, the energy intensity of the sector itself has the highest variation.
- Variations occurring to “transports” and “energy” sectors strongly influence the other sectors.
- Many sectors (as “local authorities”, “paper products”, “construction”, “textile”, etc.) have a small incidence on other sectors, while “energy sector” is low influenced by other sectors.

The SA can also be employed to foresee the changes of energy consumptions of sectors. For example, it would be possible to state how all sectors could benefit of the efficiency improvement of a generic sector (due, for example, to the introduction of new technologies or plants). Te IO analysis is then an important tool to support planning strategies and to analyse future scenarios.

Regarding the “petrochemistry” industry, the energy and environmental analysis has shown its critical role, because this sector is responsible of about a half of the total energy consumption. The previous calculations have supposed to include the petrochemistry industry to the “energy” sector (see note 6). However, other alternatives have been checked. For example, we have supposed to include petrochemistry into the “chemical industry”. This assumption has sensibly modified the values of energy and emission intensities, leading chemicals to become the most energy consuming products. However this choice is in contrast with economic tables where the “chemical” sector appears as a marginal sector of the regional economy.

A key point of the analysis is the definition of the consumption coefficient of the C matrix. Previous calculations have been based on data coming from the regional energy balance. As described in paragraph 3, secondary energy sources (as electricity) have been transformed into primary sources by means of energy conversion factors. An alternative procedure supposes to entirely assign the primary energy consumption for electricity generation to the “energy” sector. Successively, on the basis of the economic IO flows, the IO model re-distributes the energy consumptions to every sector. The analysis has therefore been repeated following these new assumptions. The results of 1992 showed that the energy intensity of “energy” sector had a large variation (+36.9%); the other sectors had smaller positive or negative variations enclosed in the range (−19.7%; +13.4%). The moderate variations show a good reliability of the IO analysis but, in the meantime, underline a limit of the model. Differences between the two approaches concerning secondary energy sources are due to different prices of energy sold to sectors. The low quality of the regional IO data, characterised by a strongly aggregated energy sector, has also affected the detected differences.

A final consideration regards the feedstock energy. It represents the energy contained into fuels employed as raw material. Feedstock is not burned and therefore do not release CO_2. These energy quantities have been therefore included into the energy balance but excluded in the estimation of emissions. In the regional energy balance feedstock energy sources represents about 34% of the total energy use, mainly due to refinery and chemical factories that produce many different oil derived products. Including feedstock into the CO_2 estimation we would have overestimated the incidence of the "energy" sector with its value of CO_2 intensity almost doubled. The total CO_2 emissions to satisfy the internal demand in 1992 would be $50.610^9\,kg_{CO2}$, about 54% bigger than the previous value. This experience shows that the inclusion or exclusion of feedstock energy into the environmental balance could sensibly change the results of the model.

Conclusion and Comments

The IO analysis has many limits that increase the uncertainty of results. First of all, these are referred to methodological assumptions (as constant technical coefficients and linear production functions) that it is not possible to avoid. Although economy does not change rapidly, IO table can not be reliable for a long time period. On the other side, the necessity to update frequently the IO tables contrasts with hard computational difficulties typical of this method. When a new technology allows either input substitution or greater efficiencies in the use of inputs, impacts to supplying industry sectors may be seriously misrepresented.

In addition, the assessment of economic flows is generally affected by large uncertainties due to the quality of data. The more disaggregated is the table the more precise and reliable are the results. Unfortunately, IO tables have often many different sectors joined together. It means a loss of information due to the aggregation operations. Furthermore, the assumption of homogeneity of production represents a strong limit; it permits an average estimation per productive sectors.

The lack of reliability of the results grows in the energy and environmental applications because of additional uncertainties as: availability of energy data, calculation of the energy flows, use of conversion factors, links between economic and energy data, use of emission factors, etc.

All these limits have been checked in the presented case study. In particular, the only available IO table, aged 1992, strictly affects results. Tables referred to other years have been indirectly estimated.

Furthermore, the employed IO table has a high aggregation level that compromises the detail of results, especially in a regional context where economy is mainly based upon a small number of sectors. Large uncertainty of results is also related to the exclusion of imports, being the regional economy largely dependent on external productions.

The greatest problems have concerned the discordance between economy and energy data. To face this problem, sectors have been further aggregated, causing so many difficulties in the attribution of primary energy consumptions. A key point was the aggregation of the petrochemistry sector, which represents about a half of the regional energy consumption.

The application of IO analysis to the regional case study should be considered as rough estimations and the employment of obtained data for Life Cycle Inventories or other detailed applications could be difficult.

However the IO analysis has many advantages, mainly due to the simplicity of the method. It allows to calculate the energy and environmental impacts per sector and to observe their trend through the years. The link among indirect consumptions, environmental impacts and products is an interesting parameter to assess sustainable/unsustainable paths. The model describes a rough but useful picture of the economy, especially if results are employed as support to the energy and environmental planning or to evaluate future scenarios related to variations of energy consumptions.

Sensitivity analysis has shown that the variations of economic data do not heavily influence the results. Furthermore, we have demonstrated that elements of main diagonal of the IO table do not affect the energy results. A larger incidence is related to the energy data. Consequently, the reliability of the model strictly depends on the reliability of energy input data.

In the Sicilian case study, authors have checked a growing trend of the energy consumptions (and air emissions) from 1989 to 1992. Because of an economy crisis, this trend has been successively inverted and the energy and environmental impacts in 1995 have been estimated similar to those in 1989. Regarding the disaggregated analysis, greatest impacts are related to “energy products” and “tertiary”. Significant is the contribution of “local authorities”, “transports” and “constructions”, while negligible are “metal industries”.

The analysis points out a general decreasing trend of energy intensities. Highest reductions have interested “energy sector”, “non-metallic mineral” and “local authorities”. These large reductions of energy intensities are mainly due to a general improvement of the “energy” sector and to a jointly increment of economic outputs of the sector itself.

However the positive effect of this energy improvement has been balanced by the growing consumptions. The analysis has shown an average increment (+12%) of CO_2 emissions in 1995 respect to 1989, confirming a growing trend largely far from the reduction targets of Kyoto’s protocol.

The analysis has also shown the importance of feedstock energy sources. They have to be included into the energy model but successively excluded from the environmental analysis. In the case study, feedstock energy plays a key role, representing about 34% of the regional consumption. Including these sources into the CO_2 assessment, emissions would be strongly overestimated.

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Chapter 23
Thermodynamic Input-Output Analysis of Economic and Ecological Systems

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Introduction

Ecological resources constitute the basic support system for all activity on earth. These resources include products such as air, water, minerals and crude oil and services such as carbon sequestration and pollution dissipation (Tilman et al. 2002; Daily 1997; Costanza et al. 1997; Odum 1996). However, traditional methods in engineering and economics often fail to account for the contribution of ecosystems despite their obvious importance. The focus of these methods tends to be on short-term economic objectives, while long-term sustainability issues get shortchanged. Such ignorance of ecosystems is widely believed to be one of the primary causes behind a significant and alarming deterioration of global ecological resources (WRI 2000; WWF 2000; UNEP 2002).

To overcome the shortcomings of existing methods, and to make them ecologically more conscious, various techniques have been developed in recent years (Holliday et al. 2002). These techniques can be broadly divided into two categories, namely preference-based and biophysical methods. The *preference-based methods* use human valuation to account for ecosystem resources (AIChE 2004; Balmford et al. 2002; Bockstael et al. 2000; Costanza et al. 1997). These methods either use a single monetary unit to readily compare economic and ecological contributions, or use multi-criteria decision making to address trade-offs between indicators in completely different units. However, preference-based methods do not necessitate

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

compliance with basic biophysical laws that all systems must satisfy, and require knowledge about the role of ecological products and services that is often inadequate or unavailable.

Biophysical methods, on the other hand, comply with the basic scientific laws such as the conservation of mass and energy (first law) and the universal degradation of energy quality (second law). These methods consider material and energetic flows of economic goods and services but ignore how people value them. *Mass-based* methods such as Material Flow Analysis (MFA), for instance, determine the material basis of economic systems and emissions from them (Adriaanse et al. 1997; Matthews et al. 2000; ConAccount 2002). These methods comply with the conservation of mass but ignore energetic streams and quality differences between different materials. *Energy-based* methods such as, Net Energy Analysis (NEA) and Full Fuel Cycle Analysis (FFCA), determine energy flows in the economy (Hannon 1982, 2001; Costanza and Herendeen 1984; Spreng 1988) and ecosystems (Hannon 1973). However, like mass, energy-based methods also comply with the first law of thermodynamics only and ignore the second law. Biophysical methods based on exergy analysis are a step forward as they do comply with the first and the second laws of thermodynamics. They have been popular for detecting thermodynamic inefficiencies in industrial processes (Szargut et al. 1988) and to analyze the behavior of ecosystems (Jørgensen 1997). These methods can accommodate variety of material and energy streams and can appreciate quality differences between them. Exergy analysis has also been extended to provide a life cycle perspective. For example, methods such as Industrial Cumulative Exergy Consumption (ICEC) analysis (Szargut et al. 1988) and Exergetic LCA (Cornelissen and Hirs 1997) determine exergy losses in various stages of a production system and its supply chain. Exergy analysis of several countries has also been developed, both at the national and sectoral levels (Ertesvag 2001). However, these methods focus only on the industrial stages of a production chain and ignore the contribution of ecosystems and impact of emissions. Furthermore, exergy analysis at the level of economic sectors is not yet available. While mass-, energy- and exergy-based methods are commonly used in engineering design, emergy-based methods have been primarily developed by systems ecologists for the joint analysis of economic and ecological systems (Odum 1996). Emergy is defined *as the available energy used directly or indirectly to make any product or service*. Consequently, emergy-based methods do a better job at accounting for ecosystem contribution. However, emergy analysis is often misunderstood, faces quantitative and algebraic challenges, and its broad claims about ecological and economic systems have been quite controversial (Brown and Herendeen 1996; Hau and Bakshi 2004a; Hau 2005). Besides, emergy analysis has not been done at the level of economic sectors either.

Many of the biophysical approaches discussed above have used input-output analysis. Since its development to study monetary interdependencies in the economic system (Leontief 1936), input-output analysis has been used to address several environmental issues pertinent to industrial ecology (Cumberland 1966; Noble 1978). For instance, Leontief et al. (1982) explored the integration of material flows of 26 non-fuel materials in conventional input-output models. Ayres developed the material-process product model to address questions on the boundary between traditional economic criteria such as cost and prices and material processing (Ayres 1972, 1978; Saxton and Ayres 1976). Duchin's structural economics approach also combines the physical interconnectedness in the economic system with corresponding representation of costs and prices (Duchin 1994). Input-output analysis has also been applied to study energy flows in the economic system (Costanza 1980; Costanza and Herendeen 1984; Casler and Hannon 1989). For example, NEA and FFCA have tried to establish a correlation between embodied energy intensities of economic goods and services and their economic prices (Bullard and Herendeen 1975; Hannon 1982; Spreng 1988). Recent development of Economic input-output LCA (Lave et al. 1995; EIOLCA 2004) also uses economic input-output models to evaluate economy-wide discharges of toxins and bulk pollutants in response to a marginal change in the exogenous final demand from any sector. However, as mentioned previously, these studies ignore the contribution of ecological resources.

Hau and Bakshi (2004a) have recently provided a more rigorous theoretical basis to connect exergy and emergy analyses by proving that emergy and cumulative exergy consumption are equivalent for identical system boundary, allocation rule and approach for combining global exergy inputs (Hau 2005). The resulting methodology, called Ecological Cumulative Exergy Consumption (ECEC) analysis, is an extension of ICEC analysis to include exergy losses in the ecological stages of a production chain. ECEC analysis also forms the foundation of Thermodynamic Input-Output Analysis (TIOA) discussed in this chapter. TIOA has many unique features that distinguish it from other contemporary thermodynamic methods and make it more suitable for environmental decision making:

- TIOA combines the best features of exergy analysis from systems engineering with the ability to account for ecosystems via emergy analysis from systems ecology.
- TIOA acknowledges the economic network and provides industry-specific results rather than aggregate results for the entire economy.
- TIOA can accommodate a wide variety of ecological products and services, human resources and impact of emissions on human and ecosystem health, making it a more holistic approach.

Further details about basic thermodynamic concepts relevant to ECEC analysis, brief history of their development and use, and a general theoretical framework that can readily incorporate input-output representation of the economic system are presented in Section "Ecological Cumulative Exergy Consumption (ECEC) Analysis" of this chapter.

The rest of the chapter is organized as follows. Section "Ecological Cumulative Exergy Consumption (ECEC) Analysis" provides basic thermodynamic concepts relevant to ECEC analysis, a brief history of their development and use, and a general theoretical framework that can readily incorporate an input-output representation of the economic system. Section "Data Requirements and Sources" describes the integrated economic–ecological–social system, and proposes the algorithm of

Thermodynamic Input-Output Analysis. Section "Aggregate Metrics for 488-Sector 1997 U.S. Economy" discusses the data requirements and sources for performing Thermodynamic Input-Output Analysis of 488-sector 1997 U.S. economy. Section "Hybrid Thermodynamic LCA of Geothermal and Coal-Fueled Electricity" presents industry-specific results and metrics, and demonstrates their applications at micro- as well as macro-scales.

Ecological Cumulative Exergy Consumption (ECEC) Analysis

Ecosystems and the Second Law

The second law predicts that all isolated systems will inevitably tend to an equilibrium that represents a state of maximum disorder, in which no further changes will occur (Box 23.1). When first stated, it brought a lot of controversy in the field of biology. Evolution did not seem to obey the second law, since life itself was far from tending to a state of total disorder. Progress in both physics and biology helped understand how evolution is possible despite the second law. In 1905, Austrian Physicist Ludwig Boltzmann suggested that the struggle for existence is a struggle for free energy available for work (Jørgensen 1997). Boltzmann's statement entails that an external source of exergy is required for life to exist. US mathematician and statistician Alfred Lotka pointed out that, systems that prevail develop designs that maximize the flow of useful energy (Lotka 1925; Jørgensen 1997). Lotka's idea implies not only that living organisms require a source of exergy to exist, but also that they need to evolve in ways that allow them to maximize this exergy inflow. Austrian Physicist Erwin Schrödinger held that organization is maintained by extracting order from the environment (Schrödinger 1944). In general, all these statements reinforce the idea that life is possible because the sun provides a source of exergy that allows ecosystems to stay away from equilibrium.

Living organisms and ecosystems are examples of *self-organized systems*. Such systems constantly restructure themselves to optimize their inflow of exergy. Self-organization is created in the presence of sustained energy or material gradients. Self-organized systems tend to stay far from equilibrium, minimize their entropy content (disorder), maximize their exergy and possibly maximize the rate of exergy consumption for themselves and systems they depend on (Fath et al. 2004). As a consequence, development and growth are limited by the availability of resources and the ability to exploit them. Ecological systems convert global energy inputs such as sunlight, crustal heat and tidal forces into ecological products and services such as water, fertile soil, wood, coal, rain, pollination, and wind (Odum 1996). In an abstract sense, ecosystems are networks of energy flow.

Box 23.1 Brief History of Thermodynamics

Thermodynamics is the branch of science concerned with the nature of heat and its conversion to other types of energy. The laws of thermodynamics are the result of several thousand years of discoveries in mechanics and in the study of heat (Goldstein and Goldstein 1993). The ancient Greeks already had a good understanding of the relation between force and work that are central to mechanics. For instance, they knew how to produce a large force by the application of a smaller force with the help of a lever. They were also aware of the existence of heat, though its relation to work was not clear. The great breakthrough for mechanics came around 1666, when English scientist Isaac Newton came up with the three laws of motion. Advances in the study of heat started with the advent of the steam engine and development of the caloric theory by the end of the eighteenth century. When it came to heat, there were disagreements between mechanics and the caloric theory; to a large extent because supporters of the caloric theory believed that heat was a material substance. Throughout the years, heat and other phenomena of nature such as kinetic and potential energy, electricity, and chemical reactions, were regarded as disconnected. They were developed independently and even measured in different units. In the early nineteenth century, it became apparent that these phenomena were interchangeable, i.e. that it was possible to produce one out of the other. This raised the question of whether there was something that did not change in the intercourse of all these transformations. It was between 1840 and 1850 that English physicist James Joule found a quantitative relation between heat and work, showing that they are just examples of energy and that heat was not a substance (Goldstein and Goldstein 1993). Joules' work led to the first law of thermodynamics, which states that the total energy of a system is conserved, regardless of the nature and number of transformations that the system undergoes. At this point, it was clear that the previously studied phenomena of nature were interchangeable, measurable in the same units and that it was their total amount what was conserved. Nowadays, the use of the first law is indispensable for the design and operation of every industrial process. The first law does not rule out the possibility of having a machine that takes in one type of energy, transforms it into heat and back again into its original form in a perpetual cycle without any need for additional energy. If electricity could be recycled this way, there would be no need for fossil fuels. Since the middle ages, scientists have intuitively known that such machines cannot exist – yet there have always been attempts to create them. This statement was not made formal until 1824 by French engineer Sadi Carnot and then in 1850, when German physicist Rudolf Clausius first proposed the second law of thermodynamics (Goldstein and Goldstein 1993). In 1865, Clausius introduced a new property of matter called *entropy* and stated the second law by saying that the entropy of the universe tends to a maximum. Although there is no simple way of defining entropy, in an abstract way, it can be interpreted as a measure of molecular disorder of matter. To cite an example, crystals have ordered molecular arrangements and low entropies, while gases have chaotic molecular structure and high entropies. The repercussions of the second

(continued)

Box 23.1 (continued)

law are tremendous because it explains why processes occur naturally in a certain direction. For instance, in a glass of water, heat will flow from the water to the ice and not the opposite. Although the reverse process obeys the first law, it violates the second. An alternative way to interpret the second law is that although energy is neither created nor destroyed, it is converted from useful to useless as work is performed. For instance, friction in pipelines diminishes the amount of useful energy in the fluids transported because it converts kinetic energy into dissipated heat, which is energy without any capacity to do work (Hau and Bakshi 2004b; Hau 2005). This useful energy is better known as *exergy*, which is more formally defined as the maximum amount of *work* that can be extracted when a system is brought to equilibrium with its surroundings (Szargut et al. 1988). Exergy is a convenient concept because it is a tangible attribute, as opposed to entropy, that is consumed and reflects the constraints of the second law, in contrast to energy.

Ecological Cumulative Exergy Consumption (ECEC) Analysis

Exergy of matter, in the absence of nuclear, magnetic, electrical and interfacial effects is defined as (Box 23.2, Szargut et al. 1988)

$$\begin{aligned} B = &\left(H - T_0 S + \dot{r}^2/2 + zg\right)_{Actual\ State} \\ &- \left(H - T_0 S + \dot{r}^2/2 + zg\right)_{Reference\ State} \end{aligned} \tag{23.1}$$

Box 23.2 List of Definitions in Thermodynamics

Heat: energy that is transferred from one body to another due to a difference in temperature.
Work: energy transferred by a force acting to displace a body. Work is equal to the product of the force and the distance through which it produces movement.
Entropy: measure of the amount of energy in a system that is no longer available for doing work; measure of disorder in a system.
First Law: total energy in a system is conserved.
Second Law: entropy of the universe will always increase; decreasing the entropy of a system will always cause a larger increase in entropy of the surroundings.
Exergy: is the maximum amount of *work* that can be extracted when a system is brought to equilibrium with its surroundings.
Industrial Cumulative Exergy Consumption: total exergy used directly and indirectly in industrial processes to produce a good or service.
Ecological Cumulative Exergy Consumption: total exergy used directly and indirectly in both ecological and industrial processes to produce a good or service.

where, H is enthalpy, T_0 is temperature of the reference state (surroundings), S is entropy, $\dot{r}$ is relative velocity, z is relative height and g is acceleration of gravity. The *reference state* is typically defined with the compositions of the substances present in the surroundings at normal temperature and pressure. *Exergy analysis* is a method popular in engineering to determine how much exergy is lost in the process and how efficient the system is in producing work. Exergy analysis has been successful in identifying imperfections and points of potential improvement in industrial systems. On the flip side, exergy analysis ignores some critical inputs such as capital and labor, and is narrow in scope due to its focus on the process while ignoring the performance of the rest of the production chain (Sciubba 2001; Hau and Bakshi 2004b). Extensions of exergy analysis such as Industrial Cumulative Exergy Consumption (ICEC) (Szargut et al. 1988) and Thermoeconomics (Bejan et al. 1996) address some of these shortcomings.

Figure 23.1 depicts an Industrial Cumulative Exergy Consumption (ICEC) analysis. A stream is considered to be a natural resource if it is a direct product from ecological processes and a raw material for human activities, for example, coal, iron and fresh water. *Industrial Cumulative Exergy Consumption* (ICEC) of a process is the sum of the exergy of all the natural resources consumed in all steps of the process and previous processes in the production chain. According to Fig. 23.1, ICEC of the production chain, C_p, is

$$C_p = \sum_{k=1}^{N_i} B_{n,k} \tag{23.2}$$

where, N_i denotes the number of process units included in the industrial production chain and $B_{n,k}$ is the exergy of the natural resource entering the *k-th* process unit. Industrial Cumulative Degree of Perfection (ICDP), η_p, is the ratio of the exergy of the final product(s) to the cumulative exergy consumed to make the product(s), that is

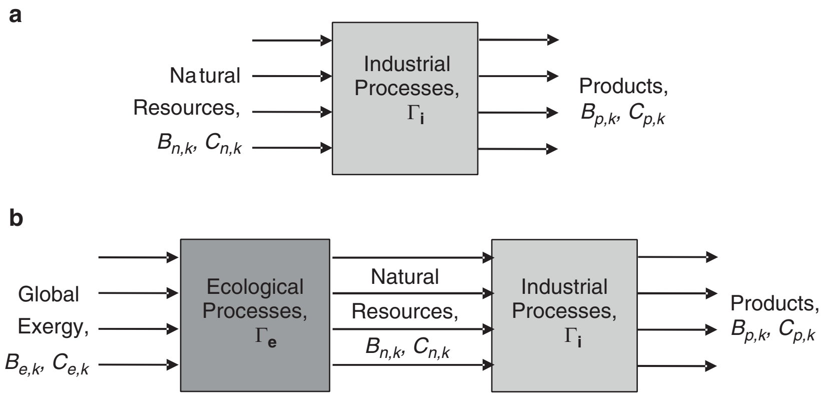

Fig. 23.1 (**a**) Industrial Cumulative Exergy Consumption (ICEC) Analysis; (**b**) Ecological Cumulative Exergy Consumption (ECEC) Analysis (Hau and Bakshi 2004b; Hau 2005)

$$\eta_p = \frac{\sum_{k=1}^{N_i} B_{p,k}}{\sum_{k=1}^{N_i} B_{n,k}} = \frac{B_p}{C_p}; \qquad \eta_{p,k} = \frac{B_{p,k}}{C_{p,k}} \tag{23.3}$$

where $\eta_{p,k}$, $B_{p,k}$ and $C_{p,k}$ are respectively ICDP, exergy and ICEC of the product(s) leaving the *k-th* process unit. ICDP gives a measure of efficiency of the system. ICEC for each unit's product(s), $C_{p,k}$, is calculated as

$$\mathbf{C_p} = \mathbf{\Gamma_i} \cdot \mathbf{B_n} \tag{23.4}$$

where, $\mathbf{B_n}$ is the vector of exergy of the natural resource(s) entering the *k-th* process unit, $C_{n,k}$, $\mathbf{C_p}$ is the vector of ICEC for the units' product(s), $C_{p,k}$. and $\mathbf{\Gamma}_\mathrm{i}$ is the $N_i \times N_i$ allocation matrix. This matrix represents the exergy flow network and the selected allocation method.

ICEC analysis shares some features of Life Cycle Assessment (LCA) since both methods consider the life cycle of the product. Unlike LCA, ICEC analysis ignores emissions and their impact. ICEC analysis has been used widely and calculations for many industrial processes are available (Szargut et al. 1988). ICEC only considers the industrial chain and ignores the contribution of ecological processes.

Ecological Cumulative Exergy Consumption (ECEC) analysis determines the exergy used by both ecological and industrial processes to produce a good or service (Hau and Bakshi 2004b; Hau 2005). According to Fig. 23.1, ECEC of the production chain, C_p, is

$$C_p = \sum_{k=1}^{N_i+N_e} B_{e,k} \tag{23.5}$$

where, N_e denotes the number of process units included in the ecological supply chain and $B_{e,k}$ is the exergy of the global exergy inputs entering the *kth* process unit.

By using an equation similar to Equation (23.4), ECEC of natural resources can be calculated as

$$\mathbf{C_n} = \mathbf{\Gamma_e} \cdot \mathbf{B_e} \tag{23.6}$$

where, $\mathbf{C_n}$ is the vector of ECEC for the natural resources $C_{n,k}$, $\mathbf{B_e}$ is the vector of exergy for the global energy inputs, and $\mathbf{\Gamma_e}$ is the allocation matrix for mapping global energy inputs to natural resource outputs. An Ecological Cumulative Degree of Perfection (ECDP) for the natural resources $\eta_{n,k}$, can be defined as the ratio of the exergy to the ECEC of the natural resource, this is

$$\eta_{n,k} = \frac{B_{n,k}}{C_{n,k}} \tag{23.7}$$

The values of ECEC and ECDP of the natural resources depend on how exergy is allocated in the ecological network. At present, the most comprehensive network can be obtained from *Emergy Analysis* (Odum 1996), which is based on several studies from the natural sciences, and is being continually updated. Emergy analysis uses transformities to connect the exergy and embodied exergy of a good or service. Transformities are analogous to the reciprocal of ECDP and their exact equivalence is proved in Hau and Bakshi (2004b) and Hau (2005). Nevertheless, because of the allocation system used in emergy analysis, calculation of ECEC for the process units is not straightforward because for most ecological systems, the network and all the outputs are unknown. In such cases, allocation is avoided by assigning the entire input cumulative exergy to all the outputs. Such an allocation approach requires special care to avoid double counting when such streams are combined. In a simplified way, if a process unit receives more than one renewable natural resource then their ECEC cannot be added. Instead, the largest value of ECEC is selected. Non-renewable resources are considered additive (Odum 1996).

If all natural resources can be added, then ECEC for each unit's product(s), $C_{p,k}$, is calculated as

$$\mathbf{C_p} = \boldsymbol{\Gamma}_\mathbf{i} \cdot \boldsymbol{\eta}_\mathbf{n}^{-1} \cdot \mathbf{B_n} \tag{23.8}$$

where $\boldsymbol{\eta}_\mathbf{n}$ is a diagonal matrix with $\eta_{n,k}$ forming the diagonal terms. The allocation matrix, $\boldsymbol{\Gamma}_\mathbf{i}$, can be calculated as

$$\boldsymbol{\Gamma}_\mathbf{i} = \boldsymbol{\gamma}_\mathbf{p} \cdot \left(\mathbf{I} - \boldsymbol{\gamma}^\mathrm{T}\right)^{-1} \tag{23.9}$$

where $\boldsymbol{\gamma}$ is the matrix of transaction coefficients representing the interaction between units γ_{ij}, and $\boldsymbol{\gamma}_\mathbf{p}$ is a diagonal matrix with coefficients representing the fraction of the units' ECEC leaving as final product $\gamma_{p,i}$. The corresponding coefficients are

$$\gamma_{ij} = \frac{B_{ij}}{\sum\limits_{j} B_{ij} + B_{p,i}} \tag{23.10}$$

and

$$\gamma_{p,i} = \frac{B_{p,i}}{\sum\limits_{j} B_{ij} + B_{p,i}} \tag{23.11}$$

When natural resource inputs cannot be added, a special algorithm must be applied on the allocation matrix $\boldsymbol{\Gamma}_\mathbf{i}$. The algorithm is described in detailed by Hau and Bakshi. The j-th column of the allocation matrix $\boldsymbol{\Gamma}_\mathbf{i}$ contains the fraction of ECEC of the j-th natural resource assigned to each product. The algorithm multiplies each column of the allocation matrix by the ECEC of its corresponding natural resource. Then, all numbers of the set of non additive inputs in each row, except the maximum, are set to zero. This algorithm is also equivalent to doing separate ECEC analyses for each natural resource input to obtain multiple ECEC values at each network edge corresponding to each ecological input. The ECEC values at each edge are added for additive ecological inputs, or the maximum value is taken for non-additive natural resources.

Thermodynamic Input-Output Analysis

Thermodynamic Input-Output Analysis recognizes the network structure of the integrated Economic–Ecological–Social (EES) system shown in Fig. 23.2. Such a system is an open thermodynamic system with energy inputs from the three fundamental sources of energy, namely sunlight, geothermal heat and tidal or gravitation forces. The fourth fundamental source, namely nuclear energy, has not been considered as it does not appear naturally in ecosystems. In addition, internal energy storages such as petroleum reservoirs, coal stocks and metallic and non-metallic mineral deposits have been considered in the proposed approach. Material may also enter the EES system in the form of national imports and exit in the form of national exports. Imports and exports, however, have not been considered in this analysis as their inclusion would require knowledge about the global economy that is beyond the scope of this chapter.

Thermodynamic Input-Output Analysis focuses on the economic system which is divided into smaller functional units called industry sectors. In the U.S., this task is accomplished by the Bureau of Economic Analysis that defines industry sectors according to Standard Industry Classification (SIC) or North American Industrial Classification System (NAICS) codes. Ecological system, on the other hand, is divided into four conceptual ecospheres that encompass land (lithosphere), water (hydrosphere), air (atmosphere) and living flora and fauna (biosphere). Such

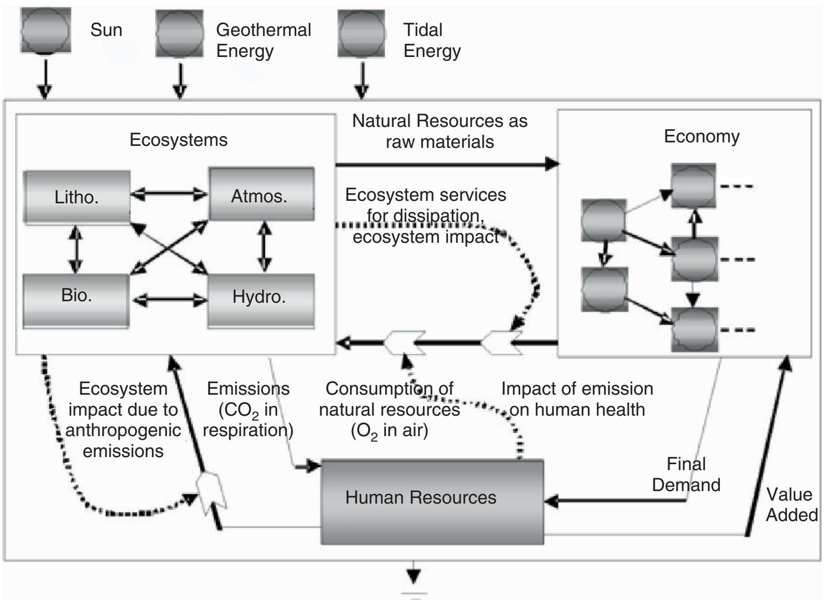

Fig. 23.2 Integrated Economic–Ecological-Human Resource System (Solid Lines Represent Tangible Interactions and Dotted Lines Represent Intangible Interactions Occurring as a Consequence of Emissions)

classification assists categorization of vast number of ecological resources into smaller groups that are easier to work with, and is not critical to the applicability of TIOA. Any other user-defined classification scheme would also work as long as renewable and non-renewable resources are distinguished.

Figure 23.2 also shows interactions between economic, ecological and social systems. Interactions represented by solid lines arise on account of resource consumption and emissions, whereas those represented by dotted lines are intangible interactions indicating impact of emissions on human and ecosystem health. For instance, the dotted arrow between the economy and the ecosystems represents ecological services required for dissipating industrial emissions and their impact on ecosystem health. The solid arrow from the ecosystems to the economy, on the contrary, represents tangible interactions that include consumption of ecological resources as raw materials by the economic activity. Figure 23.2 presents a holistic picture of all interactions between economy, ecosystem and human resources. The analysis presented in Section "Hybrid Thermodynamic LCA of Geothermal and Coal-Fueled Electricity" focuses primarily on inputs of natural resources and human resources to industry sectors and emissions from them. It also considers interactions between ecological processes implicitly through the use of transformity values.

The network structure of the economic system and monetary interactions between industry sectors are typically well-known. They are also the primary subjects of analysis in economic input-output literature (Miller and Blair 1985; Leontief, 1936). Conversely, the network structure of ecological system need not be completely known as the underlying ECEC analysis can deal with partially-known ecological networks using appropriate allocation rules, as mentioned in Section "Thermodynamic Input-Output Analysis" and described in detail by Hau and Bakshi (2004b). ECEC analysis also provides a common unit to compare economic and ecological resources, as any system, economic or ecological can be considered as a single network of energy flows (Odum 1996). The emphasis of this paper is not on predicting how a complex, holarchic and chaotic system such as the EES system would evolve under the influence of external energy sources (Kay and Reiger 2000), but to analyze available resource consumption and emissions data to understand how different industry sectors rely on ecosystems for their operations. In other words, Thermodynamic Input-Output Analysis does not attempt to forecast emergent, non-linear, non-equilibrium and self-organizing properties of the EES system, but assumes that these properties are manifested in the measured material and energy flows. The algorithm of Thermodynamic Input-Output Analysis can be summarized in the form of following three tasks.

1. *Identify and quantify ecological and human resource inputs to the economic system.* Ecological inputs include ecosystem products such as crude oil, metallic and non-metallic minerals and atmospheric nitrogen, and ecosystem services such as wind and fertile soil. Human resources include employment of labor for economic activities. Emissions and their impact on human and ecosystem health are also included.
2. *Calculate ECEC of ecological inputs* using transformity values from systems ecology. These inputs are classified as additive or non-additive to be consistent

with the network algebra rules used in emergy analysis (Odum 1996). In general, non-renewable resources are additive, while renewable resources are non-additive.

3. *Allocate direct inputs to economic sectors using input-output data and the network algebra of ECEC analysis* (Hau and Bakshi 2004b). The network algebra of ECEC analysis is based on a *static* input-output representation of the economic system. Dynamic versions of input-output analysis that consider temporal changes in the economic network are also available, and are currently being explored. Also, use of monetary data for allocation is not a limitation of the approach, but is rather caused by a lack of comprehensive material or energy accounts of inter-industry interactions.

Data Requirements and Sources

This section describes the resources considered in this analysis, along with their data sources. All required data have been obtained from non-proprietary public-domain databases.

Transformities

Ecological Cumulative Exergy Consumption of ecological and human resources has been determined via their transformity values (Odum 1996; Brown and Bardi 2001; Brandt-Williams 2002). As discussed in Section "Ecological Cumulative Exergy Consumption (ECEC) Analysis", transformities can be viewed as reciprocals of global exergetic efficiencies of ecological resources. Consequently, they enable calculation of total exergy consumption in the economic and ecological stages of a production chain. Transformities, as used in this analysis, are not subject to the controversial aspects of Odum's work such as maximum empower principle, emergy theory of value or energy consumption over geological time scales. Transformities used in this analysis correspond to the 1996 base of 9.44×10^{24} sej/year (Odum 1996). These numbers are based on the best current knowledge of the behavior of natural systems. Even though this knowledge is incomplete, accounting for the contribution of ecosystems provides valuable insight into their crucial role and complements other approaches that ignore ecosystems.

Ecosystem Products

Ecosystem products refer to ecological resources used as direct raw materials in industrial processes. They can be measured in terms of material or energy flows. Table 23.1 lists the ecosystem products considered in this analysis, the industry

Table 23.1 Ecosystem Products[a]

Resources considered	Sector receiving direct input and corresponding NAICS codes	Energy or material flow (F)	Data source for F
Lithosphere			
Crude petroleum field production	Oil and gas extraction (NAICS 211000)	1.06×10^{19} J/year	(USDOE 2004a)
Natural gas extraction	Oil and gas extraction (NAICS 211000)	18.9 MMCuF/year	(USDOE 2004b)
Iron-ore mining	Iron ore mining (NAICS 212210)	202 MMT/year	(USGS 2004a)
Copper mining	Copper, nickel, lead and zinc mining (NAICS 212230)	342 MMT/year	(USGS 2004a)
Gold mining	Gold, silver and other metal mining (NAICS 2122A0)	217 MMT/yr	(USGS, 2004a)
Crushed stone	Stone mining and quarrying (NAICS 212310)	1,390 MMT/year	(USGS 2004a)
Sand	Sand, gravel, clay and refractory mining (NAICS 212320)	961 MMT/year	(USGS 2004a)
Raw coal excluding overburden	Coal mining (NAICS 212100)	988 MMT/year	(USGS 2004a)
Nitrogen from mineralization	Farming sectors (NAICS 1111A0–1119B0)	2.96 MMT/year	(Ayres and Ayres 1998)
Phosphorous from mineralization	Farming sectors (NAICS 1111A0–1119B0)	1.97 MMT/year	(Ayres and Ayres 1998)
N-deposition from atmosphere	Farming sectors (NAICS 1111A0–1119B0)	1.97 MMT/year	(Ayres and Ayres 1998)
Return of detritus to agricultural soil	Farming sectors (NAICS 1111A0–1119B0)	−433 MMT/year	(Ayres and Ayres 1998)
Biosphere			
Wood production	Logging (NAICS 113300)	520 MMT/year of roundwood	(Ayres and Ayres 1998)
Pasture grazing	Cattle ranching and farming (NAICS 112100)	200 MMT/year of wet grass	(Ayres and Ayres 1998)
Hydrosphere			
Water consumption	Water and sanitary services (SIC 68C)	1.47×10^{14} gal/year	(USGS 2004b)
ATMOSPHERE			
CO_2 in 24-h net photosynthesis	Other agricultural products (SIC 2)	867 MMT/year	(Ayres and Ayres 1998)

(continued)

Table 23.1 (continued)

Resources considered	ICEC flow (J/year)	Transformity (τ)	Data source for τ	ECEC flow (C = F.τ) (sej/year)
Lithosphere				
Crude petroleum field production	1.06×10^{19}	53,000 sej/J	(Odum 1996)	5.61×10^{23}
Natural gas extraction	$1.99 \times 1019^{(b)}$	48,000 sej/J	(Odum 1996)	$9.58 \times 10^{23(c)}$
Iron-ore mining	$2.08 \times 1{,}016$	1×10^9 sej/g	(Odum 1996)	2.02×10^{23}
Copper mining	$2.80 \times 1{,}016$	1×10^9 sej/g	(Odum 1996)	3.42×10^{23}
Gold mining	$5.63 \times 1{,}016^{(d)}$	1×10^9 sej/g	(Odum 1996)	2.17×10^{23}
Crushed stone	$1.83 \times 1{,}017$	1×10^9 sej/g	(Odum 1996)	1.39×10^{24}
Sand	$1.27 \times 1{,}017$	1×10^9 sej/g	(Odum 1996)	9.61×10^{23}
Raw coal excluding overburden	$5.73 \times 1{,}019$	1×10^9 sej/g	(Odum 1996)	9.88×10^{23}
Nitrogen from mineralization	$1.15 \times 1{,}015$	4.19×10^9 sej/g	(Odum 1996)	1.24×10^{22}
Phosphorous from mineralization	$9.75 \times 1{,}014$	2×10^9 sej/g	(Odum 1996)	3.94×10^{21}
N-deposition from atmosphere	$7.76 \times 1{,}014$	4.19×10^9 sej/g	(Odum 1996)	8.25×10^{21}
Return of detritus to agricultural soil	-8.77×1018	2.24×10^8 sej/g of residue	(Odum 1996)	-9.70×10^{22}
Biosphere				
Wood production	$8.27 \times 1{,}018$	5.55×10^8 sej/g	(Odum 1996)	2.90×10^{23}
Pasture grazing	$1.67 \times 1{,}018$	5.83×10^{19} sej/ MMT of wet grass	(Odum 1996)	1.17×10^{22}
Hydrosphere				
Water consumption	2.73×10^{18}	7.67×10^8 sej/gal	(Brandt-Williams 2002)	1.13×10^{23}
ATMOSPHERE				
CO_2 in 24-h net photosynthesis	0	6.19 sej/g CO_2	(Odum 1996)	5.37×10^{22}

[a]Detailed calculations provided in Ukidwe and Bakshi (2004) and Ukidwe (2005) unless mentioned otherwise.

[b](18.9 MMCuF/year dry production) $\times$ (10^6ft^3/MMCuF) $\times$ (1,000 BTU/ft^3) $\times$ (1055.9 J/BTU) $= 1.99 \times 10^{19}$ J/year.

[c](18.9 MMCuF/year dry production) $\times$ (10^6ft^3/MMCuF) $\times$ (1,000 BTU/ft^3) $\times$ (1,055.9 J/BTU) $\times$ (48,000 sej/J) $= 9.58 \times 10^{23}$ sej/year.

[d](217 MMT/year) $\times$ (10^{12}g/MMT) $\times$ (259.5 J/g standard exergy for Au_2O_3) (Szargut et al. 1988) $= 5.63 \times 10^{16}$ J/year.

sectors that receive their direct inputs and corresponding data sources. Ecosystem products are not only produced but also made available to economic consumption by various natural functions. For instance, metallic and non-metallic minerals and fossil fuels are made available to extraction by the geologic cycle, whereas, aerial oxygen, used during combustion processes, is a part of the atmospheric circulation. In Table 23.1, the ecological products are assigned to the four ecospheres based on their mode of entry into the economic system. For example, N-deposition from atmosphere is considered as an input from lithosphere because nitrogenous salts enter plants through soil.

Ecosystem Services

Unlike ecosystem products, ecosystem services need not be accompanied by material or energy transactions. For instance, wind or geothermal heat used in renewable electricity alternatives can be measured in terms of their energy content. In this analysis, such services are called *supply-based* services since their contribution can be quantified independent of human valuation. On the contrary, services required for recreational and cultural purposes depend on human valuation, and need not be accompanied by material or energy flows. These are referred to as the *value-based* services. This analysis focuses only on supply-based services. Value-based services are dealt with in Costanza et al. (1997) and Balmford et al. (2002), and may be included in the future.

Human Resources

Industry sectors consume human resources in the form of labor. Amount of human resources consumed is a function of number of individuals employed and their skill-level. In this paper, average annual payroll is chosen as a measure of the quality of labor. Data about number of people employed and their average annual payroll are available from U.S. Department of Labor's Bureau of Labor Statistics (BLS 2004).

In this analysis, human resources are considered to be exogenous to the economic model representing inter-industry interactions. Therefore, in the absence of a single input-output model integrating industry sectors and social sectors, interactions between economy and human resources need to be considered independently. This is done through the use of transformity of unskilled labor, obtained from Odum (1996), and calculated as the ratio of the total emergy budget to the total population of the U.S. Odum assumes that the total emergy input to the U.S. economy is passed on to human resources via final demand which represents sale of economic goods and services to consumers, and consumers, in turn, feed the emergy flow back to the economy via value added which includes employment of labor. Hence, human resources, as considered in this analysis, incorporate natural capital flows between economy and human resources. Moreover, the per capita emergy budget of the U.S. can be used to represent unskilled labor as only half the U.S. population was employed in 1997. The remaining half comprised of minors, retirees and unemployed people.

Impact of Emission on Human Health

Industrial emissions affect human health in myriad ways. The actual impact depends on the fate of a pollutant in the natural environment and its effect on human well being. The fate itself depends on numerous physico-chemical phenomena such as dispersion, diffusion and atmospheric chemistry. There are several established procedures for calculating the impact of emissions on human health. The approach employed in this analysis represents the impact of several common pollutants on human health in terms of Disability Adjusted Life Years (DALY). This is an end-point impact assessment methodology that considers several impact categories including respiratory disorders, photochemical smog formation, ozone layer depletion, climate change and carcinogenicity (Hofstetter 1998; Goedkoop and Spriensma 1999). Table 23.3 lists pollutants considered in this work, the impact categories they belong to and corresponding DALY values per kg of emission. Emissions data were gathered from the U.S. Environmental Protection Agency's Toxics Release Inventory (TRI) (USEPA 1999). The approach for converting DALYs to ECEC has been discussed in Ukidwe and Bakshi (2004) and Ukidwe (2005). Additional pollutants are currently being included in this work. Furthermore, the analysis presented in this chapter does not consider impact of emissions on ecosystem health. This is a non-trivial task as populations and population distributions of plants and animals can vary widely in space and time and so can their response to various pollutants. Consequently impact parameters for various species of plants and animals are not readily available. Aggregate impact parameters such as Potentially Affected Fraction (PAF) and Potentially Disappeared Fraction (PDF) of vascular plant species may be used in TIOA in the future, but are beyond the scope of this chapter.

Allocation Matrix for Inter-Industry Interactions

This analysis uses a monetary, inter-industry transaction coefficient matrix to represent U.S. economic system. In the U.S. such matrix is compiled periodically by the Department of Commerce's Bureau of Economic Analysis. More specifically, results presented in Section "Hybrid Thermodynamic LCA of Geothermal and Coal-Fueled Electricity" are based on 488-sector 1997 U.S. inter-industry benchmark model (BEA 2004). Similar results have been published in the past for the 91-sector 1992 model which is a more concise and aggregated representation of the U.S. economy (Ukidwe and Bakshi 2004; Ukidwe 2005). An allocation matrix based on material or energy interactions between industry sectors would be more accurate than a monetary transaction matrix, but is not available at present. The "materials count" initiative undertaken by United States National Research Council (NRC 2004) is an example of efforts that strive to compile a biophysical transaction matrix for the U.S. economy. If this initiative materializes, more accurate data could be used for inter-industry allocation.

Aggregate Metrics for 488-Sector 1997 U.S. Economy

This section presents the aggregate metrics for the 488-sector 1997 U.S. economy. The aggregate results have been obtained by combining ECEC flows for individual resources listed in Tables 23.1, 23.2 and 23.3. Such aggregation is possible because results for all the resources are expressed in a single consistent thermodynamic unit of solar equivalent joules. Also, as mentioned in Section "Data Requirements and Sources", all the resources cannot be aggregated blindly as it may lead to double-counting. This is especially true in case of renewable ecosystem products and services that originate from the same source and are co-products of the same primary energy driver. Hence, renewable resources are considered to be non-additive, and aggregate results for them, shown in Figs. 23.3 and 23.4, are obtained by allocating each resource independently through the economic network, followed by taking the maximum along each network branch. Non-renewable ecosystem resources, human health impact of emissions and contribution of human resources, on the contrary, are considered to be additive and can be readily summed. More details about the aggregation rules can be found in Odum (1996) and Hau and Bakshi (2004b). It is also necessary to note that the choice of allocation rules is usually a subjective decision. It is a problem faced not only by TIOA but also by LCA in general. A plausible solution to address this problem is to determine the sensitivity of results obtained from TIOA to different allocation rules. It may also be possible to select system boundaries that avoid allocation altogether (Weidema 2001). The application of such techniques to the analysis presented in this chapter is a part of the ongoing research. The results shown in this section provide a unique insight into natural and economic capital flows in US macroeconomic system. Such insight is useful for understanding the implications of corporate restructuring on industrial sustainability metrics, and of outsourcing of business activities on outsourcer, outsourcee and global sustainability (Ukidwe and Bakshi 2005).

Total ECEC

Figure 23.3 shows total ECEC requirements from non-renewable and renewable ecosystem resources, human health impact of emissions, contribution of human resources and their total for the 28 major subdivisions of the U.S. economy. These

Table 23.2 Ecosystem Services[(a)]

Ecosystem service	Sector receiving direct input and corresponding SIC code	Energy or material flow (F)	Data source for F
Sunlight for photosynthesis	Farming sectors (NAICS 1111A0–1119B0)	2.23×10^{22} J/year	(USDOA 2004; NASA 2004)
	Forest nurseries, forest products and timber tracts (NAICS 113A00)	1.19×10^{22} J/year	(NASA 2004)
Hydropotential for power generation	Power generation and supply (NAICS 221100)	1.28×10^{18} J/year	(USDOE 2004c)
Geothermal heat for power generation	Power generation and supply (NAICS 221100)	5.3×10^{16} J/year	(USDOE 2004c)
Wind energy for power generation	Power generation and supply (NAICS 221100)	1.18×10^{16} J/year	(USDOE 2004c)
Fertile Soil	Farming sectors (NAICS 1111A0–1119B0)	34.49×10^{8} t/year	(Adriaanse et al. 1997; Matthews et al. 2000)
	Construction sectors (NAICS 230110–230250)	35.65×10^{8} t/year	(Adriaanse et al. 1997; Matthews et al. 2000)

Ecosystem Service	ICEC flow (J/year)	Transformity (τ)	Data source for τ	ECEC flow ($C = F \times \tau$) (sej/year)
Sunlight for photosynthesis	2.23×10^{22}	1	(Odum 1996)	2.3×10^{22}
	1.19×10^{22}	1	(Odum 1996)	1.19×10^{21}
Hydropotential for power generation	1.28×10^{18}	27,764	(Odum 1996)	3.55×10^{22}
Geothermal heat for power generation	5.83×10^{16}	6,055	(Odum 1996)	3.21×10^{20}
Wind energy for power generation	1.18×10^{16}	1,496	(Odum 1996)	1.77×10^{19}
Fertile soil	3.12×10^{18}	4.43×10^{4}	(Brandt-Williams 2002)	1.38×10^{23}[a]
	3.22×10^{18}	4.43×10^{4}	(Brandt-Williams 2002)	1.43×10^{23}

[a]Detailed calculations provided in Ukidwe and Bakshi (2004) and Ukidwe (2005).

Table 23.3 Pollutants, Immediate Destination of Emission and Impact Category

Pollutant	Immediate destination of emission	Impact category	DALY/kg of emission[a]	ECEC/kg of emission (sej/kg)
SO_2	Air	Respiratory disorders	5.46×10^{-5}	1.86×10^{12}[b]
NO_2	Air	Respiratory disorders	8.87×10^{-5}	3.03×10^{12}
PM10	Air	Respiratory disorders	3.75×10^{-4}	1.28×10^{13}
CO_2[c]	Air	Climate change	2.1×10^{-7}	7.17×10^{9}
Methanol	Air	Respiratory disorders	2.81×10^{-7}	9.59×10^{9}
Ammonia	Air	Respiratory disorders	8.5×10^{-5}	2.90×10^{12}
Toluene	Air	Respiratory disorders	1.36×10^{-6}	4.64×10^{10}
1,1,1-TCE	Air	Ozone layer depletion	1.26×10^{-4}	4.30×10^{12}
Styrene	Air	Carcinogenic effect	2.44×10^{-8}	8.33×10^{8}
Styrene	Water	Carcinogenic effect	1.22×10^{-6}	4.16×10^{10}
Styrene	Soil	Carcinogenic effect	2.09×10^{-8}	7.13×10^{8}

[a]DALY values are based on Hierarchist Perspective (Goedkoop and Spriensma 1999).
[b]Human Health Impact of emission per kilogram of SO_2 emission = (5.46×10^{-5}DALY/kg of SO_2 emission) × (365 days/year) × (9.35×10^{13}sej emergy associated with unskilled labor/workday) = 1.86×10^{12} sej/kg; Emergy of unskilled labor is obtained from emergy literature (Odum 1996), and is obtained by dividing total emergy budget of the U.S. (7.85×10^{24} sej/year) by the total population of the U.S. (230×10^{6} people).
[c]Impacts are potential impacts in future (Goedkoop and Spriensma 1999).

subdivisions are listed in Table 23.4, and have been defined by the Bureau of Economic Analysis (BEA 2004). They have also been used in economic input-output life cycle assessment (EIOLCA 2004). This aggregation scheme is preferred in this analysis as it provides a more concise overview of the economy than the three-digit NAICS codes, and yet is more detailed than the two-digit NAICS codes. The trend and general conclusions are similar for alternate methods of aggregation as well.

Figure 23.3 shows the median value for each subdivision. Mining and utilities subdivision has the highest ECEC throughput from non-renewable resources, whereas Arts, Entertainment, Recreation, Hotels and Food Services subdivision has the lowest. Agriculture, Forestry, Fishing and Hunting subdivision relies heavily on sunlight for photosynthesis and fertile soil, and consequently, has the highest me-

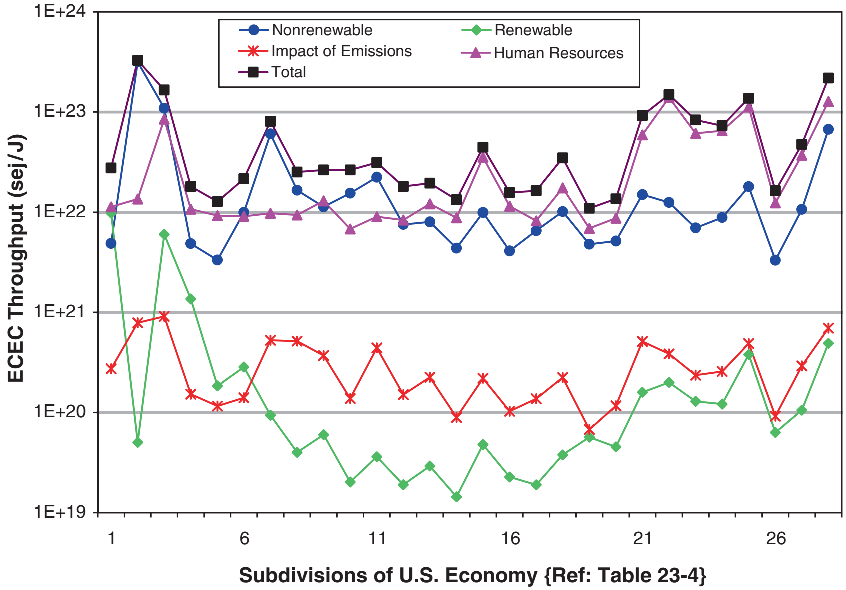

Fig. 23.3 Total ECEC Requirement

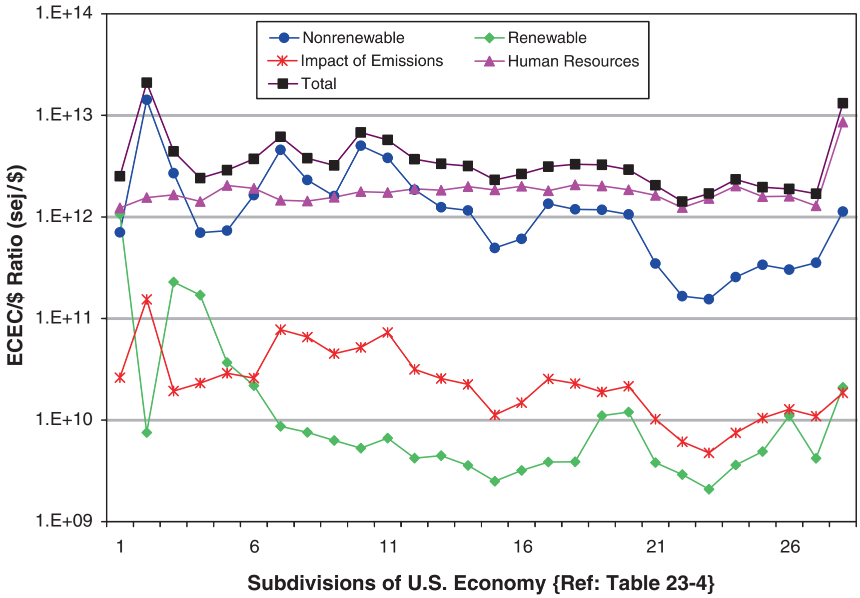

Fig. 23.4 ECEC/Money Ratios

dian throughput of renewable resources. On the contrary, Engines and Machinery subdivision has the lowest median throughput of renewable resources. Construction subdivision (Position 3 NAICS 23) has the highest median human health impact of emissions. If individual industry sectors are considered, sector of Power Generation and Supply (NAICS 221100) has the highest human health impact primarily due to high CO_2 and SO_2 emissions. On the contrary, sectors of Software Producing (NAICS 334611) and Musical Instruments Manufacturing (NAICS 339992) have some of the lowest human health impact of emissions. Service subdivisions, located at the bottom of Table 23.4, in general, have a higher contribution from human resources than the manufacturing and resource extraction subdivisions. Finance, Insurance, Real Estate, Rental and Leasing subdivision and Plastic, Rubber and Nonmetallic Mineral Products subdivision have the highest and the lowest contributions from human resources respectively.

As seen from Fig. 23.3, contribution from non-renewable resources far exceeds that from renewable resources for all subdivisions except the Agriculture, Forestry, Fishing and Hunting subdivision. This is so because a vast majority of manufacturing and service activity in the U.S. relies on non-renewable fossil energy sources, whereas agricultural activity has substantial inputs from sunlight and fertile soil, both of which are renewable resources. Similarly contribution from human resources dominates the total ECEC requirement for advanced manufacturing and service subdivisions, but is lower than the contribution from non-renewable resources for basic manufacturing and mining subdivisions. The results presented in Fig. 23.3 provide the *thermodynamic basis* or the extent to which various industrial activities rely on ecological resources, considering all direct as well as indirect interactions in the economic network. Total ECEC requirement is comparable to the concept of *ecological cost*, defined by Szargut as “the cumulative consumption of non-renewable exergy in all links of the production network and connected with the fabrication of the considered product” (Szargut 1999). Results presented in Fig. 23.3 not only calculate this cost but also enhance it in following two aspects – (i) unlike ecological cost, results presented in Fig. 23.3 consider renewable and non-renewable ecosystem products and services, human health impact of emissions and contribution from human resources, and (ii) account for the exergy consumption in the ecological *and* economic links of a production network. Results presented in Fig. 23.3 can be used to determine industry-specific pro-ecological taxes. Such taxes have been introduced in Europe, and are being debated in the U.S. (Szargut 2002). ECEC by itself is of limited use for sustainable decision making. A normalized metric that compares ECEC throughput to economic throughput is more insightful, and is discussed next.

ECEC/Money Ration

Figure 23.4 shows median ECEC/money ratios for the 28 major subdivisions of the U.S. economy listed in Table 23.4. These ratios have been calculated by dividing the

Table 23.4 Twenty-Eight Major Subdivisions of U.S. Economy and Corresponding NAICS Codes

Position in Figs. 23.2–23.4	Subdivision of U.S. economy	NAICS codes
1	Agriculture, forestry, fishing and hunting	11
2	Mining and utilities	21, 22
3	Construction	23
4	Food, beverage and tobacco	311, 312
5	Textiles, apparel and leather	313, 314, 315, 316
6	Wood paper and printing	321, 322, 323
7	Petroleum, coal and basic chemical	324, 3251
8	Resin, rubber, artificial fibers and agricultural and pharmaceutical manufacturing	3252, 3253, 3254
9	Paint, coating, adhesives, cleaning and other chemicals	3255–3259
10	Plastic, rubber and nonmetallic mineral products	326, 327
11	Ferrous and non-ferrous metal production	331, 3321
12	Cutlery, handtools, structural and metal containers	3322–3324
13	Ordnance and other metal products	3325–3329
14	Engines and machinery	333
15	Computers, audio, video and communication equipment	3341, 3342, 3343
16	Semiconductors, electronic equipment, media reproduction	3344, 3345, 3346
17	Lighting, electric components, batteries and other	335
18	Vehicles and other transportation equipments	336
19	Furniture, medical equipment and supplies	337, 3391
20	Misc. manufacturing	3399
21	Trade, transport and information	42, 45, 45, 48, 49, 51
22	Finance, insurance, real estate, rental and leasing	52, 53
23	Professional and technical services	54
24	Management, administrative and waste services	55, 56
25	Education and health care services	61, 62
26	Arts, entertainment, recreation, hotels and food services	71, 72
27	Other services except public administration	81
28	Government and special	S00101–S00500

ECEC throughput of each industry sector by corresponding economic throughput. Figure 23.4 also shows separate ECEC/dollar ratios for non-renewable and renewable ecological resources, human health impact of emissions, contribution of human resources and their total. In this case, gross economic throughput or economic activity refers to the gross output of industries expressed in monetary units. It is the sum of intermediate inputs and value added or, alternatively, the sum of intermediate outputs and final demand (Miller and Blair 1985).

The ECEC/money ratio is conceptually identical to emergy/money ratio in emergy analysis, and similar ratios in thermoeconomics (Szargut 2002; Sciubba 2003). The numerator of this ratio represents the consumption of natural capital whereas the denominator represents generation of economic capital. As a result, it may be considered as an indicator of how different industry sectors value natural capital. It quantifies the discord between the thermodynamic basis of economic activity and the willingness of people to pay. Such discord is widely believed to be the primary cause behind the inadequate appreciation of ecological resources in the economic system leading to their wide-spread degradation (Ayres 1998a, b). Results presented in Fig. 23.4 quantify the magnitude of such discord for the 28 major subdivisions of the US economy. Ratios for 488 individual industry sectors could not be included in this chapter due to size restrictions, but are available in Ukidwe (2005). ECEC/money ratios are not meant to either support or debunk any theory of value, but only to juxtapose natural capital consumption vis-à-vis economic capital generation. Industry-specific ECEC/money ratios offer a major improvement over traditional emergy analysis or thermoeconomics that provide a single, aggregate ratio for the entire economy. The wide variation in these ratios in Fig. 23.4 further emphasizes the heterogeneous nature of the contemporary economic system, and the need to distinguish between industry sectors rather than lumping everything into a single aggregate metric. Figure 23.4 leads to several notable observations, some of which are listed below along with their interpretation.

Mining and utilities subdivision has the highest ECEC/dollar ratio whereas Finance, Insurance, Real Estate, Rental and Leasing subdivision has the lowest ECEC/dollar ratio. In general, the advanced manufacturing and service subdivisions have lower ECEC/dollar ratios than the resource extraction and basic manufacturing subdivisions.

ECEC/dollar ratios for non-renewable resources are higher than those for renewable resources for all subdivisions except for Agriculture, Forestry, Fishing and Hunting subdivision. Agricultural and forestry activities convert sunlight and fertile soil into organic biomass, and rely primarily on renewable resources. Other subdivisions, on the contrary, rely more on non-renewable resource that include metallic and non-metallic minerals and fossil fuels.

The variation in ECEC/dollar ratio for human resources is an order of magnitude smaller than that for renewable and non-renewable ecological resources and human health impact of emissions. This is not surprising, as human resources are better internalized in economic prices than ecological resources. For instance, human resources are paid wages commensurate with their skill level, but ecological resources are obtained for free. In this analysis human resources are accounted for via economic data that includes number of people employed and their average annual payroll. Government and Special subdivision has the highest ECEC/dollar ratio for human resources. This is because state, local and federal government enterprises together employ the maximum number of people amongst all industry sectors, but the economic throughput in this subdivision is relatively small.

ECEC/dollar ratios for non-renewable resources dominate the total for resource extraction and infrastructure subdivisions such as Mining and Utilities, Petroleum, Coal and Basic Chemical and Plastic, Rubber and Nonmetallic Mineral Products. On the contrary, ECEC/dollar ratios for human resources dominate the total for advanced manufacturing and service subdivisions. This observation also holds within each subdivision. For instance, within the Finance, Insurance, Real estate, Rental and Leasing subdivision human-resource intensive Insurance Carriers sector has the highest relative contribution from human resources (96.4%), whereas the sector of Real Estate has the lowest relative contribution from human resources (64%), implying that the latter sector may be less dependent on intellectual capital. Whether growth of intellectual capital can be decoupled from the use of natural capital, and to what extent, and whether there are limits to this decoupling are all relevant and interesting questions that are beyond the scope of this analysis.

Recycling of material in the economy would also affect ECEC/money ratios. Since recycling can reduce the consumption of pristine ecological resources, while generating economic activity, increased recycling would lower ECEC/money ratios throughout the economic network. Operating facilities for separating and sorting recyclable materials from non-hazardous waste streams and for sorting commingled recyclable materials into distinct categories have been included in this analysis via the sector of Material Recovery Facilities that is a part of the sector of Waste Management and Remediation Services. Similarly, recycling of individual materials, though beyond the scope of this analysis, can also be included if corresponding data are available.

A look at how economic and natural capitals accumulate across economic subdivisions reveals that, in general, as one goes from the more sophisticated service subdivisions to the basic extraction subdivisions, contribution of natural capital increases disproportionately to the economic activity. This is evident from higher ECEC/money ratios for the basic infrastructure subdivisions and lower ECEC/money ratios for service subdivisions. Basic infrastructure subdivisions depend a lot more on ecosystems, but contribute relatively little to the economic activity. One plausible reason for this is that the basic infrastructure subdivisions are thermodynamically less efficient due to having to process a relatively dilute resource, and as a result, have to consume a lot of raw material to produce finished product or service. This gives rise to large *overburdens* or the material moved by extraction that does not enter the economy. Other reasons for the high ECEC/money ratio for the extractive industries could be economic subsidies and failure of market prices to fully appreciate the contribution of ecological resources and the environmental impact of these activities. Furthermore, people tend to value services and finished products much more than intermediate items, while ecosystem goods and services become economic externalities and are rarely reflected in prices.

The decreasing ratio of natural to economic capital along the economic supply chain conforms to the convex correlation between cumulative impact of emissions and cumulative value-added suggested by other studies (Clift and Wright 2000).

Environmental and economic aspects of supply chains have been studied in the past, often in the context of the effect of free trade agreements, or for specific industrial products such as electronic consumer goods. However, these studies usually do not consider natural capital or indirect effects, and focus only on environmental impact. The approach presented in this chapter does not suffer from this shortcoming and is more complete than existing analyses. It does not provide a substitute for existing economic methods, but rather complements them by bringing forth the biophysical angle.

ECEC/ICEC Ratio

This ratio estimates the extent to which traditional Industrial Cumulative Exergy Consumption (ICEC) Analysis underestimates the contribution of ecosystems. ICEC analysis focuses only on the industrial stages of a production chain ignoring the ecological stages altogether. Consequently, ICEC analysis cannot acknowledge quality differences between ecological resources including their renewable and non-renewable nature. As a result, according to ICEC analysis 1 J of sunlight is identical to 1 J of coal, though sunlight is renewable and readily available, whereas coal is non-renewable and requires a significant amount of work to be done in ecosystems in the form of geological cycles that concentrate minerals to enable their mining. ECEC analysis overcomes this shortcoming by estimating cumulative exergy consumption of ecological resources via their transformity values. Since, in general, renewable resources have lower transformities than the non-renewable resources, an industry sector relying more on renewable resources would have a lower ECEC/ICEC ratio and vice versa. *Therefore ECEC/ICEC ratio is potentially useful as a proxy-indicator of "degree of non-renewability" of industry sectors* (Berthiaume et al. 2001).

Figure 23.5 shows median ECEC/ICEC ratios for the 28 economic subdivisions listed in Table 23.4 along with the spread of distribution in each subdivision. Mining and Utilities, Government and Special and Ferrous and Non-ferrous metal Production subdivisions have the highest median ECEC/ICEC ratios suggesting that they rely on non-renewable resources the most. Agriculture, Forestry, Fishing and Hunting has the lowest median ECEC/ICEC ratio suggesting that it is least dependent on non-renewable resources. Food, Beverage and Tobacco and Wood Paper and Printing, subdivisions that rely on agricultural and forestry activities for raw materials, also have low ECEC/ICEC ratios. A more comprehensive analysis is required to evaluate the validity of this correlation. The median ECEC/ICEC ratio for the entire economy is 1,275 sej/J indicating that ecosystems have to expend 1,275 J of energy in solar equivalents to make 1 J of an average ecological resource available to an average industrial activity.

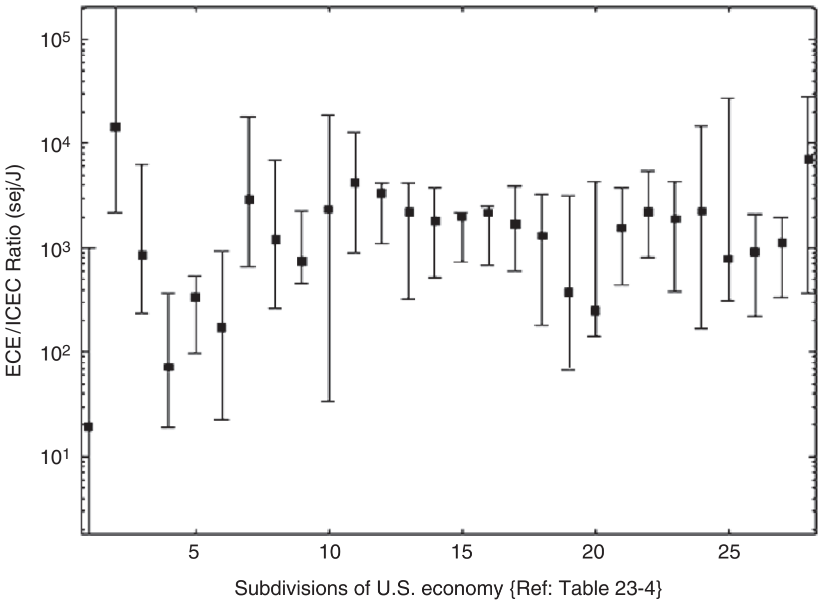

Fig. 23.5 ECEC/ICEC Ratios

Hybrid Thermodynamic LCA of Geothermal and Coal-Fueled Electricity

ECEC/money and ICEC/money ratios are particularly useful in hybrid thermodynamic life cycle analysis of industrial systems. A hybrid analysis integrates data and models of a process or a product system with economy-scale input-output information, and in the process, combines accurate, process-specific data with coarser economy-scale data (Suh et al. 2004). Consequently, hybrid analysis not only improves upon the comprehensiveness of process-LCA but also provides results specific for a product or process rather than for an entire economic sector. ECEC/money and ICEC/money ratios can come in handy in integrating process-scale information with economy-scale information because interactions of a product system with the rest of the economy are typically captured in monetary terms in annual accounts. The resultant hybrid thermodynamic analysis identifies interactions of a product system with the rest of the economy. These interactions include purchased raw materials and services, human resources and free environmental inputs along with major emissions. The purchased inputs are subsequently assigned to appropriate industry sectors and ICEC and ECEC flows associated with them are determined by multiplying the monetary value of the purchase by corresponding ICEC/money and ECEC/money ratios respectively.

The case study presented in this section compares two alternative electricity generation systems. The main objective of this case study is to demonstrate how

Table 23.5 Comparison of Geothermal and Coal-Fueled Thermoelectric Alternatives (Ukidwe and Bakshi 2004; Ukidwe 2005)

	Geothermal	Coal-fueled thermoelectric
Annual electricity production (J/year)	3.28×10^{14}	2.44×10^{16}
Total ECEC requirement (sej/year)	3.85×10^{19}	3.22×10^{21}
Efficiencies		
Exergetic efficiency	1.38×10^{-1}	2.20×10^{-1}
Industrial cumulative degree of perfection (ICDP)	1.09×10^{-1}	1.09×10^{-1}
Ecological cumulative degree of perfection (ECDP) (J/sej)	8.52×10^{-6}	7.59×10^{-6}
Metrics		
Yield ratio (total ECEC requirement/ECEC inputs from economy)	11.5	1.1
Loading ratio (ECEC from nonrenewable resources/ECEC from renewable resources)	0.08	52
Impact/value added (ECEC of human health impact/annual electricity production)	7.53×10^{2}	1.15×10^{4}

accounting for ecosystem contribution offers a different perspective than the conventional thermodynamic methods such as exergy analysis and Industrial Cumulative Exergy Consumption (ICEC) analysis. These systems have already been studied in the past (Ulgiati and Brown 2002) using emergy analysis, allowing comparison of the new results with those obtained in the past. For the purpose of this case study, ECEC/money and ICEC/money ratios for 91-sector 1992 U.S. economy were used (Ukidwe and Bakshi 2004). More details about data sources, calculations and the underlying assumptions can be found in this reference.

As seen from Table 23.5, accounting for ecosystem contribution gives a different perspective on thermodynamic efficiencies of two systems. For instance, according to exergy analysis, the thermoelectric alternative is more efficient than the geothermal alternative, whereas according to ICEC analysis the two alternatives are nearly as efficient. However, as mentioned in "Introduction", exergy and ICEC analyses fail to appreciate the fact that geothermal heat is a renewable resource whereas coal is a non-renewable resource. ECEC analysis, on the other hand, can differentiate between renewable and non-renewable resources. Renewable resources have a higher Ecological Cumulative Degree of Perfection because they are readily available, whereas non-renewable resources have a lower ECDP because they require a substantial amount of work to be spent in ecosystems. Consequently, ECDP of the geothermal alternative is higher than that of the thermoelectric one. Because of this ability to account for ecosystem products and services, ECEC analysis is a more suitable technique for environmental decision making than the existing thermodynamic techniques such as exergy analysis and ICEC analysis. ECEC analysis also seems to have some significant advantages over traditional LCA, and additional case studies are in progress to evaluate these methods.

Table 23.5 also calculates metrics for comparing the two alternatives. Calculation of such metrics is facilitated by the use of a common thermodynamics currency, which in this case, is solar equivalent joule. Yield ratio measures the reliance on purchased inputs vis-à-vis that on free environmental inputs. This ratio is higher for processes that derive a larger portion of their inputs directly from the natural environment. In this case the yield ratio is higher for the geothermal alternative because geothermal heat is a direct environmental input. On the contrary, coal in the thermoelectric alternative is a purchased input because it is bought from the sector of coal mining. On similar lines, the loading ratio compares the reliance on renewable resources vis-à-vis that on non-renewable resources, and is higher for processes relying more on non-renewable resources. This ratio is higher for the thermoelectric alternative for obvious reasons. Finally human health impact of emissions per unit electricity production is 15 times higher for the thermoelectric alternative. A significant portion of this impact arises from direct SO_2 and NO_x emissions from the combustion of coal.

Conclusions

Ecological resources are imperative to any activity on earth. However, these resources, being mostly outside the realm of conventional markets, are often consumed in an unsustainable fashion. Existing methods for engineering design also concentrate on economic objectives while turning a blind eye on ecosystem contribution. The result is business enterprises that are viable in the short-term but potentially unsustainable in the long-term. This chapter presents a novel approach for including the contribution of ecosystems into cumulative exergy-based methods, and applies it to study the 1997 U.S. macroeconomic system. The new technique, called Thermodynamic Input-Output Analysis, synthesizes available resource consumption and emission data from various public-domain databases and transformity values from systems ecology literature to determine direct inputs to the economic system. Furthermore, it uses the 488-sector 1997 U.S. industry-by-industry input-output model to allocate exergy flows in the economic network. Such industry-specific ECEC analysis offers an insight into addressing several policy- and design-related issues at the micro- as well as the macro-scales.

The results obtained in this analysis have several unique features in comparison with the traditional thermodynamic methods for environmental decision-making, some of which are summarized here. Firstly, TIOA considers exergy lost in the ecological stages during the production of ecological resources. Since such exergy losses are higher for non-renewable resources and vice versa, TIOA can successfully acknowledge quality differences between ecological resources. Traditional exergy and ICEC analyses fail in this regard, as they ignore exergy losses in ecosystems. As a result ECEC analysis is a more powerful technique for environmental decision-making as illustrated by the electricity generation case study in Section “Hybrid Thermodynamic LCA of Geothermal and Coal-Fueled Electricity”.

Secondly, unlike exergy or emergy analyses for the entire national or global economy, TIOA considers the network structure of the economic system via input-output models. Consequently, TIOA provides industry-specific results that are more disaggregate and accurate than similar, but aggregate metrics for the entire economy. The industry-specific ECEC/money ratios, for instance, can be readily used to replace the single emergy/dollar ratio for the entire economy in emergy analysis. Thirdly, TIOA offers a systematic way of combining diverse flows including those of materials, energy, ecological products and services, emissions and their impact on human and ecosystem health and human resources that are typically measured in disparate units. TIOA does this by expressing all the flows in terms of single thermodynamic unit, namely solar equivalent joules (sej). This facilitates construction of hierarchical thermodynamic metrics of sustainability that are stackable, robust and protective of proprietary information (Yi et al. 2004).

In the future the techniques presented in this chapter can be made more comprehensive by including more ecosystem products and services. Besides human health, other impact categories such as ecosystem health and land use can also be included. Results presented in this work are based on a purely deterministic analysis. Considering the fact that all data are susceptible to uncertainties of various types, a stochastic analysis needs to be done to determine confidence bounds on the presented results. Different allocation approaches, along with ways to avoid allocation must be tried. In addition, current knowledge about ecosystems is quite limited and presents an important obstacle that must be overcome for improving the accuracy of ECEC analysis. However, even approximate quantification of the contribution of ecosystems seems better than ignoring them entirely. Applications to various products and processes are essential to validate the expected benefits of the proposed methods. Finally, the analysis presented in this chapter is not meant to compete with valuation-based techniques, but rather, the prospects of using TIOA to provide a sound biophysical basic to valuation-based methods must be explored.

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Chapter 24
A Step-Wise Guide for Energy Analysis: How to Calculate the Primary Energy Requirements of Households?

Kees Vringer, Kornelis Blok, and Barend van Engelenburg

Introduction

Not only activities of humans in households require energy, occurring in the form of natural gas, coal, petrol and electricity (direct energy requirement), but other consumption goods and services also require energy for their production, transport and trade (indirect energy requirement). In many cases a method is needed to determine the energy requirement associated with consumption patterns that is quick and fairly accurate with respect to the individual consumption categories. In other words, the method should be accurate enough to detect possible differences between the consumption categories (not between individual product variants or brands within a consumption category).

This chapter starts off by briefly discussing two existing methods for analysing the energy requirement of consumption categories, i.e. process analysis and input-output analysis. This is followed by a proposal for creating a tiered hybrid (see Suh et al. 2004) from these two methods to analyse the energy requirement for the various consumption categories. The hybrid method will be illustrated using the refrigerator as an example. The chapter ends with a discussion on the suitability of this method for calculating the total energy requirement of household consumption.

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

Determining the Energy Requirement of Consumer Goods

The analysis of the required energy for the whole life cycle of products had been widely practised since the early 1970s. The methods originally developed for life cycle energy analysis have been much further developed and refined in environmental Life Cycle Analysis (LCA). Even ISO made standards apply to LCA analyses (see e.g. ISO 14040 1997). However, in contrast to LCA, the focus in this chapter will not be on environmental impacts. As in the original life cycle energy analysis, the focus will be on energy use, which is an important determinant for a variety of environmental impacts. The two basic methods for calculating the energy requirement for the life cycle of a consumer good,[1] (i) input-output analysis and (ii) process analysis, will be described in this section.

In *input–output* analysis the energy requirement is determined using an economic–statistical approach. The transactions between the various sectors of an economy are collected in an input–output matrix (Leontief 1966). For each combination of two sectors, the input–output matrix contains, in monetary terms, the supply from one sector to the other sector. A certain direct energy requirement can be attributed to each sector in the input–output matrix, for instance, on the basis of energy statistics. Subsequently, by applying several mathematical operations to the matrix, one can calculate the energy requirement associated with the delivery of the final goods to consumers. The use of input–output analysis for this aim was described and applied by Bullard and Herendeen (1975) and Wright (1974).

We can easily calculate the energy requirement of a complete life cycle from a consumer good through an input-output analysis. The method, however, is not very accurate because no distinction can be made between different products produced in the same sector, e.g. cut flowers and cherries are both produced in the same sector, i.e. horticulture. Input–output analysis implicitly assumes a sector in the input–output table to be homogeneous. In reality, a range of products is produced in one sector; some products may be relatively energy-intensive (cut flowers) and others not very energy-intensive (cherries). The input–output approach ignores these differences.

The second approach is *process analysis*, Process analysis for a certain product starts with a definition of the *life cycle*, in which all the activities required for producing, transporting, using and disposing of a product are listed. This means that an inventory has to be made of the feedstock and intermediate products and the processes involved in the production of each feedstock. Subsequently, each process occurring in the life cycle is analysed to calculate its direct energy requirement. An initial extended description of the method was given at an IFIAS meeting in 1975 (IFIAS 1978). In the years following, this method was developed further and applied widely (Boustead and Hancock 1979). Process analysis is more accurate than input–output analysis. However, typical life cycle analysis methods based

[1] The phrase ‘consumer goods’ is not only used for material goods but also for services purchased by consumers.

on process analysis are very data-intensive and therefore also labor-intensive. Another problem is that in many cases not all data required for a process analysis are available.

A hybrid approach, already suggested by Bullard et al. (1978), combines the best elements of the two methods discussed before. On the basis of this proposal we developed a concrete calculation method (first published in 1994, see Van Engelenburg et al. 1994). Nowadays, there is a growing interest in hybrid methods, both for energy analysis and for environmental LCA. Suh et al. (2004) puts the hybrid approaches into three groups, namely, tiered hybrid analysis, input-output based analysis and integrated hybrid analysis. In a tiered hybrid analysis the life cycle is split into two parts: major processes and so-called remaining processes. The major processes are those that will most probably make an important contribution to the energy requirement of the product. The process analysis approach is used for the main processes, while the input–output analysis approach is used for the remaining processes. In the input-output based hybrid analysis, important input-output sectors are further disaggregated if more detailed sectoral monetary data are available. In integrated hybrid analysis the process-based system is represented in a technology matrix by physical units per operation time of each process, while the input-output-based system is represented by monetary units. Detailed unit process level information in physical quantities is fully incorporated into the input-output model. In this taxonomy, the approach used in this thesis can be considered as a tiered hybrid. The hybrid method will be described in Section "The Hybrid Method for Energy Analysis with the Domestic Refrigerator as an Example".

The Hybrid Method for Energy Analysis with the Domestic Refrigerator as an Example

In this hybrid method for energy analysis, we calculate the primary energy requirement of a consumer good in ten steps. In the first step a flow chart of the life cycle has to be constructed, while in steps 2 and 3, a mass balance and a financial balance of the product are determined. In steps 4–10, numerical values are attributed to the energy requirements of the various activities in the life cycle. Finally, the various contributions made by the activities to the energy requirement are added up. The hybrid method for energy analysis is described below and illustrated by applying it to the production and use of a domestic refrigerator. For an extended description see Van Engelenburg et al. (1991, 1994).

Note that all megajoules (MJ), mentioned in this chapter refer to primary megajoules. All monetary units are converted from Dutch guilders (Dfl. 1990) to Euros. One Dfl. is about €0.45. In April 2005, 1 Euro (€) was about equivalent to 1.28 dollar (US$).

The First Step: Construction of a Flow Chart

The first step is to make a flow chart of the life cycle for the consumer good concerned. The flow chart should include all the activities that will probably make an important contribution to the energy requirement: i.e. production, trade and transport, consumption and waste disposal. In elaborating the flow chart one also has to select the so-called **basic materials**. These play an important role in the energy requirement connected with the complete life cycle of the product. The energy requirement for the basic materials is determined using process analysis.

In addition to the basic materials, other inputs are required for the production of the consumer good, e.g. materials with an expected small energy impact, some final processing of basic materials and services to the production. These inputs are called **residual goods**. The energy required for residual goods is determined using an input–output analysis. The energy requirement of **capital goods**, such as production equipment or an office building, is relatively small, and much effort will be needed to establish the energy requirement using process analysis. For this reason, the energy requirement for capital goods is established with an input–output analysis and considered separately.

In this first step, a number of choices have to be made. One can achieve greater accuracy by making a more detailed flow chart and selecting an increased number of basic materials; however, this also increases the amount of work involved. See Fig. 24.1 for an example of the elements in a flow chart showing a life cycle.

The life cycle of the domestic refrigerator starts with the assembly of the refrigerator in the factory (industry sector). In the next phase, the refrigerator will be delivered to the consumer (trade sector). The refrigerator will then be disposed after use. Part of the waste will be disposed of and the remainder recycled. The refrigerator is produced in the electrical engineering industry. A standard domestic refrigerator with a capacity of 140 l and a lifetime of 15 years is chosen as the functional unit.

The basic materials used for the refrigerator are steel (compressor, outside wall, etc.), polyethylene (inside wall), polyurethane (insulation), aluminium (evaporator) and copper (wiring). The packaging for the refrigerator consists of a cardboard box, plastic protection materials and a single-use wooden pallet. These packaging materials are also added to the basic materials (Philips 1989). Figure 24.2 shows the flow chart for the refrigerator's life cycle.

The Second Step: The Mass Balance

With regard to the basic materials selected, a mass balance is first compiled for the life cycle determined in the first step. In many cases the composition of the product allows us to make a fairly accurate estimate of the total basic materials used in the life cycle. If there is a considerable loss of material during production, this loss should be taken into account too. Special attention should be paid to packaging materials.

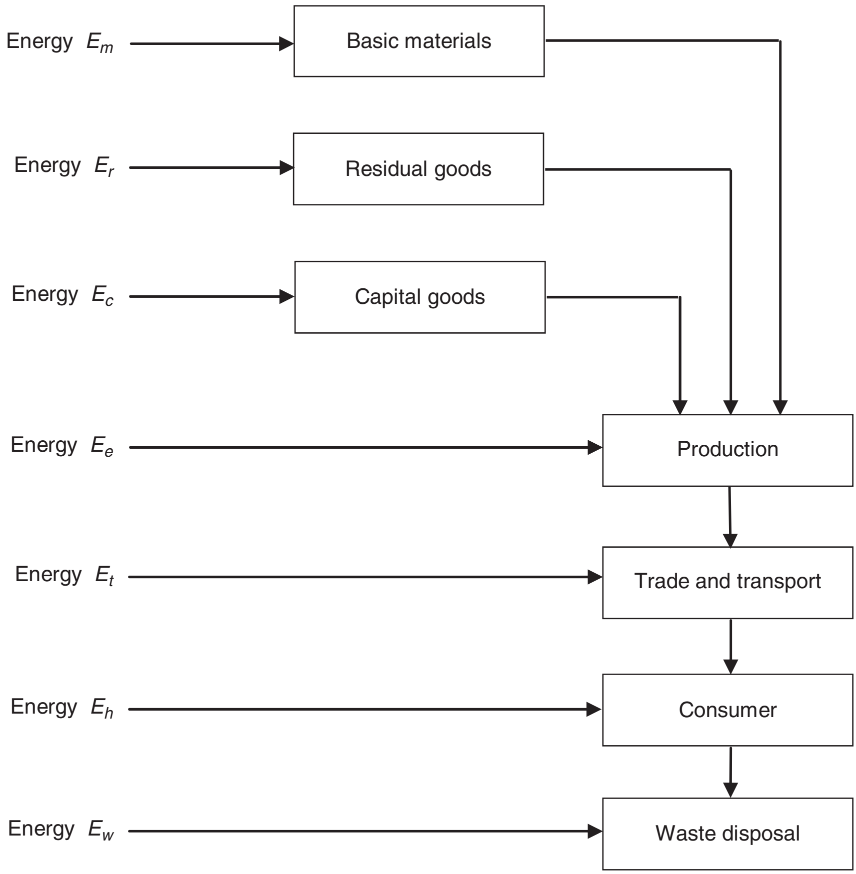

Fig. 24.1 Example of the Elements Requiring Energy in a Flow Chart Showing a Life Cycle

The total weight, excluding packaging, of the one-door refrigerator chosen is about 35 kg (Philips 1989) and the refrigerator consists of the basic materials listed in Table 24.2 (data provided by Miele bv and IRE Services bv).

The Third Step: The Financial Balance

The costs of all the activities in the life cycle are defined in this step. The retail price of the product must be broken down into the following components:

- Trade margin (including taxes)
- Costs of the basic materials purchased by the manufacturer
- Costs of the direct energy requirement of the product manufacture

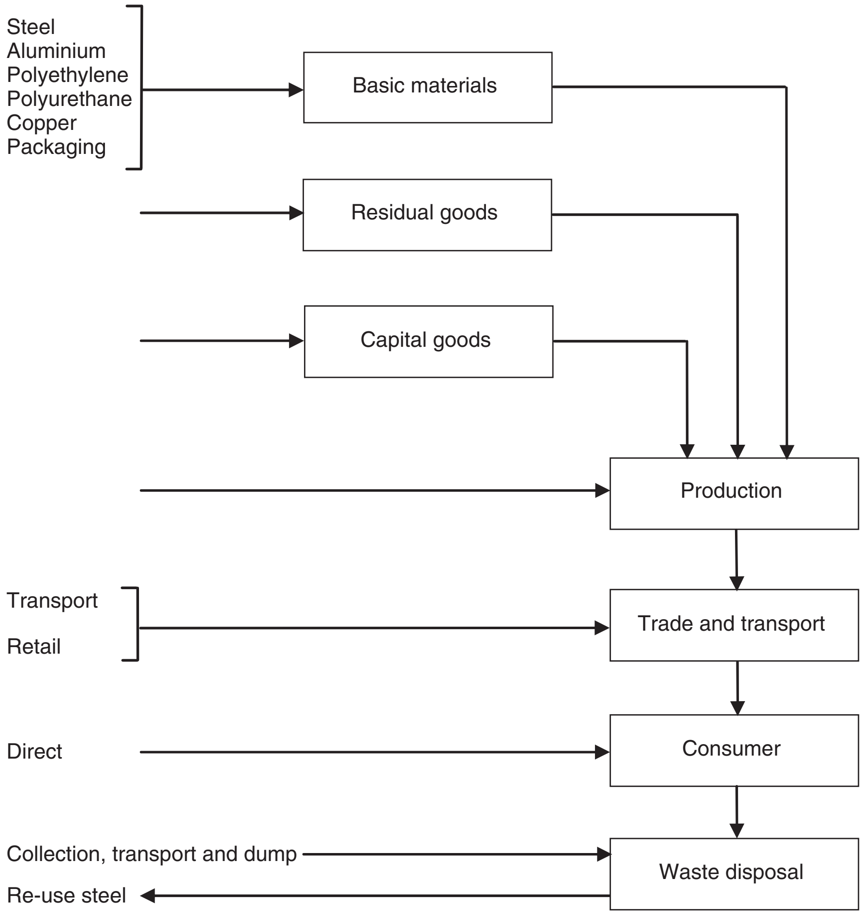

Fig. 24.2 Flow Chart of a Refrigerator's Life Cycle

- Depreciation incurred by the manufacturer
- Added value (excluding depreciation) realised by the manufacturer and
- Purchase of residual goods by the manufacturer

In most cases there are no specific figures available from the manufacturers or the trade sector involved in producing and selling a specific product, so approximations have to be made. In the approximation made here, one first of all has to determine an average product price, for example, on the basis of information provided by retailers, retailers' associations or consumer associations. The costs of basic materials are assessed on the basis of the mass balance, combined with the specific costs for the various materials, and expressed as costs per kilograms. From national statistical data, such as production statistics and input–output tables, one can obtain sector-averaged values for the trade margin, depreciation and value added. The remaining

Table 24.1 Breakdown of the Price of a Refrigerator (Excl. VAT)

Cost component	Costs[a] per refrigerator (€)
Basic materials in costs per kg (steel 0.5, aluminium 1.4, polyethylene 0.7, polyurethane 3.6, copper 1.6, cardboard 0.9, polystyrene 1 and wood 0.4)	43
Refrigerator energy manufacturing requirement	1.2
Depreciation	8.2
Value added	67
Retail margin	130
Residual goods	57

[a]Most of the costs for basic materials are derived from national statistics data for 1986 or 1990, collected by Wilting (1992).

Table 24.2 Energy Requirement for the Production of Basic Materials (Van Heijningen et al. 1992/1993; Fraanje 1990; Krekel van der Woerd Wouterse 1983)

Basic material	Mass (kg)	GER (MJ/kg)	Primary energy requirement (MJ)
Steel	25.0	23.4	585
Aluminium	0.5	198	99
Polyethylene	2.5	71	178
Polyurethane	6.0	190	1,140
Copper	0.5	100	50
Cardboard (packaging)	1.5	26	39
Plastic (packaging)	0.5	70	35
Wood (packaging)	10.0	33	330
Total	46.5		2,456

costs are attributed to the closing entry: the so-called *residual goods*. The consumer price of the refrigerator was about €360, incl. 18.5% VAT (Philips 1989). This price can be broken down as shown in Table 24.1.

The Fourth Step: Energy Requirement for Producing the Basic Materials (E_m)

The cumulative energy E_m required for producing the basic materials is calculated by adding up the gross energy requirements for all basic materials. The energy requirement relating to the use of basic materials for the refrigerator is shown in Table 24.2.

The Fifth Step: Energy Requirement of the Residual Goods (E_r)

In addition to basic materials, various other goods or modifications, called residual goods, are used by the manufacturing sector. The cost of residual goods was calculated in step 3. The energy intensity of residual goods was calculated with an input–output analysis. However, this approach will have to be modified, since the basic materials, of which the energy requirements have already been taken into account, have to be omitted from the analysis. This modification is carried out by ‘ignoring’ the contribution made to the energy requirements by the sectors producing the selected basic materials, i.e. by setting the direct energy requirement of these sectors at zero (see Wilting 1996 for an extended description).

In the second step, the cost price of the residual goods for the refrigerator was calculated at €57. The basic materials used in the production sector come from the:

- Timber industry, including furniture
- Paper and paper-product industry
- Chemical industry and
- Base metal industry

According to our hybrid approach, the energy requirements of these sectors will be set at zero. The energy intensity for the residual goods can be calculated using this assumption. Energy intensity is calculated at 5.7 MJ/€, resulting in an energy requirement for the residual goods of 323 MJ per refrigerator.

The Sixth Step: Direct Energy Requirement for Manufacturing the Product (E_e)

This step determines the direct energy requirement of the production process. This energy requirement can be calculated using process analysis. Since, in most cases, no process data are available, we can use the average energy intensity derived from national statistics data for the production sector in which the product was manufactured.

The direct energy requirement for the production of a refrigerator could not be calculated through process analysis because of lack of data. We therefore used the average energy requirement of the sector as derived from National Statistics (CBS). The direct energy intensity (= energy requirement per unit production value) in the electrical engineering industry is 2 MJ/€ (CBS 1991). Since the production price was €176, the direct energy requirement per refrigerator is calculated at 351 MJ.

The Seventh Step: Energy Requirement for the Manufacture of Capital Goods (E_c)

The input–output tables published by national statistics offices generally include the investments (purchase of capital goods required to produce consumer goods, e.g. buildings) in the final demand category and not in the internal supplies of the various sectors delivering to each other. Consequently, the investments in buildings and other capital goods are not included in the energy requirement calculated for consumer goods by means of input–output analysis. To correct for this deficiency we have to calculate the demand that the production of capital goods makes on primary energy carriers. The energy intensity of investments is calculated by applying input–output analysis, as described by Bullard and Herendeen (1975), and results in one figure, 9 MJ/€, for all sectors (Wilting 1992). The depreciation of the capital goods in the manufacturing industry per refrigerator is €8.1. The associated energy requirement is calculated at 73 MJ per refrigerator.

The Eighth Step: Energy Requirement for the Transport and Trade Sector (E_t)

Transport and trade form part of most life cycles. The product is usually transported from the factory (sometimes via the wholesale trade) to the retailer and from the retailer to the household. The weight of the product (i.e. the load) and the distance over which the product has to be transported must be specified for each mode of transport (e.g. train, lorry, ship). Energy is also used by the wholesale, distributive and retail trades.

The refrigerator is transported from factory to retailer and from retailer to household. The distance from the factory to the retailer is estimated at 500 km (the refrigerator is produced in Germany and sold in the Netherlands). This route, covered by lorry/truck, requires 2.5 MJ/t-km (Boustead and Hancock 1979; BGC 1991). The distance from the retailer to household, estimated at 15 km, is made by a delivery van and requires 8.5 MJ/t-km (Boustead and Hancock 1979; BGC 1991). The energy requirement for transport of the refrigerator (including packaging) can now be calculated at 65 MJ.

The trade sector also uses energy by supplying the product or service to the household. The value added from the trade sector was calculated in step 3. The value added (CBS 1992a), multiplied by the energy intensity of the trade sector results in the energy requirement for the trade sector, which, per refrigerator, is $130\ (€) \times 4.6\ (\text{MJ}/€) = 600\ \text{MJ}$.

The Ninth Step: Direct Energy Requirement in the Consumption Phase (E_h)

Some products, such as cars, refrigerators and cookers, require energy during the consumption phase. With an ambient temperature of 18°C, the refrigerator uses approximately 0.5 kWh electricity in 24 h or 180 kWh per year (Philips 1989). This annual requirement is equal to 1854 MJ of primary energy. The lifetime of a refrigerator is assumed to be 15 years, so the total direct energy requirement of the refrigerator is 27.8 GJ of primary energy.

The Tenth Step: Energy Requirement for Waste Disposal (E_w)

The life cycle ought to take into account the waste disposal associated with the consumer good. Waste disposal can consume energy, for instance, in connection with collection and transport. But disposal can also yield energy if the materials are recycled or incinerated.

The energy needed for collection and transport of the refrigerator amounts to about 14 MJ primary energy (DHV 1985). The steel of the refrigerator will be re-used, while the remainder will be dumped, with 22 kg waste requiring 2.0 MJ (DHV 1985). The re-use of 25 kg steel saves 400 MJ (Wilting 1992). So the waste disposal for the refrigerator results in an energy gain of 384 MJ per refrigerator.

The Final Step: Adding up the Energy Requirements

Finally, the various contributions made to the energy requirement by feedstock supply, manufacturing, use and disposal of a product can be added up. We have now calculated the total energy requirement of the product and its use. If the fraction of the residual goods contained in the cumulative energy requirement is decided to be too large, a more detailed life cycle should be constructed and the whole analysis for the modified part of the life cycle repeated. Mind that a threshold depends on the purpose of the analysis.

Figure 24.3 shows the results of the preceding steps, inserted into the flow chart of the life cycle for the refrigerator, as shown in Fig. 24.2. The cumulative energy requirement for the production, consumption and disposal of one refrigerator is calculated at 31 GJ over its entire lifetime of 15 years. The figures show the indirect fraction for the refrigerator to be about 10%. The energy intensity of a consumer good is defined as the total energy requirement divided by the purchase costs of the product. The energy intensity of the refrigerator is 9.5 MJ/€ when only the equipment itself is taken into account and 51 MJ/€ when the direct electricity requirement in the household is also included.

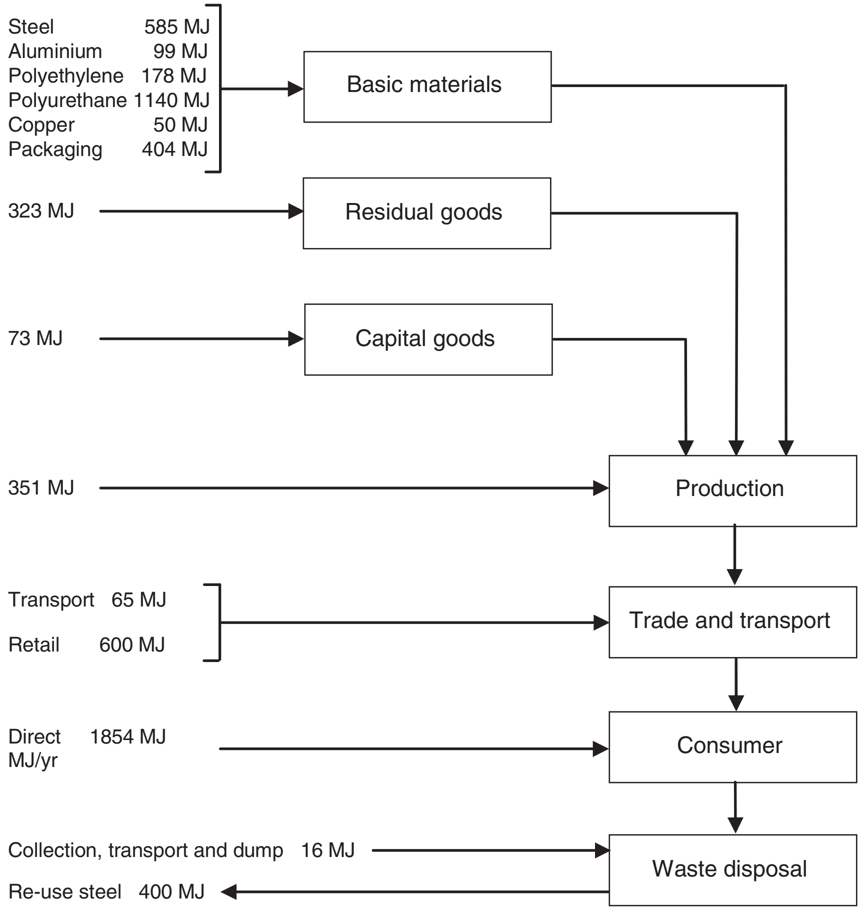

Fig. 24.3 Flow Chart of the Life Cycle of the Refrigerator, Together with the Energy Requirements in the Various Steps

The Suitability of the Hybrid Method for Determining the Energy Requirement of Consumption Patterns

As previously stated, if the primary energy requirement of consumption patterns is to be analysed, the energy analysis method has to be rapid. The energy analysis method must also be accurate enough to detect the differences between consumption categories and consumption patterns. Below, we discuss the calculation speed and the accuracy of the hybrid method in analysing the energy requirement of consumer goods.

Making a Quick Energy Analysis of Consumer Goods

The hybrid method for energy analysis described above may look very labor-intensive due to the large amount of input data required. But it should be pointed out that these input data can be standardised to a large extent and thus be used for many consumer goods. The hybrid method for energy analysis, along with databases containing a standardised input data set for the Netherlands, have been incorporated into a computer program called the Energy Analysis Program (EAP) (Wilting 1992; Wilting et al. 1999; Benders et al. 2001). The energy requirement and energy intensity of large numbers of consumer goods can be calculated relatively quickly with the EAP.

A lot of data are available in the EAP program. Only limited additional data of the product analysed (e.g. weight, price, country of production and most important materials) are required for the analysis. The rest of the required data can be estimated quite easily, e.g. data from the production and trade sectors, transportation distances and kinds of waste disposal. In this way all 350 consumption categories from CBS (1992b) (covering the complete Dutch consumption package) were analysed in about two person-years (De Paauw and Perrels 1993; Kok et al. 1993; Vringer and Blok 1993; Vringer et al. 1993). This comes to only about 10 h per consumption category, which makes the hybrid method for energy analysis applicable to calculating the energy requirement of consumer goods without the classic data problems of process analysis.

Accuracy of the Hybrid Method for Determining the Energy Requirement of Consumer Goods

The highest inaccuracy in the hybrid method for energy analysis in calculating the energy requirement of consumer goods will probably be caused by the use of input–output analysis to calculate the energy requirement for producing residual goods and the energy requirement for trade. However, the uncertainties that stem from the use of input–output analysis for residual goods can be partly avoided by minimising the use of this analysis through incorporation of sufficient process data on the basic materials.

Accuracy in the Energy Requirement of Trade

The energy requirement for retail trade is an example of a component of the life cycle of a product, where the energy requirement is calculated by using energy intensities on a monetary basis. For some products, the share of retail trade in the total calculated indirect energy requirement is more than 25% (see, for example, Vringer et al. 1993; De Paauw and Perrels 1993). The energy requirement for retail trade is assigned on a financial basis. This means that if the price of the product doubles, the energy requirement allocated to retail trade also doubles. This ‘financial’ way of assigning the energy requirement to retail trade may result in an overestimation of the retail trade energy requirement for more expensive products and an underestimation of cheaper products of the same kind. The retail trade energy requirement can also be assigned on a physical basis. In this case the energy requirement is assigned per item, per kilogram or cubic metre of product and is not affected by the price of the product. This assignment or ‘physical’ accounting method may result in an underestimation of the energy requirement of the retail trade for the more expensive products, since fewer products per square metre of retail space will have to be sold to realise the same turnover per square metre.

Vringer and Blok (1996) have provided an estimation of the error, made by assigning the energy requirement of the retail trade, either on a financial or physical basis. They made a detailed energy analysis, based on the annual sales per square metre floor, of two retail branches: clothing shops and shoe shops. Compared with this alternative detailed accounting method of the energy requirement of the retail trade, the *financial* accounting method indicates an overestimation for expensive clothes and shoes (4–14%), and an underestimation for cheaper clothes and shoes (−6%). The calculated energy requirement for clothes and shoes using the *physical* accounting method is about 2–10% too high for the low-price level shops and 2–17% too low for the high-price level shops. It is quite conceivable that more expensive shops will require relatively more energy for lighting and heating per square metre than cheaper shops. This means that the energy requirement of the retail trade will be higher for more expensive products and lower for cheaper products of the same kind than estimated here.

Vringer and Blok (1996) concluded that both financial and physical accounting methods for the energy requirement of retail trade would cause errors for products with a price level deviating from the average price. For individual purchases of clothes and shoes, the systematic error may be about 5–15% of the total indirect energy requirement. However, for the average of all shoes or all clothes, the energy requirement would be about right.

Conclusions

The hybrid method for energy analysis as proposed by Van Engelenburg et al. (1994) and worked out by Wilting (1992) and Wilting et al. (1999) can be concluded as being suitable for rapidly calculating the direct and indirect energy requirement associated with the purchase and use of large numbers of consumer goods. The hybrid method detects differences between consumption categories, even if they are produced by the same economic sector. The use of input–output analysis, based on a financial accounting method, for parts of the calculations can cause deviations for individual products, with a price level deviating from the average price. However, on average, the calculated energy requirement will be correct. Although the error margins for individual products can be reduced by using more process data, more effort will be needed to make an analysis.

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Chapter 25
Application of IO Energy Analysis for CO_2 Emissions by the Portuguese Economy: The Case of Portugal

Luís M.G. Cruz

Introduction

Objectives

One of the main aims of this study is to explore the links between energy, economy and environment from different perspectives, but always with a policy-oriented focus. This will be done by implementing and developing an input-output model with satellite accounts, to analyze the links between the different economic sectors, energy production and use, and the 'corresponding' production of CO_2 emissions in Portugal.

For this, the paper is organized as follows. In Section "The Input-Output Framework", there will be presented a brief outline of the basic input-output model, and then succinctly discussed the core aspects of its extensions for the consideration of environmental and energy issues. In Section "CO_2 Emissions by the Portuguese Economy", there will be presented the data sets used for the Portuguese case, and then an extended input-output empirical application, from which is assessed the (sectoral and aggregate) production of CO_2 emissions (derived from fossil fuels use) by the Portuguese economy. There will be also offered a succinct reflection on the use of elasticities of CO_2 emissions with some of the model parameters, as measures of sensitivity analysis of the level of emissions. Accordingly, a summary of the key lessons learned and a discussion of their policy relevance will be offered in Section "Final Comments".

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

Historical Background

For analyzing possible energy futures and designing new policies it is useful to present some background information about the current state and recent trends of the Portuguese energy system. Accordingly, there will be presented a brief overview of the role and importance of energy in Portugal (contextualized within the European Union), and how it has been developing through the last decade,[1] as well on the importance of CO_2 emissions in the current political debate (in the context of the Kyoto Protocol).

To start with, it is crucial to note that since Portuguese accession to the European Union (in 1986), its environmental and energy policies reflect the principles, aims and actions of the corresponding European policies. Accordingly, it comes as no surprise that trade-offs among three objectives – energy security, environmental protection, and economic growth – have been dominant concerns in Portuguese energy policy making for the last 3 decades, though they have been pursued with changing emphasis, depending on the historical situation and emerging issues and constraints. For example, one can say that after the Portuguese accession to the European Union (1986), and increasingly over the 1990s, although energy security concerns has by no means disappeared, it has lost considerable weight to competitiveness, and at a slower rate to environmental concerns (mainly the climate change problem).

Concerning some of the 'progress' made in the energy area over the last decade, it can be emphasized that:

- Portugal has a small energy market, of around ten million inhabitants, and has the lowest per capita energy consumption in the European Union (EU-15) (thought it has been growing at considerably higher rates than GDP per capita).
- Primary and final energy intensities present a worrying upward trend. Moreover, concerning absolute energy intensity levels, Portugal presents a situation clearly unfavorable compared to the European Union (EU-15) average.
- Portugal does not have its own fossil energy resources but it has a structure of consumption that is based on oil products; therefore, the country imports most of the energy consumed.
- The limited domestic energy resources produced in Portugal are renewables, such as hydropower and biomass. Indeed, the hydroelectric component is significant in the Portuguese electricity system.

Moreover, it is also essential to take into consideration that, under the terms of the European Union allocation agreement (the 'burden sharing' system), Portugal may

[1] It is worth mentioning that the International Energy Agency releases annually a review analyzing energy policies and energy market developments in its Member Countries, which include the EU Member States (e.g. IEA/OECD 2000b). Furthermore, the European Environment Agency has produced several reports which generally contain detailed data and analysis concerning, among others, environmental and energy issues, for each of the European Union Member States (e.g. EEA 1998, 1999, 2000, 2002b). Concerning Portugal, reference can be made to DGE/ME (2002) and IEA/OECD (2000a). Thus, these works are recommended for those interested in a more exhaustive analysis.

fulfill its Kyoto commitments by limiting its increase of greenhouse gas (GHG) emissions to 27% above 1990 levels over the period 2008–2012. Concerning CO_2 emissions, the limit for its increase is 40%. This latter 'Kyoto target' is the focus of our interest, though restricted to the consideration of the CO_2 emissions that result from the combustion of fossil fuels. From some historic data concerning emissions it is relevant to call attention that:

- In the year 2000, CO_2 emissions contributed to 74.6% of total Portuguese GHG emissions. Moreover, from 1990 to 2000, CO_2 emissions increased 43.6%, which means that the limit of 40% increase for 2008–2012 was already passed in the year 2000.
- CO_2 emissions that result from fuel combustion represented 90–91% of the total CO_2 emissions produced in the 1990s, and from 1990 to 2000, CO_2 emissions from fossil fuel burning increased 44.5%.

From all this results that presently the 'Kyoto target' for Portuguese CO_2 emissions is not any more 'to control the growth', but rather to reverse the current trend and therefore 'to reduce' present CO_2 emissions. Thus, more than ever, it is manifest that CO_2 emissions are of foremost importance in the current political debate in Portugal. Accordingly, measures to reduce energy-related GHG emissions, and specially CO_2 emissions, are clearly one of the biggest challenges for energy policy makers.

The Input-Output Framework

In an input-output approach the economic structure is defined in terms of sectors. It can be said that the relative simplicity of such a systematic connection of a set of economic variables provides a modeling framework suitable for calculating economic impacts (over all of the economy) of several human activities.

The Basic Input-Output Model[2]

The basic principle of input–output analysis states that each sector's production process can be represented by a vector of structural coefficients that describe the relationship between the inputs it absorbs and the outputs it produces.[3]

[2] The basic concepts of input-output analysis were discussed in detail by Wassily Leontief in the 1960s (Leontief 1966), and more recently by Miller and Blair (1985), and Proops et al. (1993).

[3] General assumptions of the basic input-output model are: homogeneity (i.e. each sector or industry produces a single product) and linear production functions (which implies proportionality of inputs with outputs in each sector and excludes both the possibility of economies or diseconomies of scale, and of substitution between production factors).

As the total output (production) of a sector i (X_i) can be delivered for intermediate or for final demand, an output equation may be defined by:

$$X_i = \sum_j x_{ij} + Y_i \tag{25.1}$$

where the element x_{ij} represents the 'value' of input from sector i to sector j (where i represents the number of the row and j the number of the column), and Y_i represents the total final demand for sector i (which includes production for consumption (of households and governments), investment purposes (fixed capital formation, changes in stocks) or exports).

Considering constant returns to scale, the output (or supply) equation of one generic sector becomes:

$$X_i = \sum_j a_{ij} X_j + Y_i \tag{25.2}$$

where the coefficients a_{ij}, defined as the delivery from sector i to j per unit of sector's j output, are known as the 'technical' or 'technological coefficients'.

To represent the nation's productive system, we will have a system of n (linear) simultaneous equations, each one describing the distributions of one sector's product through the economy. As the algebraic manipulation of such a system is very complex, it is useful to use its representation in matrix (condensed) form[4]:

$$\mathbf{Ax} + \mathbf{y} = \mathbf{x} \tag{25.3}$$

where **A** is the matrix of the technological coefficients, **y** is the vector of final demand, and **x** is the vector of corresponding total outputs.

Using the basic concepts of matrix algebra, with **I** as the unit matrix, Equation (25.3) can be reorganized, to give:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{25.4}$$

This expression is the fundamental matrix representation of input-output analysis, and the inverse matrix $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the 'Leontief inverse matrix' (or also as the 'multiplier matrix').

By decomposing Equation (25.4) (which can be seen as the result of an iterative process that shows the progressive adjustments of output to final demand and input requirements), one can separate out the direct from the indirect requirements for production in the economy, which are necessary to satisfy a certain vector of final demand commodities (Gay and Proops 1993:115–116):

$$\mathbf{x} = \mathbf{y} + \mathbf{Ay} + \mathbf{A}^2\mathbf{y} + \cdots + \mathbf{A}^\mathbf{t}\mathbf{y} + \cdots \tag{25.5}$$

[4] Notational conventions: upper case bold letters are used to denote matrices, and lower case italic letters with subscript indices to denote its elements; lower case bold letters are used to denote vectors, and upper case italic letters with subscript indices to denote its elements; and lower case italic letters are used to denote scalars.

So, as Proops et al. (1993: 112) point out, we can decompose the total demand for the *n* goods produced in the economy as follows:

- **Y** is required for final demand. This is the direct effect.
- **Ay** is the production necessary to allow the production of a final demand vector, **y**. This is the 'first-round indirect effect'.
- $\mathbf{A}^t\mathbf{y} = \mathbf{A}(\mathbf{A}^{t-1}\mathbf{y})$ is needed to produce the goods $\mathbf{A}^{t-1}\mathbf{y}$. This is the 'tth-round indirect effect'.

Clearly, the total indirect effects (or intermediate demand) are the sum of the first-round, second-round, etc. (Gay and Proops 1993: 115–116).

Extensions of the Basic Model to Account for Energy–Economy–Environment Interactions

Having established the basic input-output framework, it is time to move on to discuss some extensions of this technique, in order to make particularly explicit the link between the level of economic activity in a country, its corresponding impact on the environment, and/or the corresponding energy interactions.

Extensions of the application of input-output models to the examination of interactions between economic activity and environmental issues date back to the late 1960s and early 1970s.[5] These studies can be considered as benchmarks of an approach that would be further developed by some energy analysts during the 1970s and the 1980s, extending the use of input-output analysis to consider energy–economy interactions.[6]

But, over time, the modeling approaches have become more and more complex, to allow, for example, the consideration of global environmental issues such as the greenhouse effect and the 'resulting' climate change problem. This has led to the development of numerous theoretical models and empirical studies that combine both perspectives, making it hard to distinguish between environment and energy models, and therefore it become usual to talk about 'energy–economy–environment' models (Faucheaux and Levarlet 1999: 1123).

Thus, it is not surprising that also the input-output models have been extended to deal with both environmental and energy issues. Therefore, in this section, it is intended to illustrate some of the potentialities of the energy–economy–environment models, applying the input-output technique to the structural analysis of energy

[5] Detailed surveys of environmental input-output models, with many references, including theoretical extensions and applications are provided, for example, by: Hawdon and Pearson (1995), Miller and Blair (1985: Chapter 7), Richardson (1972: Chapter 11), Victor (1972: Chapter 2). Cruz et al. (2004) offer an overview of how IO methods began to be adopted as a method of integrating economic activity with the environment, indicating the main strands of development over the past 40 years, and in particular noting the recent work in the literature.

[6] Detailed surveys of energy input-output analysis are presented, for example, by Miller and Blair (1985: Chapter 6), and Casler and Wilbur (1984).

requirements and CO_2 emissions by economies, relating this pollution with the use of fuels. This will be done using an approach very similar to the one used by Gay and Proops (1993), Proops et al. (1993) and Cruz (2002c).[7]

To start, it is important to note that we need to introduce two kinds of distinctions into the analysis:

1. The division of the fossil fuel use, and the corresponding pollution emissions, into what concerns to energy directly demanded by household consumers (for lighting, cooking, heating/cooling, transport, etc.), and energy (directly and indirectly) demanded by industrial and agricultural producers of goods to 'power' the production process (Proops 1988: 202). The former will be designated as 'direct consumption demand' and the latter as (direct plus indirect) 'production demand'.
2. The distinction between various forms of primary (fossil) fuels,[8] namely solid (coal), liquid (oil) and gaseous (natural gas), since they have different pollution emissions per unit mass, and per unit of energy delivered.

Accordingly, it is considered in this model that the total (primary) energy requirements by an economy (given by the 3-vector $\mathbf{f}$) can be considered as the sum of the production energy requirements (given by the 3-vector $[\mathbf{f_{ind}} = \mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}]$), and final demand energy requirements (given by the 3-vector $[\mathbf{f_{dem}} = \mathbf{PHy}]$), i.e.:

$$\mathbf{f} = \mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} + \mathbf{PHy} \qquad (25.6)$$[9]

where: $\mathbf{C}$ is a $(3 \times n)$ matrix, whose generic element (c_{fi}) represents the (physical) quantity of fuel f used by sector i per unit of total output (i.e. the 'energy intensities corresponding to direct production demand'); $\mathbf{P}$ is a $(3 \times n)$ matrix, which has only three non-zero elements, one for each fuel type, expressing the (physical) quantity of fossil fuel use per unit of final demand (i.e. the 'energy intensities corresponding to direct consumption demand'); and $\mathbf{H}$ is a $(n \times n)$ diagonal matrix, with only three non-zero elements, which are the ratios of the sum of 'final consumption of households' and 'collective consumption', to total final demand, for the three fossil fuel sectors.[10]

[7] The basic concepts and explanations of the method to apply here have been discussed in detail by Proops et al. (1993: Chapter 8) and Cruz (2002c: Chapter 7). Therefore, the main equations and explanation of its contents will just be restated briefly.

[8] Applying an input-output approach to fuel use, as it is the case, "only primary fuels need be consider directly", since the use of secondary fuels is "dealt with automatically within the inter-industry demand structure" (Gay and Proops 1993: 116). This means that the manufacture of secondary fuels (such as, e.g. electricity or gasoline) should be ignored in the main calculation of CO_2 emissions so that double counting is avoided (IPCC 1996).

[9] This expression is also the result of some considerations, namely: n activity sectors; three types of fossil fuels: natural gas, coal and oil; and the assumption that the use of fossil fuels by any sector is proportional to the total output from that sector.

[10] The final demand for fossil fuels corresponding to investment is not used (burnt), and consequently do not correspond to CO_2 emissions. Furthermore, the final demand for fossil fuels

Correspondingly, it is considered in this study that the total CO_2 emissions by an economy (given by the scalar c) can be considered as the sum of the production CO_2 emissions [$\mathbf{c_{ind}} = \mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$] and final demand CO_2 emissions [$\mathbf{c_{dem}} = \mathbf{e}'\mathbf{PHy}$],[11] that is:

$$c = \mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} + \mathbf{e}'\mathbf{PHy} \Leftrightarrow c = \left[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1} + \mathbf{e}'\mathbf{PH}\right]\mathbf{y} \qquad (25.7)^{12}$$

where $\mathbf{e}'$ is the transpose of a 3-vector, $\mathbf{e}$, whose generic element (e_f) represents the amount of CO_2 emission per unit of fuel f.

Furthermore, we can decompose the total CO_2 emissions as the result of an iterative process that shows CO_2 emissions progressive adjustments to final demand and fossil fuel requirements:

$$c = [\mathbf{e}'\mathbf{PHy} + \mathbf{e}'\mathbf{Cy}] + [\mathbf{e}'\mathbf{CAy} + \mathbf{e}'\mathbf{CA}^2\mathbf{y} + \cdots + \mathbf{e}'\mathbf{CA}^{t-1}\mathbf{y} + \cdots] \qquad (25.8)$$

where ($\mathbf{e}'\mathbf{PHy}$) represents the CO_2 emissions attributable to direct consumption demand for fossil fuels, while ($\mathbf{e}'\mathbf{Cy}$) represents the CO_2 emissions attributable to direct, and the sum of all the others [$\mathbf{e}'(\mathbf{CA} + \mathbf{CA}^2 + \cdots)\mathbf{y}$] to indirect production demand.

The 'Attribution' of the Energy Requirements and CO_2 Emissions

Equations (25.6) and (25.7) make clear that both the energy requirements and the total CO_2 emissions produced by an economy can be attributed to total final demand for goods and services (represented by the final demand vector, $\mathbf{y}$). This can be particularly useful for policy analysis purposes, as this ultimately imputes all fossil fuel use and CO_2 emissions to households' purchases.

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corresponding to exports, as these fuels leave the country concerned, are used elsewhere and therefore does not corresponds to domestic CO_2 emissions. Thus, as interest is directed towards only those fuels which were burnt (Proops et al. 1993: 154), there is need to consider only the final consumption ('final consumption of households' plus 'collective consumption'). Accordingly, we can 'modify' the final demand vector ($\mathbf{y}$) to 'exclude' the investment and export components, by premultiplying it by a suitable ($n \times n$) scaling matrix, $\mathbf{H}$, and therefore using a modified final demand vector ($\mathbf{Hy}$).

[11] For reasons of completeness, other minor sources of CO_2 emissions – other then fossil-fuel burning – should have been included in the analysis. Proops et al. (1993) do this in their analysis. However, in this specific study, and because of a lack of detailed information for Portugal, the production of CO_2 emissions from non-fuel sources will not be covered, which can be considered as a shortcoming of this work.

[12] If we use $\hat{\mathbf{e}}$ (where $\hat{\mathbf{e}}$ is a (3×3) matrix, with the vector $\mathbf{e}$ on the diagonal) instead of $\mathbf{e}'$, the fuel sources fundamentally responsible for CO_2 emissions are explicitly identified, since a vector of pollution intensities for each of the fuels combusted in the economy is estimated. If we use $\mathbf{e}'$, as is the case here, then the scalar of pollution obtained represents pollution intensities for the total fuels burnt.

Moreover, according to the ‘components’ of the final demand considered, it is possible to distinguish energy requirements and CO_2 emissions attributable to domestic consumption, from that attributable to exports, as well as to estimate the levels of energy and CO_2 emissions ‘embodied’ in the country’s imports. It is then possible to estimate primary energy and CO_2 emissions ‘embodied’ in a country’s international trade, as well as the country’s ‘responsibility’ for CO_2 emissions (i.e. the CO_2 emissions attributable to consumption by a country’s economy, whether arising from domestic or from foreign goods and services), and the CO_2 emissions produced by the country’s economy (i.e. the CO_2 emissions attributable to the production made in the country’s economy, whether demanded by national or by foreign final consumers and industries).[13]

Such an exhaustive analysis of the energy requirements and CO_2 emissions attributable to the different ‘components’ of the final demand was performed elsewhere for the Portuguese case (Cruz 2002a). Here, as the interest is on the analysis of the accomplishment of the Portuguese CO_2 emissions target established under the Kyoto Protocol, we shall concentrate on the appraisal of the CO_2 emissions attributable to the production made in the Portuguese economy (and therefore released on Portuguese territory).[14]

The Elasticities of CO_2 Emissions with the Model Parameters

According to the modeling framework presented above, the CO_2 emissions were seen to be dependent upon: the structure of final demand (i.e. the elements of vector $\mathbf{y}$); the fuel use coefficients (i.e. the elements of matrices $\mathbf{C}$ and $\mathbf{P}$); the structure of inter-industry relations (i.e. the elements of matrix $\mathbf{A}$); etc. Moreover, it was assumed that these parameters are known and constant.

In this section, there will be analyzed the study of the sensitivity of the level of CO_2 emissions to changes in these parameters and variables, namely through the usual measure of sensitivity used by economists – elasticity.[15] There are two main kinds of purpose behind the performance of this sensitivity analysis. On the one hand, as interest is in identifying policies that may reduce CO_2 emissions, one may

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[13] Also, it is important to recall that what is considered in the input-output table is the domestic output by sector (i.e., imports are excluded); therefore, the energy requirements and ‘consequent’ CO_2 emissions correspond to goods and services produced in the country.

[14] Indeed, the Kyoto Protocol, as well as other international agreements, focuses on activity solely in the national boundary. This is so because, among other factors, as the Protocol is legally binding, no government can be held responsible for the actions that occur in another country.

[15] Elasticity is the proportional (or percentage) change in one variable relative to the proportional change in another variable. In this particular case, it measures the percentage responsiveness of the level of CO_2 emissions to a 1% change in another variable. In order to calculate a particular elasticity, there is the need to know the partial derivative of one variable (in this case the level of CO_2 emissions) with respect to the other, as well as the values of the variable at the point at which the elasticity is required.

consider how changing these parameters may be effective in achieving this aim. On the other hand, as the data used is not perfectly known, this analysis can provide a guide to which components of the data set need to be collected most accurately.

However, the number of elasticities that may be calculated using this study's data set is colossal. As there is need to condense information, so that it can be comprehended and thus allow policy conclusions to be drawn, there will be considered 'only' the final demand, fuel use and intermediate trading elasticities of the CO_2 emissions produced by a country's economy. This will be done using an approach very similar to the one presented by Proops et al. (1993) and Cruz (2002c), which should be seen by those interested in deeper insights into the subject. Thus, what follows is no more than a brief restatement of the mathematical analysis presented in those works in order to make the calculation of the several elasticities more apparent.

Final Demand Elasticities of CO_2 Emissions

In this subsection, there will be derived the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to one component of total final demand (Y_i), whose formal definition is given by:

$$\boldsymbol{\varepsilon}_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} \big/ c_{emis}}{\partial Y_i \big/ Y_i} \Leftrightarrow \boldsymbol{\varepsilon}_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} \big/ \partial Y_i}{c_{emis} \big/ Y_i} \tag{25.9}$$

To calculate the partial derivative of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to one component of total final demand (Y_i), we have to differentiate Equation (25.7) with respect to Y_i. Therefore, Equation (25.9) becomes:

$$\boldsymbol{\varepsilon}_{Y_i}^{c_{emis}} = \frac{\partial c_{emis} \big/ \partial Y_i}{c_{emis} \big/ Y_i} = \frac{\left[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1} + \mathbf{e}'\mathbf{PH}\right] \frac{\partial \mathbf{y}}{\partial Y_i}}{c_{emis} \big/ Y_i} = \frac{\left[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1} + \mathbf{e}'\mathbf{PH}\right]_i Y_i}{c_{emis}} \tag{25.10}$$

where $[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1} + \mathbf{e}'\mathbf{PH}]_i$ is the ith element of the vector $[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1} + \mathbf{e}'\mathbf{PH}]$.

Fuel Use Elasticities of CO_2 Emissions

Production Fuel Use Elasticities of CO_2 Emissions

By similar reasoning to that used to derive the elasticity previously presented, one can obtain other elasticities, such as, e.g., the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the production fuel use coefficients (c_{fi}) as:

$$\varepsilon_{c_{fi}}^{c_{emis}} = \frac{\partial c_{emis} \Big/ \partial c_{fi}}{c_{emis} \Big/ c_{fi}} = \frac{\mathbf{e}' \frac{\partial \mathbf{C}}{\partial c_{fi}} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}}{c_{emis} \Big/ c_{fi}} = \frac{e_f \left[(\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \right]_i c_{fi}}{c_{emis}} = \frac{e_f X_i c_{fi}}{c_{emis}}, \tag{25.11}$$

where f is, as usual, the type of primary fuel under consideration (i.e.: f = coal, oil, natural gas).

Final Demand Fuel Use Elasticities of CO_2 Emissions

The elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the final demand fuel use coefficients (p_{fi}) is given by:

$$\varepsilon_{p_{fi}}^{c_{emis}} = \frac{\partial c_{emis} \Big/ \partial p_{fi}}{c c_{emis} \Big/ p_{fi}} = \frac{\mathbf{e}' \frac{\partial \mathbf{P}}{\partial p_{fi}} \mathbf{H} \mathbf{y}}{c_{emis} \Big/ p_{fi}} = \frac{e_f \, [\mathbf{H} \mathbf{y}]_i \, p_{fi}}{c_{emis}} \tag{25.12}$$

Of course, there are only three non-zero elasticities, one for each of the primary fuels directly used by final consumers.

Intermediate Trading Elasticities of CO_2 Emissions

The Technical Coefficients Elasticity of CO_2 Emissions

The elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the technical coefficients (a_{ij}) is given by:

$$\varepsilon_{a_{ij}}^{c_{emis}} = \frac{\partial c_{emis} \Big/ \partial a_{ij}}{c_{emis} \Big/ a_{ij}} = \frac{\mathbf{e}' \mathbf{C} \frac{\partial \left[(\mathbf{I} - \mathbf{A})^{-1} \right]}{\partial a_{ij}} \mathbf{y}}{c_{emis} \Big/ a_{ij}}. \tag{25.13}$$

To differentiate $(\mathbf{I} - \mathbf{A})^{-1}$ with respect to a_{ij} $\left(\text{i.e.,} \frac{\partial \left[(\mathbf{I} - \mathbf{A})^{-1} \right]}{\partial a_{ij}} \right)$ we write:

$$(\mathbf{I} - \mathbf{A})^{-1} [(\mathbf{I} - \mathbf{A})^{-1}]^{-1} = \mathbf{I} \Leftrightarrow (\mathbf{I} - \mathbf{A})^{-1} (\mathbf{I} - \mathbf{A}) = \mathbf{I}. \tag{25.14}$$

Differentiating both sides of Equation (25.14) with respect to a_{ij} gives:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{I}-\mathbf{A})\right]}{\partial a_{ij}} = 0 \Leftrightarrow \frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}(\mathbf{I}-\mathbf{A}) + (\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}} = 0 \Leftrightarrow$$
$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}(\mathbf{I}-\mathbf{A}) = -(\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}}. \tag{25.15}$$

Now, if we post-multiply both sides of Equation (25.15) by $(\mathbf{I}-\mathbf{A})^{-1}$ we get:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}}\mathbf{I} = -(\mathbf{I}-\mathbf{A})^{-1}\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}}(\mathbf{I}-\mathbf{A})^{-1}. \tag{25.16}$$

So now we need to differentiate **(I-A)**with respect to a_{ij}. One can write:

$$\frac{\partial(\mathbf{I}-\mathbf{A})}{\partial a_{ij}} = -\mathbf{F}^{\mathrm{ij}}, \tag{25.17}$$

where we define the matrix $\mathbf{F}^{\mathrm{ij}}$ as:

$$\mathbf{F}^{\mathrm{ij}}_{rs} = \begin{Bmatrix} 1, r = i, s = j \\ 0, \text{otherwise} \end{Bmatrix}. \tag{25.18}$$

Therefore, substituting Equations (25.17) into (25.16) we obtain:

$$\frac{\partial\left[(\mathbf{I}-\mathbf{A})^{-1}\right]}{\partial a_{ij}} = -(\mathbf{I}-\mathbf{A})^{-1}\left(-\mathbf{F}^{\mathrm{ij}}\right)(\mathbf{I}-\mathbf{A})^{-1} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{F}^{\mathrm{ij}}(\mathbf{I}-\mathbf{A})^{-1}. \tag{25.19}$$

Thus, substituting Equation (25.19) into Equation (25.13), the elasticity of CO_2 emissions with respect to the technical coefficients (a_{ij}) will be given by:

$$\boldsymbol{\varepsilon}^{c_{emis}}_{a_{ij}} = \frac{\mathbf{e}'\mathbf{C}\left[(\mathbf{I}-\mathbf{A})^{-1}\mathbf{F}^{\mathrm{ij}}(\mathbf{I}-\mathbf{A})^{-1}\right]\mathbf{y}}{c_{emis}/a_{ij}}. \tag{25.20}$$

Since the effect of the matrix $\mathbf{F}^{\mathbf{ij}}$ is to pick out the required elements of the other matrices (this matrix has a single element, the one which we are differentiating), Equation (25.20) becomes:

$$\boldsymbol{\varepsilon}^{c_{emis}}_{a_{ij}} = \frac{\left[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\right]_i\left[(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}\right]_j a_{ij}}{c_{emis}} = \frac{\left[\mathbf{e}'\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}\right]_i X_j a_{ij}}{c_{emis}}. \tag{25.21}$$

As the input-output table which will be used is a (38×38) industry-by-industry table, this means that we can calculate $38 \times 38 = 1{,}444$ elasticities of the CO_2 emissions (c_{emis}) with respect to the technical coefficients (a_{ij}). Of course, this means that it is problematic to deal with such an amount of data, particularly for policy purposes. Therefore, in order to 'condense' such information, as suggested by Proops et al. (1993: 145), there will be employed technology elasticities related to one sector at a time, namely calculating the elasticities corresponding to the technology of inputs to a sector, as well as the ones corresponding to the technology of outputs from a sector.

The Technology of Inputs to a Sector's Elasticity of CO_2 Emissions

The relationship of the technology of inputs to a sector may be summarized as the column sum of the technical coefficients, i.e.:

$$a_{.j} = \sum\nolimits_{i=1}^{n} a_{ij}. \tag{25.22}$$

Accordingly, the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the column sum of the technical coefficients ($a_{.j}$) may be expressed as the weighted sum of the single coefficient elasticities, $\boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}}$, i.e., it is given by:

$$\boldsymbol{\varepsilon}_{a_{.j}}^{c_{emis}} = \frac{\partial c_{emis} \big/ \partial a_{.j}}{c_{emis} \big/ a_{.j}} = \frac{1}{\sum_{i=1}^{n} \frac{a_{ij}}{a_{.j}} \frac{1}{\boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}}}} = \sum\nolimits_{i=1}^{n} \boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}} \tag{25.23}$$

The Technology of Outputs from a Sector's Elasticity of CO_2 Emissions

Similarly, the relationship of the technology of outputs from a sector may be summarized as the row sum of the technical coefficients, i.e.:

$$a_{i.} = \sum\nolimits_{j=1}^{n} a_{ij} \tag{25.24}$$

Hence, the elasticity of the CO_2 emissions produced by the country's economy (c_{emis}) with respect to the row sum of the technical coefficients ($a_{i.}$) may also be expressed as the weighted sum of the single coefficient elasticities, $\boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}}$, i.e., it is given by:

$$\boldsymbol{\varepsilon}_{a_{i.}}^{c_{emis}} = \frac{\partial c_{emis} \big/ \partial a_{i.}}{c_{emis} \big/ a_{i.}} = \frac{1}{\sum_{j=1}^{n} \frac{a_{ij}}{a_{i.}} \frac{1}{\boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}}}} = \sum\nolimits_{j=1}^{n} \boldsymbol{\varepsilon}_{a_{ij}}^{c_{emis}} \tag{25.25}$$

CO_2 Emissions by the Portuguese Economy

In this section, there will be presented an input-output empirical application of the energy–economy–environment interactions for Portugal, especially concerning the energy intensities and CO_2 emissions derived from fossil fuels use, according to the modeling approach described above.

Data Preparation[16]

Portuguese National Accounts and the Input-Output Table

A number of adjustments needs to be made to the way figures are presented by the Portuguese system of economic accounts, published by the National Institute of Statistics (INE 1999), to achieve a valuation of the supply and use flows as consistently and homogenously as possible, and obtain the input-output tables that are the basis for the empirical analysis to be performed in this work. However, the estimation of such tables was only possible for 1992,[17] because the 'auxiliary' data to perform the required treatments is only surveyed with a breakdown of all inter-industry transactions (by industries and by products) and of final uses by product for the 1992 Portuguese national accounts.

It is also important to mention that in order to be able to explore alternative scenarios for electricity generation (see Cruz 2002b), the electricity sector was disaggregated into three 'sub-sectors'[18]: 6A – Fossil Fuel Electricity Generation, 6B – Hydroelectricity, and 6C – Electricity Distribution. To perform this disaggregation, following Gay and Proops (1993), and Proops et al. (1993), it is assumed that:

- The two generating sectors (6A and 6B) sell all of their output to the distribution sector (6C).[19]
- The fuel inputs to electricity are attributed entirely to fossil fuel generation,[20] and all other inputs are split between the two generating sectors in proportion to their total output.
- All purchases of electricity by the remaining sectors and by final demand are supplied by electricity distribution.

This resulted in the use of a (38×38) industry-by-industry input-output table, for Portugal, in 1992. From this table was derived the matrix $\mathbf{A}$, by dividing inter-industry flows by the total inputs (= total outputs) by industry at basic prices, as usual. It was also from this table that was derived matrix $\mathbf{H}$, as well as the final demand vector $\mathbf{y}$.

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[16] A detailed description of the adjustments made to the Portuguese national accounts, as well as the characteristics and the adjustments made in the Portuguese energy data used may be found in Cruz (2002c).

[17] Of course, the absence of more up-to-date data may constitute a restriction to providing useful information for practical policy decisions. However, the basic economic structure of the economy changes relatively slowly over time and therefore, for many aspects, the table(s) will be relevant over a reasonable period of time (Miller and Blair 1985: 269). Nevertheless, the performance of the analysis for more recent years and the investigation of the reasons behind the changes which might have occurred (through structural decomposition analysis), should be explored as soon as the information becomes available, particularly concerning National Accounts.

[18] This was done because of the need to distinguish fossil-fuel electricity generation from other electricity generation, since electricity obtained, e.g., from hydro, wind, and solar sources, do not correspond to CO_2 emissions.

[19] This means that the two electricity-generating sectors have zero final demand.

[20] Which means that hydroelectricity generation and the distribution side of electricity are recorded as using no fossil fuel at all, which is clearly an underestimate (Gay and Proops 1993: 123).

The Physical Quantities of Primary Fossil Fuels Used in the Portuguese Economy

To perform the study there is also the need to consider the (physical) quantities of primary fossil fuels used by each industry per unit of total output, as well as the quantities of fossil fuels used per unit of final demand. However, such data was generally not directly available in the appropriate, or consistent, form. Therefore, there was the need to make some assumptions and estimations in order to correlate the different data sources, namely the input-output tables (provided by the INE) and the energy balance statistics (supplied by the Portuguese Directorate General of Energy – DGE).

According to the 'Energy Balance' statistics for 1992 (DGE 1995), the Portuguese economy total consumption of coal and (crude) oil was of 2,949,576 and 13,148,058 t of oil equivalent (toe), respectively. These values were considered as credible totals of domestic energy use (by type of fuel) and it was from these that were derived the physical quantities of coal and oil used by each of the 38 sectors and by final consumers in 1992.[21] Then, dividing these values by the corresponding element of the total input (= total output) vector or by the final demand vector, it was possible to determine the primary energy intensities (or requirements) per unit of total output by sector (the 2×38 matrix **C**) and per unit of final demand (the 2×38 matrix **P**).

The Carbon Content of Primary Fuels

CO_2 emissions are produced when carbon-based fuels are burned. Therefore, after adjusting primary energy figures, it is possible to estimate CO_2 emissions from fuel combustion, by considering the carbon contents of each type of fuel. For this purpose, conversion factors from primary energy to CO_2 were applied. These conversion factors were calculated following the IPCC's default methodology to make countries' GHG emissions inventories (IPCC 1996), and were arranged in a vector of CO_2 emission per unit (toe) of fuel burnt (the 2-vector e). Accordingly, it is assumed that each toe of coal burnt generates 3.88 t of CO_2, and that each toe of oil burnt generates 3.04 t of CO_2. These figures clearly show that the amounts of CO_2 emitted directly depend on the fuel, with more CO_2 being emitted per unit of energy content for coal than for oil (and for natural gas[22]).

[21] It is important to note that the use of natural gas was introduced in Portugal only in 1997. Thus, as the analysis done in this study is for 1992, only two primary energy sources were considered. Consequently, matrices **C** and **P** are of dimension (2×38), and vector **e** is a 2-vector.

[22] Likewise, it was also estimated that each toe of natural gas combusted generates 2.34 t of CO_2. This result was not used here, as in 1992 there was no use of natural gas in Portugal.

Box 25.1 Portuguese Input-Output Table

In Portugal, collecting and publishing national accounting data is a primary responsibility of the National Institute of Statistics – INE (www.ine.pt). As a European Union (EU) member, Portuguese system of economic accounts has recently converted its national definitions, classifications and accounting rules according to the European system of national and regional accounts in the EU, ESA 95 (European System of Accounts 1995) (see European Commission, 1996, Council Regulation of 25 June 1996 on the European system of national and regional accounts in the Community, Council Regulation 1996/2223/EC, JOL 310, 30/11/96, Office for Official Publications of the European Communities, Luxembourg). Therefore, supply and use tables are expected to be produced annually for the reporting year t-3 according to the regulations of ESA 95.

For the purposes of the modeling exercises performed in Chapters 25 and 28, a number of additional adjustments to the way figures are offered by the Portuguese system of economic accounts had been pursued to achieve a valuation of the supply and use flows as consistently and homogenously as possible. However, data to perform these essential adjustments was only surveyed with the required desegregation concerning 1992 Portuguese national accounts (which was yet organized under an old system of accounts, with a main breakdown of 49 products and 49 industries). Thus, the level of sectoral aggregation used in the input-output models presented in Chapters 25 and 28 of this handbook correspond to the authors proposal of a compromise between the 'old' and the 'new' classification (see the Appendix for a detailed list).

Recently, several working papers have been published by the Department of Prospective and Planning (DPP) of the Portuguese Government (www.dpp.pt), concerning input-output data specificities in the Portuguese national accounts. Accordingly, DPP has recently made available (under request) input-output tables for 1999, with a desegregation of 60 products and 60 industries, which are directly usable for modeling purposes.

The Input-Output Assessment of CO_2 Emissions

In this section there will first be determined the CO_2 intensities per unit of total output and per unit of final demand, in terms of tons of CO_2 per million Portuguese Escudos (PTE). Subsequently, there will be reported the total CO_2 emissions for a given structure of final consumption, both in aggregate and disaggregated to 38 sectors.

The CO_2 Intensities

As derived from Equation (25.8), the elements of the row-vector ($\mathbf{e}'\mathbf{C}$) represent the tons of CO_2 emitted directly by each sector, per million PTE of final demand for the output of that sector; and the elements of $[\mathbf{e}'\mathbf{C}(\mathbf{A} + \mathbf{A}^2 + \ldots)]$ represent tons of CO_2 emitted throughout the rest of the economy (i.e. indirectly) by each sector, per million PTE of final demand for the output of that sector. Moreover, the elements of the vector $(\mathbf{e}'\mathbf{P})$, containing only two non-zero elements (one for each type of fuel), represent tons of CO_2 emitted per million PTE of demand by consumers for fuels. Thus, the sum of CO_2 intensities corresponding to total production and to direct consumption demand, represents tons of CO_2 emitted per million PTE of final demand, for each sector. Table 25.1 contains the estimated corresponding figures.

Concerning total CO_2 intensities, the energy sectors (except Hydroelectricity) are unsurprisingly the ones that appear in the upper ranking, followed also predictably by the Land Transport sector (see Fig. 25.1).

The total CO_2 intensity of the two top sectors (Mining and Manufacture of Coal By-Products and Extraction of Crude Petroleum and Natural Gas; and Manufactured Refined Petroleum Products) is dominated (in 91.3% and 94.3%, respectively) by the intensities corresponding to direct consumption demand. For all the other sectors, the CO_2 intensities correspond only to production demand (on the clear majority of them mainly to indirect production demand).

CO_2 Emissions Produced by the Portuguese Economy

From Equation (25.8), multiplying the CO_2 intensities presented above by the final demand vector, one achieves the corresponding tons of CO_2 emitted by each sector, which are shown also in Table 25.1.

In 1992, according to the estimation made through the model, 51,413.8 kt of CO_2 were emitted on Portuguese territory, derived from the use of fossil fuels, in order to satisfy the domestic and foreign final demand for goods and services domestically produced.[23]

The top five sectors 'responsible' for those CO_2 emissions are Extraction of Crude Petroleum, and Manufacture of Refined Petroleum Products (16.5%), Electricity Distribution (11.2%), Construction (9.9%), Land Transport and Transport Via Pipeline Services (9.9%), and Wholesale and Retail Trade (7%). This means that the former four sectors account for almost half of total CO_2 emissions attributable to production in the Portuguese economy (see Fig. 25.2). Moreover, as the CO_2 emissions by the Extraction of Crude Petroleum, and Manufacture of Refined Petroleum Products sector are mainly associated with the use of private cars, and as the production of CO_2 emissions by the Land Transport and Transport Via Pipeline Services is mainly connected with freight and passengers transport, one can say that (per-

[23] This figure is slightly higher than the 45,165.9 kt of CO_2 reported by EEA (2002a), which were estimated also following the IPCC Guidelines (IPCC 1996). It is important to remember that not only are some components of the data used in this work of poor quality, which implied the making of some assumptions, but also that only one coefficient was used for each fuel, which may have had some effect in this discrepancy.

Table 25.1 CO_2 Intensities and CO_2 Emissions Produced by the Portuguese Economy

CO_2 intensities and CO_2 emissions produced by the Portuguese economy	CO_2 intensities (corresponding to:)						CO_2 emissions produced by the Portuguese economy (attributable to:)									
	Direct production demand +	Indirect production demand =	Total production demand +	Direct consumption demand =	Final demand		Direct production demand	+	Indirect production demand	=	Total production demand +	Direct consumption demand	=	Final demand		
unit for CO_2 intensities: tonnes of CO_2/million PTE *unit for CO_2 emissions: 10^3 t of CO_2*	e'C	e'C $(A+A^2+...)$	e'C $(I-A)^{-1}$	e'P	Total CO_2 Intensity	*Total CO_2 Intens. Rank.*	e'Cy	(6)/(10)	e'C $(A+A^2+...)y$	(7)/(10)	e'C $(I-A)^{-1}y$	e'PZy	(9)/(10)	Total CO_2 emissions	*Total CO_2 Emis. Rank.*	*% Distrib of CO_2 Emis. by Ind.*
	(1)	(2) = (3)-(1)	(3)	(4)	(5) = (3)+(4)		(6)	%	(7) = (8)-(6)	%	(8)	(9)	%	(10) = (8)+(9)		
01 Agriculture, Hunting and Related Service Activities	1.12	1.89	3.01	0.00	3.01	17	394.0	37.1	668.2	62.9	1,062.2	0.0	0.0	1,062.2	12	2.1
02 Forestry, Logging and Related Service Activities	0.71	0.36	1.07	0.00	1.07	28	17.5	66.5	8.8	33.5	26.3	0.0	0.0	26.3	36	0.1
03 Fishing and Related Service Activities	3.20	0.97	4.17	0.00	4.17	13	191.1	76.7	58.0	23.3	249.0	0.0	0.0	249.0	26	0.5
04 Mining and Manufacture of Coal By-Products	34.99	2.94	37.93	397.56	435.49	1	13.6	30.6	1.1	2.6	14.8	29.8	66.8	44.6	33	0.1
05 Extr. Crude Petrol. ..., & Man. Refined Petroleum Prod.	7.67	1.87	9.54	158.85	168.39	2	844.7	9.9	205.7	2.4	1,050.3	7,448.3	87.6	8,498.7	1	16.5
6A Fossil Fuel Electricity Generation	73.74	1.00	74.75	0.00	74.75	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37	0.0
6B Hydroelectricity	0.00	0.17	0.17	0.00	0.17	38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37	0.0
6C Electricity Distribution	0.00	33.83	33.83	0.00	33.83	4	0.0	0.0	5,735.5	100.0	5,735.5	0.0	0.0	5,735.5	2	11.2
07 Gas Production and Distribution	14.06	9.58	23.64	0.00	23.64	6	142.1	59.5	96.8	40.5	238.9	0.0	0.0	238.9	27	0.5
08 Water Supply	0.00	6.01	6.01	0.00	6.01	11	0.0	0.0	161.8	100.0	161.8	0.0	0.0	161.8	29	0.3
09 Extr. & Man. of Ferrous & Non-Ferrous Ores & Metals	5.24	6.31	11.55	0.00	11.55	7	327.9	0.0	394.7	0.0	722.6	0.0	0.0	722.6	19	1.4
10 Extraction and Manuf. of Non-Metallic Minerals	6.09	4.71	10.80	0.00	10.80	8	865.2	56.4	668.3	43.6	1,533.5	0.0	0.0	1,533.5	10	3.0
11 Manuf. of Chemicals and Chemical Products	5.98	2.55	8.53	0.00	8.53	9	1,515.8	70.1	646.4	29.9	2,162.2	0.0	0.0	2,162.2	8	4.2
12 Manufacture of Fabricated Metal Products	0.19	2.99	3.18	0.00	3.18	16	43.4	6.0	682.0	94.0	725.4	0.0	0.0	725.4	18	1.4
13 Man. of Electrical and Non-Electrical Machinery & Equipm.	0.06	1.26	1.32	0.00	1.32	25	35.6	4.9	694.1	95.1	729.7	0.0	0.0	729.7	17	1.4
14 Manufacture of Transport Equipment	0.15	1.11	1.26	0.00	1.26	27	57.9	11.7	437.4	88.3	495.3	0.0	0.0	495.3	21	1.0
15 Manufacture of Food Products and Beverages	0.36	1.97	2.34	0.00	2.34	22	431.8	15.6	2,336.6	84.4	2,768.4	0.0	0.0	2,768.4	7	5.4
16 Manufacture of Tobacco and Tobacco Products	0.19	0.29	0.48	0.00	0.48	37	27.9	39.2	43.3	60.8	71.2	0.0	0.0	71.2	32	0.1
17 Manufacture of Textiles and Clothing	0.37	2.40	2.78	0.00	2.78	19	388.7	13.5	2,495.1	86.5	2,883.8	0.0	0.0	2,883.8	6	5.6
18 Manufacture of Leather and Footwear	0.20	1.10	1.30	0.00	1.30	26	66.2	15.3	367.3	84.7	433.5	0.0	0.0	433.5	24	0.8
19 Other Manuf. Products (incl. Wood, Cork & Furniture)	0.68	1.97	2.65	0.00	2.65	21	202.9	25.7	587.7	74.3	790.6	0.0	0.0	790.6	16	1.5
20 Man. of Pulp, Paper, Paper Prod. & Printing Products	1.18	3.09	4.27	0.00	4.27	12	225.4	27.7	587.7	72.3	813.1	0.0	0.0	813.1	15	1.6
21 Manufacture of Rubber and Plastic Products	0.18	2.80	2.98	0.00	2.98	18	11.3	6.0	177.9	94.0	189.2	0.0	0.0	189.2	28	0.4
22 Construction	0.67	2.76	3.42	0.00	3.42	14	995.1	19.5	4,103.3	80.5	5,098.4	0.0	0.0	5,098.4	3	9.9
23 Recycling, Recovery and Repair services	0.20	0.34	0.53	0.00	0.53	36	48.5	36.6	84.0	63.4	132.6	0.0	0.0	132.6	31	0.3
24 Wholesale and Retail Trade	0.16	1.93	2.09	0.00	2.09	23	269.0	7.5	3,325.8	92.5	3,594.8	0.0	0.0	3,594.8	5	7.0
25 Hotel and Restaurant Services	0.12	2.56	2.67	0.00	2.67	20	86.8	4.4	1,902.3	95.6	1,989.0	0.0	0.0	1,989.0	9	3.9
26 Land Transport and Transport Via Pipeline Serv.	21.24	2.50	23.74	0.00	23.74	5	4,545.2	89.5	535.3	10.5	5,080.5	0.0	0.0	5,080.5	4	9.9
27 Water and Air Transport Services	4.91	1.52	6.43	0.00	6.43	10	726.5	76.4	224.5	23.6	951.0	0.0	0.0	951.0	14	1.8
28 Supporting and Auxiliary Transport Services	0.17	3.11	3.27	0.00	3.27	15	17.4	5.1	324.7	94.9	342.1	0.0	0.0	342.1	25	0.7
29 Post and Telecommunication Services	0.03	1.01	1.04	0.00	1.04	30	4.4	3.2	132.5	96.8	136.9	0.0	0.0	136.9	30	0.3
30 Financial Intermediation Services (except Insurance and ...)	0.00	0.56	0.56	0.00	0.56	35	0.1	0.2	37.8	99.8	37.8	0.0	0.0	37.8	35	0.1
31 Insurance and Pension Funding Services	0.06	1.54	1.59	0.00	1.59	24	1.4	3.5	38.8	96.5	40.2	0.0	0.0	40.2	34	0.1
32 Real Estate Services and Other Renting Services	0.01	0.99	1.00	0.00	1.00	31	14.3	1.5	954.4	98.5	968.7	0.0	0.0	968.7	13	1.9
33 Education and R & D Services	0.02	0.55	0.57	0.00	0.57	34	17.3	3.6	463.9	96.4	481.2	0.0	0.0	481.2	22	0.9
34 Health and Veterinary Market Services	0.01	0.82	0.83	0.00	0.83	33	7.6	1.6	464.5	98.4	472.1	0.0	0.0	472.1	23	0.9
35 Other Services (Market and Non-Market)	0.07	0.91	0.98	0.00	0.98	32	39.6	6.8	542.3	93.2	581.9	0.0	0.0	581.9	20	1.1
36 Public Administration Non-Market Services	0.09	0.97	1.06	0.00	1.06	29	100.7	8.6	1,070.4	91.4	1,171.1	0.0	0.0	1,171.1	11	2.3
							12,676.8	**24.7**	**31,258.9**	**60.8**	**43,935.7**	**7,478.1**	**14.5**	**51,413.8**		100

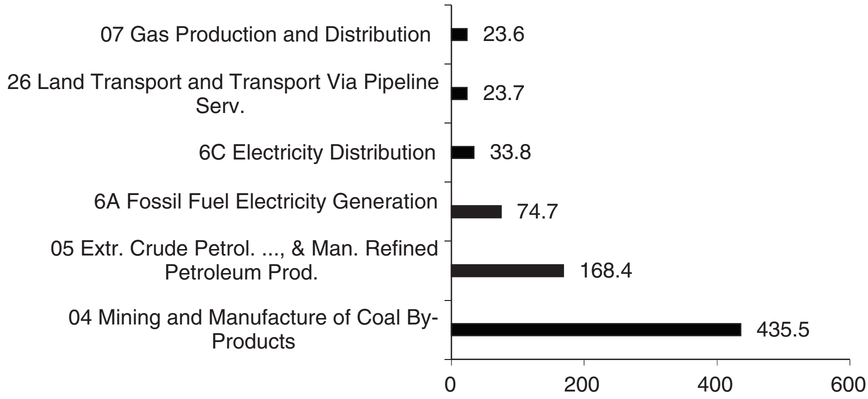

Fig. 25.1 CO_2 Intensities

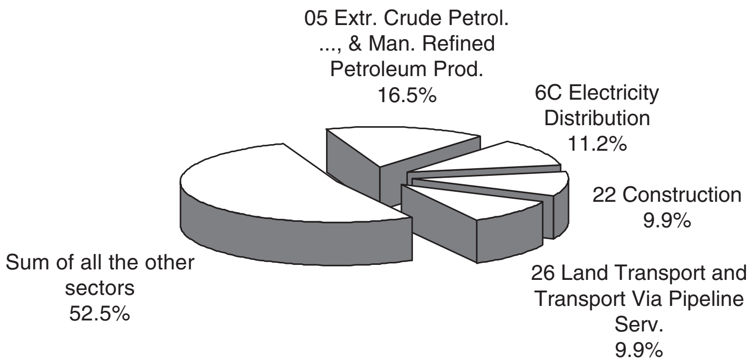

Fig. 25.2 Distribution of CO_2 Emissions Produced by the Portuguese Economy by Sector

sonal and public) transport (of passengers and goods) was 'responsible' for almost one-quarter of all the emissions that occurred in Portugal in 1992.

Relating these results with those concerning CO_2 intensities, one can notice that the sectors that are more highly CO_2 intensive are not necessarily the ones whose production generates more CO_2 emissions. This is explained by what might be called the 'scale effect' of the final demand (corresponding to the fact that the total CO_2 emissions of any sector are given by the product of the intensity per unit of final demand and the level of final demand).

Another key result is the significant importance of the indirect production demand for fuels in the production of CO_2 emissions (see Fig. 25.3). Indeed, more than half (60.8%) of the CO_2 emissions are attributable to indirect demand, while 24.7% of the emissions are attributable to direct demand for fossil fuels by industries; the remaining 14.5% are directly attributable to household demand for fossil fuels.

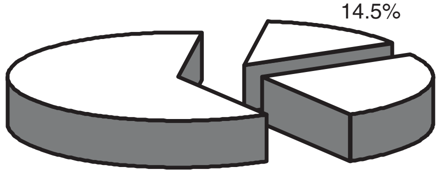

Fig. 25.3 CO_2 Emissions Attributable to … for Fuels

The Elasticities of Total CO_2 Emissions Produced by the Portuguese Economy

In this section, there will be offered an examination of the impacts of changes in specific parameters at the level of Portuguese energy-related CO_2 emissions. This will be done by analyzing the elasticities of total CO_2 emissions produced by the Portuguese economy with respect to (some of) the parameters. The figures are presented in Table 25.2, corresponding to situations of *ceteris paribus*, and were obtained according to the details given in Section "The Elasticities of CO_2 Emissions with the Model Parameters".

Column (1) presents the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to each component of total final demand. For example, the value of 0.17 for the elasticity of CO_2 emissions with respect to the final demand for the Extraction of Crude Petroleum and Natural Gas, and Manufacture of Refined Petroleum Products sector, indicates that if the final demand for this sector increases (decreases) by 1%, then total CO_2 emissions in the Portuguese economy will increase (diminish) by 0.17%. Additionally, one can say that the final demand for this sector's output is the one to which the Portuguese CO_2 emissions are most sensitive, followed by the final demand for the outputs of the following sectors: Electricity Distribution (0.11), Construction (0.10), Land Transport and Transport Via Pipeline Services (0.10), and Wholesale and Retail Trade (0.07).[24]

Moreover, as results from the definition of these elasticities (Equation (25.10)), their sum is equal to one, which means that if the final demand of all the sectors in the economy increase (decrease) by 1%, then total CO_2 emissions will enlarge (decline) in 1%.

In columns (2) and (3) are shown the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to production fuel use coefficients.

Concerning coal, by far the largest elasticity is the one corresponding to its use by the Fossil Fuel Electricity Generation sector. Indeed, the 0.17 figure is more than four times bigger than the next largest value, which is 0.04 for the Extraction and Manufacture of Non-Metallic Minerals sector. It is also noticeable that the great

[24] As there are 38 sectors, one would expect that all of these values would be considerably less than unity.

Table 25.2 Elasticity of Total CO_2 Emissions Produced by the Portuguese Economy

Elasticity of total CO_2 emissions produced by the Portuguese economy (c_{emis}) with respect to the...	Final demand		Production fossil fuel use coefficients				Final demand fossil fuel use coefficients		Column sum of the technological coefficients		Row sum of the technological coefficients	
	$\varepsilon^{c_{emis}}_{Y_i}$		$\varepsilon^{c_{emis}}_{c_{coal,i}}$		$\varepsilon^{c_{emis}}_{c_{oil,i}}$		$\varepsilon^{c_{emis}}_{p_{coal,i}}$	$\varepsilon^{c_{emis}}_{p_{oil,i}}$	$\varepsilon^{c_{emis}}_{a_{.j}}$		$\varepsilon^{c_{emis}}_{a_{i.}}$	
unit: % change	(1)	*ranking*	(2)	*ranking*	(3)	*ranking*	(4)	(5)	(6)	*ranking*	(7)	*ranking*
01 Agriculture, Hunting and Related Service Activities	0.02	12	0.00		0.02	8	0.00	0.00	0.03	9	0.03	7
02 Forestry, Logging and Related Service Activities	0.00	36	0.00		0.00	20	0.00	0.00	0.00	36	0.00	30
03 Fishing and Related Service Activities	0.00	26	0.00		0.01	14	0.00	0.00	0.00	34	0.00	27
04 Mining and Manufacture of Coal By-Products	0.00	33	0.01	4	0.00	33	0.00	0.00	0.00	37	0.01	21
05 Extr. Crude Petrol. ..., & Man. Refined Petroleum Prod.	0.17	1	0.00		0.04	4	0.00	0.14	0.01	21	0.03	8
6A Fossil Fuel Electricity Generation	0.00	37	0.17	1	0.18	1	0.00	0.00	0.00	30	0.35	1
6B Hydroelectricity	0.00	37	0.00		0.00	36	0.00	0.00	0.00	38	0.00	36
6C Electricity Distribution	0.11	2	0.00		0.00	36	0.00	0.00	0.35	1	0.24	2
07 Gas Production and Distribution	0.00	27	0.00		0.01	15	0.00	0.00	0.00	31	0.00	25
08 Water Supply	0.00	29	0.00		0.00	36	0.00	0.00	0.01	27	0.00	23
09 Extr. & Man. of Ferrous & Non-Ferrous Ores & Metals	0.01	19	0.01	3	0.00	16	0.00	0.00	0.02	15	0.02	11
10 Extraction and Manuf. of Non-Metallic Minerals	0.03	10	0.04	2	0.02	5	0.00	0.00	0.05	6	0.07	4
11 Manuf. of Chemicals and Chemical Products	0.04	8	0.00	5	0.07	3	0.00	0.00	0.03	10	0.07	5
12 Manufacture of Fabricated Metal Products	0.01	18	0.00		0.00	22	0.00	0.00	0.02	12	0.01	16
13 Man. of Electrical and Non-Electrical Machinery & Equipm.	0.01	17	0.00		0.00	26	0.00	0.00	0.02	18	0.00	26
14 Manufacture of Transport Equipment	0.01	21	0.00		0.00	23	0.00	0.00	0.01	20	0.00	31
15 Manufacture of Food Products and Beverages	0.05	7	0.00	8	0.01	9	0.00	0.00	0.07	4	0.03	9
16 Manufacture of Tobacco and Tobacco Products	0.00	32	0.00		0.00	27	0.00	0.00	0.00	35	0.00	38
17 Manufacture of Textiles and Clothing	0.06	6	0.00		0.01	11	0.00	0.00	0.07	5	0.02	12
18 Manufacture of Leather and Footwear	0.01	24	0.00		0.00	21	0.00	0.00	0.01	25	0.00	32
19 Other Manuf. Products (incl. Wood, Cork & Furniture)	0.02	16	0.00	6	0.01	13	0.00	0.00	0.02	16	0.01	17
20 Man. of Pulp, Paper, Paper Prod. & Printing Products	0.02	15	0.00		0.01	10	0.00	0.00	0.03	11	0.02	10
21 Manufacture of Rubber and Plastic Products	0.00	28	0.00		0.00	29	0.00	0.00	0.01	26	0.00	22
22 Construction	0.10	3	0.00		0.02	6	0.00	0.00	0.09	3	0.01	14
23 Recycling, Recovery and Repair services	0.00	31	0.00		0.00	19	0.00	0.00	0.00	32	0.00	29
24 Wholesale and Retail Trade	0.07	5	0.00		0.01	12	0.00	0.00	0.10	2	0.04	6
25 Hotel and Restaurant Services	0.04	9	0.00		0.00	18	0.00	0.00	0.04	7	0.01	20
26 Land Transport and Transport Via Pipeline Serv.	0.10	4	0.00	7	0.17	2	0.00	0.00	0.02	14	0.10	3
27 Water and Air Transport Services	0.02	14	0.00		0.02	7	0.00	0.00	0.01	28	0.01	18
28 Supporting and Auxiliary Transport Services	0.01	25	0.00		0.00	24	0.00	0.00	0.02	17	0.01	15
29 Post and Telecommunication Services	0.00	30	0.00		0.00	31	0.00	0.00	0.01	29	0.00	24
30 Financial Intermediation Services (except Insurance and ...)	0.00	35	0.00		0.00	35	0.00	0.00	0.01	24	0.01	19
31 Insurance and Pension Funding Services	0.00	34	0.00		0.00	34	0.00	0.00	0.00	33	0.00	34
32 Real Estate Services and Other Renting Services	0.02	13	0.00		0.00	28	0.00	0.00	0.03	8	0.02	13
33 Education and R & D Services	0.01	22	0.00		0.00	30	0.00	0.00	0.01	23	0.00	37
34 Health and Veterinary Market Services	0.01	23	0.00		0.00	32	0.00	0.00	0.01	22	0.00	35
35 Other Services (Market and Non-Market)	0.01	20	0.00		0.00	25	0.00	0.00	0.01	19	0.00	28
36 Public Administration Non-Market Services	0.02	11	0.00		0.00	17	0.00	0.00	0.02	13	0.00	33
	1.00		0.22	+	0.63	+	0.00	+ 0.14				
								1.00				

majority of the values in column (2) are zero, as there is no direct use of coal in the production of the corresponding sectors.

Regarding the use of oil, the largest elasticity is also for Fossil Fuel Electricity Generation (0.18), followed by Land Transport and Transport Via Pipeline Services (0.17), Manufacture of Chemicals and Chemical Products (0.07), Extraction of Crude Petroleum and Natural Gas, and Manufacture of Refined Petroleum Products (0.04), and Extraction and Manufacture of Non-Metallic Minerals (0.02).

From the analysis of the figures in columns (2) and (3), it can also be said that if all the sectors raise (reduce) the direct use of coal in their production by 1%, the overall augment (reduction) in CO_2 emissions would be of 0.22%, while the same percent change in the direct use of oil by all the sectors would imply a change of 0.63% in CO_2 emissions.

In the fourth and fifth columns, there are only two non-zero values. This is logical, as they represent the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the final demand fuel use coefficients (for coal and oil, respectively). Thus, the value of 0.001 in column (4) means that by changing the final demand for coal by 1%, the overall CO_2 emissions will vary by 0.001%; and the value of 0.14 in column (5) signifies that if the final demand for oil increases (decreases) by 1%, the total CO_2 emissions will increase (decrease) by 0.14%. Therefore, one can say that the CO_2 emissions are much more sensitive to the final demand for oil than to the final demand for coal.

Therefore, the results of the elasticities of total CO_2 emissions with respect to the production (columns (2) and (3)) and to the final demand (columns (4) and (5)) fuel use coefficients, suggest that any policy to fight against CO_2 emissions by directly interfering with industries or households direct consumption of fuels, has better chances of reaching more significant effects in CO_2 emissions by marginally 'acting' on oil than on coal use,[25] as the reader would have already thought (whether based on the results presented on the previous sections, or only on the basis of a sensible perception of the way the Portuguese economy performs).

The sixth column contains the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the column sum of the technical coefficients ($a_{.j}$). For example, the value of 0.35 for the Electricity Distribution sector means that if this sector raises (reduces) the use of all its inputs by 1%, then the CO_2 emissions will increase (decline) by 0.35%. Thus, it is possible to say that, following the Electricity Distribution sector, the sectors whose contribution can be bigger to reduce CO_2 emissions in Portugal, by becoming more efficient in their use of inputs are: Wholesale and Retail Trade; Construction; Manufacture of Food Products and Beverages; and Manufacture of Textiles and Clothing.

[25] Moreover, as results from the definition of these elasticities (and obviously, first of all, from the fact that the total use of fuels in the economy is 'divided' in fuel use for production demand and fuel use for final demand, and the CO_2 emissions here estimated are only the ones that result from coal and oil combustion), the sum of the totals of columns (2), (3), (4) and (5) is equal to one. This means that if all the sectors raise (reduce) the direct use of coal and oil in their production by 1%, and simultaneously the final demand for coal and oil increase (decrease) also by 1%, then total CO_2 emissions will enlarge (decline) in 1%.

Column (7) shows the elasticities of the CO_2 emissions produced by the Portuguese economy with respect to the row sum of the technical coefficients ($a_{i.}$). As an example, the result of 0.35 in Fossil Fuel Electricity Generation means that if the use of the sector's output as an input to all the sectors increases (decreases) by 1%, the overall CO_2 emissions will increase (decrease) by 0.35%. Moreover, the other products whose more efficient use (as inputs) by all the sectors may lead to more significant reductions in CO_2 emissions are those from the following sectors: Electricity Distribution; Land Transport and Transport Via Pipeline Services; Extraction and Manufacture of Non-Metallic Minerals; and Manufacture of Chemicals and Chemical Products. This clearly indicates that the greatest reduction in CO_2 emissions is to be achieved if all the sectors become more efficient in the use of first electricity, and then transport.

Final Comments

The results obtained in this empirical application are clear evidence of the 'value-added' that the input-output technique may bring to policy analysis, as an approach which takes economic interrelations into account when analyzing CO_2 production (Gay and Proops 1993).

Indeed, it appears that there is significant general awareness about the CO_2 emissions that occur from direct energy use in households and private cars, as well as about the CO_2 emitted directly in energy industries and by the transport sectors. But more significant is that it appears that there does not exist a general awareness about the major importance of industries' indirect production demand for fuels, and consequently of the fact that the great majority of direct consumption is 'responsible' for much more CO_2 production indirectly than directly.

Therefore, the analysis performed here may help policy-makers in dealing with the problem of CO_2 emissions as they are better informed about the root causes of some outcomes.

It may also help to make final consumers aware that the non-primary energy goods and services they purchase from industry sectors have entailed CO_2 emissions in their production. Indeed, through adequate sensitization campaigns it is possible to show to final consumers that they have much more 'responsibility' for CO_2 emissions than they usually assume. Then, it is possible to pass the 'message' to them that their individual action in terms of the goods and services they purchase (or not) may 'count' in the global struggle against climate change.

Concerning the sensitivity analysis of the CO_2 emissions produced by the Portuguese economy, is possible to say that two major kinds of conclusion can be made from it.

On the one hand, as the data we use is not perfectly known, this analysis can provide a guide to which components of the data set need to be determined most accurately. Actually, e.g., if the elasticity of total CO_2 emissions with respect to a specific item of data is large, the inaccuracy in such a particular item of data matters much more than if the elasticity is small.

On the other hand, such an analysis has a role to play in policy analysis and formulation. Indeed, it was here shown that its use allows, e.g., the identification of the potential for reducing CO_2 emissions through changes in the technologies used (through the analysis of the elasticities associated with the elements of the technological matrices **A**, **C** and **P**), as well as the examination of the changes in the structure of the final demand which would be most worthwhile for reducing CO_2 emissions (through the analysis of the elasticities associated with the specific elements of the final demand vector **y**). This is a particularly valuable feature, because as interest is in identifying policies that may reduce CO_2 emissions, one may consider how changing these parameters may be effective in achieving this aim.

Thus, it is possible to claim that one of the key accomplishments of the use of this type of modeling, which integrates economic, energy and environmental interactions in an input-output framework, is that it allows the analysis of how energy, and therefore CO_2 emissions, are related to industrial production, and ultimately to final demand, making it a tool particularly important for (*ex ante*[26] and/or *ex post*) policy analysis purposes.

Appendix List of Sectors in Portuguese

Box 25.2 List of Sectors in Portuguese Input-Output Table (IOT)

Proposed designation adopted for the IOT used in Chapters 25 and 28	Portuguese National Accounts Nomenclature (SEC-95, Base 95)
01 Agriculture, hunting and related service activities	01 Agriculture, hunting and related service activities
02 Forestry, logging and related service activities	02 Forestry, logging and related service activities
03 Fishing and related service activities	05 Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing
04 Mining and manufacture of coal by-products	10 Mining of coal and lignite; extraction of peat
05 Extraction of crude petroleum and natural gas, and manufacture of refined petroleum products	11 Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying 23 Manufacture of coke, refined petroleum products and nuclear fuel
06 Electricity production, transport and distribution	40 Electricity, gas, steam and hot water supply
07 Gas production and distribution	

(continued)

[26] Indeed, both the model and the database are formulated in terms of detailed technical parameters, on a multisectoral basis, that can be directly evaluated by technical experts and readily changed in order to explore the consequences of alternative scenarios (see Cruz 2002b, c).

Proposed designation adopted for the IOT used in Chapters 25 and 28	Portuguese National Accounts Nomenclature (SEC-95, Base 95)
08 Water supply	41 Collection, purification and distribution of water
09 Extraction and manufacture of ferrous and non-ferrous Ores and metals	12 Mining of uranium and thorium ores
	13 Mining of metal ores
	27 Manufacture of basic metals
10 Extraction and manufacture of non-metallic minerals	14 Other mining and quarrying
	26 Manufacture of other non-metallic mineral products
11 Manufacture of chemicals and chemical products	24 Manufacture of chemicals and chemical products
12 Manufacture of fabricated metal products	28 Manufacture of fabricated metal products, except machinery and equipment
13 Manufacture of electrical and non-electrical machinery and equipment	29 Manufacture of machinery and equipment n.e.c
	30 Manufacture of office machinery and computers
	31 Manufacture of electrical machinery and apparatus n.e.c.
	32 Manufacture of radio, television and communication equipment and apparatus
14 Manufacture of transport equipment	34 Manufacture of motor vehicles, trailers and semi-trailers
	35 Manufacture of other transport equipment
15 Manufacture of food products and beverages	15 Manufacture of food products and beverages
16 Manufacture of tobacco and tobacco products	16 Manufacture of tobacco products
17 Manufacture of textiles and clothing	17 Manufacture of textiles
	18 Manufacture of wearing apparel; dressing and dyeing of fur
18 Manufacture of leather and footwear	19 Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
19 Other manufacturing products (including wood, cork and furniture)	20 Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
	33 Manufacture of medical, precision and optical instruments, watches and clocks
	36 Manufacture of furniture; manufacturing n.e.c.
20 Manufacture of pulp, paper, paper products and printing products	21 Manufacture of pulp, paper and paper products
	22 Publishing, printing and reproduction of recorded media

(continued)

Proposed designation adopted for the IOT used in Chapters 25 and 28	Portuguese National Accounts Nomenclature (SEC-95, Base 95)
21 Manufacture of rubber and plastic products	25 Manufacture of rubber and plastic products
22 Construction	45 Construction
23 Recycling, recovery and repair services	37 Recycling
	50 Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel
24 Wholesale and retail trade	51Wholesale trade and commission trade services, except of motor vehicles and motorcycles
	52 Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods
25 Hotel and restaurant services	55 Hotel and restaurant services
26 Land transport and transport via pipeline services	60 Land transport and transport via pipeline services
27 Water and air transport services	61 Water transport services
	62 Air transport services
28 Supporting and auxiliary transport services	63 Supporting and auxiliary transport services; travel agency services
29 Post and telecommunication services	64 Post and telecommunication services
30 Financial intermediation services (except insurance and pension funding services)	65 Financial intermediation services, except insurance and pension funding services
31 Insurance and pension funding services	66 Insurance and pension funding services, except compulsory social security services
	67 Services auxiliary to financial intermediation
32 Real estate services and other renting services	70 Real estate services
	71 Renting services of machinery and equipment without operator and of personal and household goods
33 Education and research and development services	73 Research and development services
	80 Education services
34 Health and veterinary market services	85 Health and social work services
35 Other services (market and non-market)	72 Computer and related services
	74 Other business services
	91 Membership organization services n.e.c.
	92 Recreational, cultural and sporting services
	93 Other services
	95 Private households with employed persons
36 Public administration non-market services	75 Public administration and defense services; compulsory social security services
	90 Sewage and refuse disposal services, sanitation and similar services

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Chapter 26
Models for National CO_2 Accounting

Jesper Munksgaard, Jan Christoph Minx, Line Block Christoffersen, and Lise-Lotte Pade

Introduction

In international climate change negotiations a country is commonly held responsible for all CO_2 emitted from its domestic territory. In the literature this commonly applied CO_2 accounting method is called "territorial" or "producer responsibility". Driven by concerns about carbon leakage (Wyckoff and Roop 1994; Kondo et al. 1998; Ahmad and Wyckoff 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_2 accounting method.[1]

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_2 embodied in exports or imports (or a

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[1] 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.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

combination of both). With world trade growing more than twice as fast as world GDP,[2] the way how to account for CO_2 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_2 to the atmosphere – the producer or the consumer. This has been extensively discussed in the literature before (e.g. Wyckoff 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_2 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.

The structure of the article is as follows. Section "Responsibility and IO Models" 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 "Literature Review". In Section "Model Descriptions" the methodology of key models will be developed from a consistent multi-regional input-output framework. The data set will be introduced in Section "Data Description", before the results will be presented and discussed in Section "Results and Discussion". Section "Model Applications For Policy" turns to policy implications and potential model applications of both accounting methods and Section "Conclusion" concludes.

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 not only taking into account 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.[3] In particular, these kinds of models allow assessing physical flows from the natural environment into and out of the economic system

[2] This figure refers to the growth in trade between the Kyoto reference year 1990 and 1999 (WTO 2000).

[3] In fact, this has motivated a whole new branch of research called environmental input-output lifecycle assessment (EIOLCA) (see for example: Hendrickson et al. 1998; Matthews 1999; Joshi 2000). However, it has shown to be most fruitful to combine conventional process lifecycle analysis with EIOLCA in hybrid LCA models as proposed by (Bullard et al. 1978) and later

(such as fuel inputs and CO_2 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_2 emissions in an additional, national accounting sense. The principle of *producer responsibility* assigns CO_2 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. This is shown in Fig. 26.1, where emissions associated with exports to the rest of the world (ROW) (quadrant 2) are added to country A's "domestic"[4] CO_2 account (quadrant 1). The *consumer responsibility* method books CO_2 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_2 (quadrant 1) in order to set up a consumer responsibility account. Subtracting quadrant 3 from 2 gives country A's CO_2 *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.

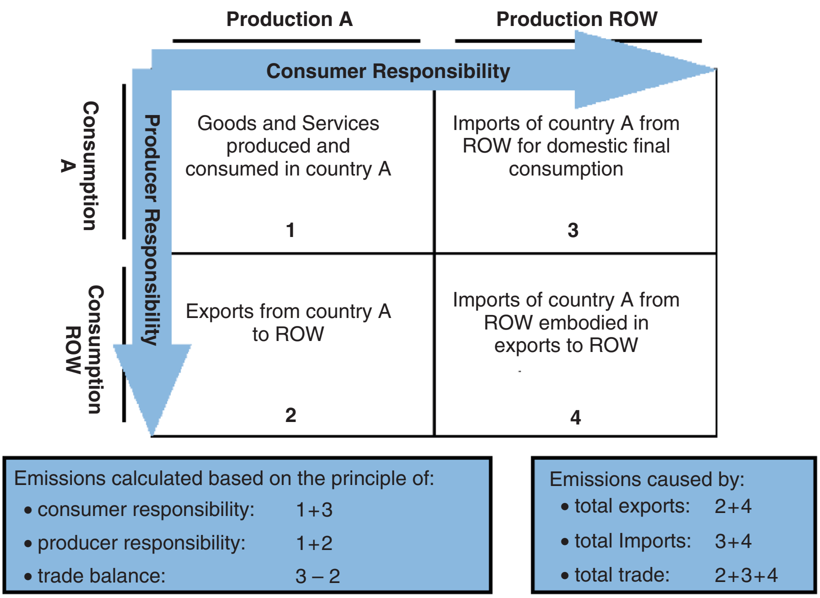

Fig. 26.1 Producer Versus Consumer Responsibility

extended by Treloar (1997) and Lenzen (2001) among others. For a good introduction with key references see Nielsen and Weidema (2001).

[4] We refer to domestic here consistently in the sense of domestically produced and consumed goods and services. This means that "domestic" always excludes exports.

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_2 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 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 methodological sound respond 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 labor intensity of the task.

Notwithstanding those difficulties, first serious attempts have recently been made to estimate import-related emissions from multi-regional models by Lenzen et al. (2002, 2004) and Ahmad and Wyckoff (2003). Better and more comprehensive data availability due to current efforts to improve international pollution inventories (GTAP 2003),[5] 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, where only the latter takes inter-regional feedback effects into account, cf. van der Linden and Oosterhaven (1995).

These characteristics lead to seven major model categories as shown in Fig. 26.2, where an additional subdivision can be achieved by assigning the emissions

[5] 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.

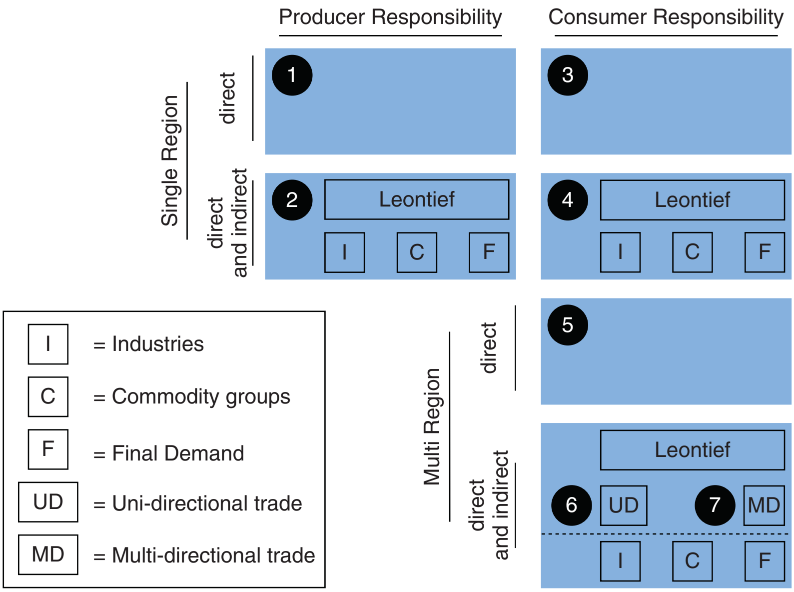

Fig. 26.2 Classification of CO_2 Accounting Models

to different institutions or functional units within the economy (industries versus commodity groups for different final demand entities at different levels of disaggregation).

Literature Review

Producer Responsibility Models

The least data intensive way to set up a producer responsibility CO_2 account is to use a direct emission model (model 1, Fig. 26.2). Such models have mainly been applied in environmental accounting (Harris 2001) and assign the emissions to those sectors actually emitting CO_2. 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_2 account based on structural decomposition analysis.[6]

[6] Interestingly, this allows him also to quantify the contribution of changes in Japan's trade structure on total emission change, and evaluate changes in the development of the trade balance indicator within a producer responsibility framework.

However, most input-output studies use direct and indirect emission models to set up a CO_2 account facilitated by the application of a total requirement matrix (the Leontief Inverse in the standard demand side input-output model) (model 2, Fig. 26.2). 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_2 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_2 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_2 account.

Consumer Responsibility Models

Direct emission models have been rarely applied to estimate a nation's consumer responsibility CO_2 account. The only notable exception both in a single-region and multi-regional data framework (models 3 and 5, Fig. 26.2) is Harris (2001). Therefore, on-site emissions of all products consumed in an economy are summed across sectors and households. Clearly this includes domestic and imported products.

The majority of studies uses a direct and indirect emission formulation in single-region models (model 4, Fig. 26.2). Therefore, many authors have followed the spirit of the consumer responsibility principle also on a subnational level and assigned CO_2 *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_2 emission estimates depending on the treatment of trade in single-region, uni-directional or multi-directional input-output models. Recently, Ahmad and Wyckoff (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_2 accounting perspective. There are mainly three types. First, there are studies which *only* estimate trade-related emissions being essentially concerned with the CO_2 trade balance of countries as defined in Fig. 26.1. Therefore, they have played an important role in the national CO_2 accounting literature as they have informed about the extent of differences in producer and consumer responsibility CO_2 accounts and "winners" and "losers" of current accounting practices (see Wyckoff and Roop 1994; Schaeffer and De 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 emission related to consumption activities of households. Often those studies calculate the total emission 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).

Model Descriptions

In this section the different national CO_2 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 math 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: 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_2 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 $[n \times 1]$ vector of domestic output $\boldsymbol{x}$ by industrial sector
   - A $[n \times 1$ vector of final demand $\mathbf{y}$ by industrial sector including exports to other countries
   - A $[n \times n]$ matrix of technical coefficients $\mathbf{A}$ indicating the input requirements of the *jth* sector for intermediate goods from the *ith* sector per monetary unit output of sector j
2. An $[m \times n]$ energy use matrix $\mathbf{E}_{\text{ind}}$ indicating the fuel use of the *kth* fuel type per unit output of the *jth* industrial sector and an $[m \times n]$ energy use matrix $\mathbf{E}_{\text{fd}}$ giving

the household's fuel use of the *kth* fuel type per monetary unit of final demand for goods of the *jth* industrial sector.

3. A [m × 1] vector $\boldsymbol{c}$ of CO_2 emission per unit fuel used of the *kth* type.

To set up national CO_2 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

Bilateral import coefficient matrices $\mathbf{A}^{ij}$ $(for\ i \neq j)$, 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 $\mathbf{A}$ will be denoted $\mathbf{A}^{ii}$.

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_2 emissions. Model 1 shows direct CO_2 emissions from on-site energy use, and model 2 shows direct and indirect CO_2 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.

Model 1: Direct Emissions from Production

One way to establish a CO_2 account based on the principle of producer responsibility denoted by Ω_{δ}^{PR} is to add up the emissions from industries δ_{ind}^{PR} and from final demand[7] δ_{fd} arising from the direct use of energy goods and services. We can obtain an estimate of δ_{ind}^{PR} by premultiplying the total output vector $\boldsymbol{x}$ by the transposed emissions coefficient vector $\mathbf{c}$ and the industrial energy intensity matrix $\mathbf{E}_{\mathrm{ind}}$, that is

$$\delta_{ind}^{PR} = \mathbf{c}'\boldsymbol{E}_{ind}\boldsymbol{x} \tag{26.1}$$

Note that $\boldsymbol{x}$ 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 δ_{fd} can be established by

$$\delta_{fd} = \boldsymbol{c}'\boldsymbol{E}_{fd}\boldsymbol{y} \tag{26.2}$$

where $\boldsymbol{y}$ is the final demand vector. Putting Equations (26.1) and (26.2) together we can set up the desired producer responsibility CO_2 account, that is

$$\Omega_{\delta}^{PR} = \delta_{ind}^{PR} + \delta_{fd} = \boldsymbol{c}'\boldsymbol{E}_{ind}\boldsymbol{x} + \boldsymbol{c}'\boldsymbol{E}_{fd}\boldsymbol{y} \tag{26.3}$$

[7] Note that households are usually treated as the only emitting domestic final demand entity in national fuel use statistics.

Model 2: Direct and Indirect Emissions from Production

In direct and indirect emission models a producer responsibility account Ω_{σ}^{PR} can be estimated by adding up the direct and indirect emissions of industries σ_{ind}^{PR} and the direct emissions of final demand δ_{fd} as calculated in Equation (26.2). σ_{ind}^{PR} can be written as,

$$\sigma_{ind}^{PR} = \boldsymbol{c}'\boldsymbol{E}_{ind}(\boldsymbol{i} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{26.4}$$

where **A** is the [n × n] domestic direct requirement matrix and, **I** is an identity matrix of the same size and $(\mathbf{I} - \mathbf{A})^{-1}$ is the domestic Leontief inverse. Combining Equations (26.4) with (26.2) gives the desired direct and indirect emission model for calculating national CO_2 accounts based on the concept of producer responsibility Ω_{σ}^{PR}, that is

$$\begin{aligned} \Omega_{\sigma}^{PR} &= \delta_{fd} + \sigma_{ind}^{PR} = \boldsymbol{c}'\boldsymbol{E}_{fd}\boldsymbol{y} + \boldsymbol{c}'\boldsymbol{E}_{ind}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \\ &= \boldsymbol{c}'\left[\boldsymbol{E}_{fd} + \boldsymbol{E}_{ind}(\boldsymbol{I} - \boldsymbol{A})^{-1}\right]\boldsymbol{y} \end{aligned} \tag{26.5}$$

It should be clear that the *total* emission estimates Ω_{δ}^{PR} and Ω_{σ}^{PR} are identical. However, they differ in their *sectoral* emission assignments as Equation (26.1) accounts all emissions at the source sector and Equation (26.4) re-allocates emissions according to the sector of final use using the Leontief inverse.

Consumer Responsibility Models

The consumer responsibility models developed in this section are also based on a distinction between direct and indirect CO_2 emissions. Besides, the models are specified as single-region or multi-region models.

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 than in the domestic economy, i.e. domestic energy and fuel coefficients can also be used for the calculation of CO_2 emissions from imported goods and services.

Model 3: Direct Emissions in a Single-Region Model

Direct emissions from industries in the single-region consumer responsibility model δ_{ind}^{CR} can be estimated similar to Equation (26.1). The only difference is that we exclude exports and include imports in our estimations, that is

$$\delta_{ind}^{CR} = \mathbf{c}'\mathbf{E}_{ind}(\mathbf{x}_{tot} - \mathbf{y}_{ex}) \tag{26.6}$$

where $\mathbf{x}_{\text{tot}} = \mathbf{x} + \mathbf{x}_{\text{imp}}$ is the total industrial output including total domestic production, exports and imports and $\mathbf{y}_{\text{ex}}$ is the exports vector. Meanwhile the direct emission estimate as provided in Equation (26.2) remains unchanged, because all import-related emissions are accounted for in Equation (26.6). Therefore, we can estimate our consumer responsibility account $\Omega_{\sigma,SR}^{CR}$ using a direct emission formulation, that is

$$\Omega_{\delta,SR}^{CR} = \delta_{ind}^{CR} + \delta_{fd} = \mathbf{c}'\mathbf{E}_{ind}(\mathbf{x}_{tot} - \mathbf{y}_{ex}) + \mathbf{c}'\mathbf{E}_{fd}\mathbf{y} \tag{26.7}$$

Model 4: Direct and Indirect Emissions in a Single-Region Model

A consumer responsibility CO_2 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 δ_{fd}. $\sigma_{SR,ind}^{CR}$ consist of three components: *First*, emissions arising from domestic production for domestic final demand (excluding exports), s*econd*, 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,

$$\begin{aligned}\sigma_{SR,ind}^{CR} = \mathbf{c}'\mathbf{E}_{ind}\Big[&(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\neq\text{exp}} + \left((\mathbf{I}-\mathbf{A}_{tot})^{-1} - (\mathbf{I}-\mathbf{A})^{-1}\right)\mathbf{y}_{\neq\text{exp}} \\ &+(\mathbf{I}-\mathbf{A}_{tot})^{-1}\mathbf{y}_{imp_{\neq\text{exp}}}\Big]\end{aligned} \tag{26.8}$$

where $\mathbf{A}_{tot} = \mathbf{A} + \mathbf{A}_{imp}$, $\mathbf{y}_{tot} = \mathbf{y} + \mathbf{y}_{imp}$ and $\mathbf{y}_{\neq\text{exp}}$ are the domestic final demand vectors (excluding exports). By merging equations Equations (26.9) and (26.2), we can set up $\Omega_{\sigma,SR}^{CR}$, that is

$$\begin{aligned}\Omega_{SR,\sigma}^{CR} &= \sigma_{SR,ind}^{CR} + \delta_{fd} \\ &= \mathbf{c}'\Big[\mathbf{E}_{ind}\Big((\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\neq\text{exp}} + \left((\mathbf{I}-\mathbf{A}_{tot})^{-1} - (\mathbf{I}-\mathbf{A})^{-1}\right)\mathbf{y}_{\neq\text{exp}} \\ &\quad +(\mathbf{I}-\mathbf{A}_{tot})^{-1}\mathbf{y}_{imp_{\neq\text{exp}}}\Big)+\mathbf{E}_{fd}\mathbf{y}_{hh}\Big]\end{aligned} \tag{26.9}$$

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.

Multi-region Approach

In this section we relax the assumption of similar production technologies between the countries considered. By using information about production and environmental technologies in other countries, we are able to calculate emissions for national CO_2 accounts in a multi-regional setting.

Model 5: Direct Emissions in a Multi-region Model

The direct emissions from industries $\delta^{CR}_{MR,ind}$ 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

$$\delta^{CR}_{MR,ind} = \sum_{i=1}^{I} (\mathbf{c}^i)'\mathbf{E}^i\mathbf{x}^{ij} \tag{26.10}$$

where $\boldsymbol{c}^i$ and $\boldsymbol{E}^i$ $(for\ i \neq j)$ represent environmental technology in the exporting countries, $\boldsymbol{x}^{ij}$ 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 $\Omega^{CR}_{MR,\delta}$ by

$$\Omega^{CR}_{\delta} = \delta^{CR}_{MR,ind} + \delta_{fd} = \sum_{i=1}^{I} (\mathbf{c}^i)'\mathbf{E}^i\mathbf{x}^{ij} + (\mathbf{c}^j)'\mathbf{E}^j_{fd}\mathbf{y}^{jj} \tag{26.11}$$

where the second term on the right-hand side corresponds to Equation (26.2) when adding a country index.

Model 6: Direct and Indirect Emissions in a Uni-Directional Trade 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 $\sigma^{CR}_{UD,ind}$. Afterwards $\sigma^{CR}_{UD,ind}$ will be generalised for the n-country case, when we set up the consumer responsibility account $\Omega^{CR}_{UR,\sigma}$ for uni-directional trade models. Within our three country setting, $\sigma^{CR}_{UD,ind}$ can be calculated as follows,

$$\sigma^{CR}_{UD,ind} = \begin{pmatrix} \mathbf{c}^{1\prime}\mathbf{E}^1_{ind} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{c}^{2\prime}\mathbf{E}^2_{ind} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{c}^{3\prime}\mathbf{E}^3_{ind} \end{pmatrix} \left[\begin{pmatrix} \mathbf{I} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{11} & \mathbf{O} & \mathbf{O} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{O} \\ \mathbf{A}^{31} & \mathbf{O} & \mathbf{A}^{33} \end{pmatrix} \right]^{-1} \begin{pmatrix} \mathbf{y}^{11}_{\neq \exp} \\ \mathbf{y}^{21} \\ \mathbf{y}^{31} \end{pmatrix} \tag{26.12}$$

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, $\mathbf{y}^{11}_{\neq \exp}$ is domestic final consumption and y^{i1} $(for\ i = 2,3)$ are the import final demand vectors from country 2 and 3 (ROW), respectively.

Equations (26.2) and a version of Equation (26.12) generalised for the n-country case can be merged to set up a consumer responsibility account for country j in $\Omega^{CR}_{UD,\sigma}$ the uni-directional model, that is

$$\begin{aligned} \Omega^{CR}_{UD,\sigma} &= \sigma^{CR}_{UD,ind} + \delta_{fd} = \\ &= \mathbf{c}^j \left[\mathbf{E}^j_{fd}\mathbf{y}^{jj} + \mathbf{E}^j_{ind}(\mathbf{I} - \mathbf{A}^{jj})^{-1}\mathbf{y}^{jj} \right] \\ &\quad + \sum_{\substack{i=1 \\ i \neq j}}^{I} \mathbf{c}^i \mathbf{E}^i_{ind} \left[\left(\mathbf{I} - \mathbf{A}^{ii}\right)^{-1} \mathbf{y}^{ij} + (\mathbf{I} - \mathbf{A}^{ij})^{-1}\mathbf{y}^{jj} \right] \end{aligned} \tag{26.13}$$

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.

Model 7: 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 $\Omega^{CR}_{MD,\sigma}$ we calculate the direct and indirect emissions of industries for country 1 in a multi-lateral setting $\sigma^{CR}_{MD,ind}$ very similar to Equation (26.13), that is

$$\sigma^{CR}_{MD,ind} = \begin{pmatrix} \mathbf{c}^{1\prime}\mathbf{E}^1_{ind} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{c}^{2\prime}\mathbf{E}^2_{ind} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{c}^{3\prime}\mathbf{E}^3_{ind} \end{pmatrix} \left[\begin{pmatrix} \mathbf{I} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \mathbf{A}^{13} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{A}^{23} \\ \mathbf{A}^{31} & \mathbf{A}^{32} & \mathbf{A}^{33} \end{pmatrix} \right]^{-1} \begin{pmatrix} \mathbf{y}^{11}_{\neq \exp} \\ \mathbf{y}^{21} \\ \mathbf{y}^{31} \end{pmatrix} \tag{26.14}$$

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 Equations (26.12) and (26.14) 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_2 account in a multi-regional model $\Omega^{CR}_{MD,\sigma}$ for country j, we can write in a generalised way for the n-country case,

$$\begin{aligned}\Omega^{CR}_{MD,\sigma} &= \sigma^{CR}_{MD,ind} + \delta_{fd} = \\ &= \mathbf{c}^j \left[\mathbf{E}^j_{fd}\mathbf{y}^{jj} + \mathbf{E}^j_{ind}(\mathbf{I}-\mathbf{A}^{jj})^{-1}\mathbf{y}^{jj}\right] \\ &\quad + \sum_{\substack{i=1 \\ i\neq j}}^{I} \mathbf{c}^i\mathbf{E}^i_{ind}\left[\left(\mathbf{I}-\mathbf{A}^{ii}\right)^{-1}\mathbf{y}^{ij} + (\mathbf{I}-\mathbf{A}^{ij})^{-1}\mathbf{y}^{jj} + (\mathbf{I}-\mathbf{A}^{ij})^{-1}\mathbf{y}^{ij}\right]\end{aligned} \tag{26.15}$$

Data Description

In Section "Results and Discussion" each of the CO_2 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.

Table 26.1 summarises the input-output, energy and CO_2 data used for the model estimations in Section "Results and Discussion". 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 1,309 to 229 commodities.

As indicated above, the rest of the world account was modelled on the basis of Australian input-output, energy and CO_2 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_2 inputs reflect world average production conditions, except for beef-cattle grazing and forestry, where CO_2 emissions from land use changes were excluded, and except for electricity generation, aluminium, basic iron and

Table 26.1 Data Sources and Features

Region	Input-output data			Energy and CO_2 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 Centralbyrån 2002	23	Statistiska Centralbyrån 2002
Norway	118	229	Statistisk Sentralbyrå 2002	23	Statistisk Sentralbyrå 2002
ROW	106	134	Australian Bureau of Statistics 2001	29	Australian Bureau of Agricultural and Resource Economics 2000 Australian Greenhouse Office 1999

steel manufacturing, for which world average energy and CO_2 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 scrutinising 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 Wyckoff 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 recorded in US dollar currency conversion rates were applied to convert it into the exporting countries currency.

Emission data were restricted to CO_2 which makes the main part of all greenhouse gases. Moreover, only the CO_2 emission from energy use has 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 1 year or less as CO_2 neutral.[8] Therefore those are assigned an emission coefficient of zero. Contrary, renewable energy sources having a lifecycle longer than 1 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 [1,204×1,204] as shown in Lenzen et al. (2004) and estimated based on an industry technology assumption.

Results and Discussion

Tables 26.2 shows the Danish production CO_2 account broken down into 11 commodity groups for the direct and indirect part of the account and 5 groups of direct energy use in households. CO_2 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_2 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_2 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_2 emissions.

Tables 26.3–26.5 are the Danish consumer CO_2 accounts for each of the model approaches used to the treatment of imports: Single region model, uni-directional trade model and multi-directional trade model. The consumer CO_2 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.

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_2. 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_2 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.

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.

[8] Bio-fuels with a lifecycle of 1 year absorb the same amount of CO_2 as it liberates when broken down or combusted during 1 year.

Table 26.2 Producer CO_2 Responsibility Account for Denmark, 1997, Million Tons

	Direct emissions from household energy use	Direct and indirect emissions from Danish industries Domestic use	Exports
Model Equation no.	Model 1 Equation (2)	Model 2 Equation (4)	
Commodity groups			
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 household equipments.	–	1.361	2.430
Medical products, health services	–	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
Energy use in households			
Electricity	0	–	–
Gas	1.667	–	–
Liquid fuels	3.649	–	–
Hot water, steam, etc.	533	–	–
Fuels and lubricants	5.771	–	–
Total	11.620	34.509	19.773
Model		Model 2	
Equation no.		Equation (5)	
Total responsibility		65.902	

CO_2 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_2 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_2 emissions. These comparisons on commodity level indicate that global CO_2 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_2 embodiments will occur if a more detailed commodity level is applied in the analyses.

Table 26.3 Consumer CO_2 Responsibility Account for Denmark, 1997, Million Tons: Single-Region Model

	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
Model Equation no.	Model 1 Equation (2)	Model 4 Equation (8)	
Commodity groups			
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 household equipments	–	1.186	2.333
Medical products, health services	–	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
Energy use in households			
Electricity	0	–	–
Gas	1.667	–	–
Liquid fuels	3.649	–	–
Hot water, steam, etc.	533	–	–
Fuels and lubricants	5.771	–	–
Total	11.620	34.509	6.791
Model		Model 4	
Equation no.		Equation (9)	
Total responsibility		58.812	

Making the comparison between producer and consumer responsibility[9] 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_2 emission when comparing the two accounting principles. As producer responsibility exceeds consumer responsibility by 2.7 million tons the problem of net CO_2 exports pointed out for 1990 still remains in the Danish 1997 accounts. However, this surplus is more than 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

[9] The comparison is made by adding “direct and indirect emissions” by “export” in the producer account, respectively “indirect emissions” and “import” in the consumer account.

Table 26.4 Consumer CO_2 Responsibility Account for Denmark, 1997, Million Tons: Uni-Directional Trade Model

	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
Model Equation no.	Model 1 Equation (2)	Model 6 Equation (12)	
Commodity groups			
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 household equipments	–	1.600	2.965
Medical products, health services	–	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
Energy use in households			
Electricity	0	–	–
Gas	1.667	–	–
Liquid fuels	3.649	–	–
Hot water, steam, etc.	533	–	–
Fuels and lubricants	5.771	–	–
Total	11.620	46.091	11.453
Model		Model 6	
Equation no.		Equation (13)	
Total responsibility		69.164	

than 1 million tons of CO_2. 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.

Model Applications For Policy

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_2 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

Table 26.5 Consumer CO_2 Responsibility Account for Denmark, 1997, Million Tons: Multi-Directional Trade Model

	Direct emissions from household energy use	Direct and indirect emissions from Danish industries	Imports
Model	Model 1	Model 7	
Equation no.	Equation (2)	Equation (14)	
Commodity groups			
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 household equipments	–	1.635	3.187
Medical products, health services	–	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
Energy use in households			
Electricity	0	–	–
Gas	1.667	–	–
Liquid fuels	3.649	–	–
Hot water, steam, etc.	533	–	–
Fuels and lubricants	5.771	–	–
Total	11.620	46.585	12.011
Model		Model 7	
Equation no.		Equation (15)	
Total responsibility		70.216	

be used, data sources and consistency. Presently, national CO_2 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_2emissions, 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_2 emissions to a figure much below average. As a result, electricity import had an indirect influence on the amount of Danish CO_2 emissions allowed according to the Kyoto Protocol. Facing this drawback the Danish energy administration decided to adjust Danish CO_2 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_2 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_2. 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_2 accounting.

This illustrative case of conflict between national CO_2 targets and power market integration highlights the general problem of trade between open economies, which face CO_2 targets. The results in Section "Results and Discussion" show that a significant amount of CO_2 is embodied in commodities traded between countries. Countries with net CO_2 exports might push the issue of considering the CO_2 trade balance in order to receive a CO_2 discount for emissions accounted for in the baseline scenario applied for the national CO_2 target. Taking such imbalances in foreign trade into account might reduce the reluctance of some open economies to accept a certain baseline for CO_2 emissions when negotiating future agreements on the allocation of national reduction targets.

The concept of a CO_2 trade balance making explicit the difference between embodied CO_2 in exports and import (Munksgaard and Pedersen 2001) could have implications for future negotiations on CO_2 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_2 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 labor-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 emission enters 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_2 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_2 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_2 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_2 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 "Model Descriptions"?

Model 1 on direct emissions from production is the one actually agreed upon for reporting national CO_2 emissions under the Kyoto agreement. The model serves the need to identify who is the actual emitter of CO_2 from combusting fuels. Thereby the model could be used to target a CO_2 reduction policy based on CO_2 taxes on energy use or CO_2 permissions. High direct CO_2 emissions will be an indicator for the tax burden to bear when a CO_2 tax regime is introduced.

Model 2 on direct and indirect emissions from production is a lifecycle approach to account for the emissions of CO_2 in production. The result of the model calculation is CO_2 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 3–7 are models within the consumer responsibility approach. Consequently, all models are accounting for the CO_2 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_2 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_2 emissions. The direct CO_2 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_2 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 mean to account for savings in domestic CO_2 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_2 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_2 emissions. The model is also suitable for analysing the CO_2 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 point to a need for elaborating multinational models like GTAP (Global Trade Analysis Project, cf. Hertel 1997) to be used for national CO_2 accounts. Such models, however, have to be agreed upon by the countries participating in international agreements. As conflicting interests might occur between actual CO_2 exporting and importing countries, this is of course not an easy task.

Conclusion

The survey made in this study shows that the concept of national CO_2 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_2 emissions. Consumer responsibility says that final demand (consumption) is responsible for all upstream CO_2 emissions from domestic as well as foreign production activities.

In the growing field of interest for national CO_2 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_2 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_2 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_2 emission accounts by using a five country dataset. Results show that Danish consumers are responsible for more CO_2 emissions than Danish producers. A difference of 4.3 million tons CO_2 between the two accounts points to an equivalent deficit on the Danish CO_2 trade balance. Results also indicate that the proper treatment of import is a key issue if in an international framework for consumer responsibility has to be implemented. Danish CO_2 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_2.

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 exits. 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_2 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.

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Part VII
Waste Management

Chapter 27
Waste Input-Output Analysis, LCA and LCC

Shinichiro Nakamura and Yasushi Kondo

Introduction

Any economic activity generates waste of some kind, which needs to be treated by some waste treatment method. Corresponding to any flow of goods among different sectors of the economy, there exists the associated flow of waste involving waste treatment sectors. The conventional IOA was originally developed to represent the intersectoral flow of goods and hence is not designed to take account of the flow of waste associated with it. Consequently, in its conventional form, IOA is not able to take proper account of the effects that result from the interaction between the flows of goods and wastes.

The pioneering study in the field of environmental IOA (EIO) that is relevant to waste management issues is the Leontief pollution abatement model (Leontief 1970, 1972). Leontief extended the conventional IOA to take account of the emission of pollutants, their elimination activity, and the interdependence between conventional goods-producing sectors and pollution abatement sectors. With regard to their relevance to issues of waste management, the Leontief pollution abatement model and its extension by Faye Duchin (1990) can be characterized by the fact that they assume the existence of a strict one-to-one correspondence between a pollutant (waste) and its abatement (waste treatment) method.

However, in waste management, the joint treatment of a wide range of different types of waste in a single treatment method is commonly observed. It is also true that a wide range of different treatment methods can be applied to a given type of waste. In short, the one-to-one correspondence between waste types and treatment methods does not hold in the empirically relevant case of waste management that involves a large number of waste types and treatment methods. The assumption in the Leontief EIO model is not consistent with the reality of waste management.

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The WIO (waste input-output) model (Nakamura 1999; Nakamura and Kondo 2002) generalized the Leontief EIO model to make it applicable to waste management issues. It can deal with an arbitrary combination of treatment methods applied to an arbitrary combination of waste types provided that the combinations are technically feasible. The number of waste types and treatment methods can be set arbitrarily and are not required to be equal. Furthermore, it can take account of waste generated from virtually any waste source in the economy, including municipal solid waste (MSW) from final demand sectors, industrial and commercial waste from the goods- and service-producing sectors, and treatment residues from waste treatment sectors.

In this chapter we explain the basic concepts of the WIO table and model, and illustrate its application to LCA (Life Cycle Assessment) and LCC (Life Cycle Costing). Section "Waste Input-Output Table" first introduces the basic notations and explains the basic structure of the WIO table. Section "The WIO Model" is devoted to the derivation of theoretical WIO models. In the conventional IOA it is well known that corresponding to a quantity model there does exist a cost/price model which is dual to it. The duality of the conventional IOA does not apply to the WIO quantity model due to its peculiar natures except under special conditions. Still, it is possible to obtain a cost/price counterpart of the WIO model. Section "Application of WIO to LCA and LCC" illustrates the application of the WIO models to LCA and LCC for a case study of the recycling of end-of-life electric appliances. A brief mention of some recent applications and extensions of WIO closes the chapter.

Waste Input-Output Table

We shall first introduce notations. Let there be n^{I} goods- and service-producing sectors (henceforth "goods sector"), n^{II} waste treatment sectors, n^{W} waste types, and $n := n^{\mathrm{I}} + n^{\mathrm{II}}$. We define the sets of natural numbers referring to each of these sectors and waste types by $N^{\mathrm{I}} := \{1, \ldots, n^{\mathrm{I}}\}$, $N^{\mathrm{II}} := \{n^{\mathrm{I}} + 1, \ldots, n^{\mathrm{I}} + n^{\mathrm{II}}\}$, $N := N^{\mathrm{I}} \cup N^{\mathrm{II}}$, and $N^{\mathrm{W}} := \{1, \ldots, n^{\mathrm{W}}\}$. We then denote, for sector j $(j \in N)$, its output by x_j, the input from sector i $(i \in N)$ by X_{ij}, and the generation and input of waste k $(k \in N^{\mathrm{W}})$ by $W^{\oplus}_{kj}$ and $W^{\ominus}_{kj}$, respectively. The flow of waste is net of intra-sectoral recycling, and is measured in a physical unit. For a waste treatment sector, its "output" refers to the amount of waste it treated. Similarly, we denote the final demand for i $(i \in N)$ by $X_{i\mathrm{F}}$, the generation of waste k $(k \in N^{\mathrm{W}})$ from the final demand sector by $W^{\oplus}_{k\mathrm{F}}$, and the input of waste k into the final demand sector by $W^{\ominus}_{k\mathrm{F}}$.

Table 27.1 shows a schematic representation of the waste input-output table (WIOT). Bold-faced capital letters refer to matrices and small letters to vectors. For instance, $\mathbf{W}^{\oplus}_{\cdot,\mathrm{I}}$ refers to an $n^{\mathrm{W}} \times n^{\mathrm{I}}$ matrix, the (k, j)-element of which is $W^{\oplus}_{kj}$, $\mathbf{X}_{\mathrm{I,II}}$ to an $n^{\mathrm{I}} \times n^{\mathrm{II}}$ matrix the (i, j)-element of which is $X_{i,n^{\mathrm{I}}+j}$, and $\mathbf{x}_{\mathrm{I}}$ to an n^{I}-vector of x_j's. The generation of waste from waste treatment sectors $\mathbf{W}^{\oplus}_{\cdot,\mathrm{II}}$ represents the outcome of waste conversion in treatment processes such as the generation of ash from an incinerating process or the generation of metals from a shredding process.

Table 27.1 Schematic Form of Waste Input-Output Table

	Goods-producing sectors	Treatment sectors	Final demand	Total
Goods input	$\mathbf{X}_{\mathrm{I,I}}$	$\mathbf{X}_{\mathrm{I,II}}$	$\mathbf{X}_{\mathrm{I,F}}$	$\mathbf{x}_{\mathrm{I}}$
Waste generation	$\mathbf{W}^{\oplus}_{\cdot,\mathrm{I}}$	$\mathbf{W}^{\oplus}_{\cdot,\mathrm{II}}$	$\mathbf{W}^{\oplus}_{\cdot,\mathrm{F}}$	$\mathbf{w}^{\oplus}$
Waste input	$\mathbf{W}^{\ominus}_{\cdot,\mathrm{I}}$	$\mathbf{W}^{\ominus}_{\cdot,\mathrm{II}}$	$\mathbf{W}^{\ominus}_{\cdot,\mathrm{F}}$	$\mathbf{w}^{\ominus}$
Env. load emission	$\mathbf{E}_{\cdot,\mathrm{I}}$	$\mathbf{E}_{\cdot,\mathrm{II}}$	$\mathbf{E}_{\cdot,\mathrm{F}}$	$\mathbf{e}$
Value added	$\mathbf{V}_{\cdot,\mathrm{I}}$	$\mathbf{V}_{\cdot,\mathrm{II}}$		

On the other hand, $\mathbf{W}^{\ominus}_{\cdot,\mathrm{II}}$ refers to the input of waste for use in treatment processes but not to the waste feedstock to be treated. As an accounting framework, the WIOT is a special case of NAMEA (Haan and Keuning 1996), which is characterized by a detailed description of waste management.

We denote by $W_{kj} := W^{\oplus}_{kj} - W^{\ominus}_{kj}$ the net generation of waste k from sector j. When $W_{kj} > 0$, sector j generates greater amount of waste k than it uses as input, and creates a positive demand for waste treatment. On the other hand, when $W_{kj} < 0$, sector j reduces the amount of waste k that has to be treated as waste. The sum of W_{kj}'s for all j, $w_k = w^{\oplus}_k - w^{\ominus}_k$, then gives the total amount of waste k that undergoes waste treatment. It is assumed that $W^{\oplus}_{kj}$ and $W^{\ominus}_{kj}$ are measured net of the input of waste k generated within sector j; intra-sectoral transactions of waste are netted out. This excludes the case where $W^{\oplus}_{kj}$ and $W^{\ominus}_{kj}$ take non-zero values simultaneously; hence, we have

$$W^{\oplus}_{kj} \cdot W^{\ominus}_{kj} = 0, \quad (k \in N^{\mathrm{W}}, j \in N \cup \{\mathrm{F}\}). \tag{27.1}$$

The WIO Model

The Quantity Model

The conventional IOT is a square matrix with an equal number of columns and rows. In contrast, the WIOT is non-square because in general $n^{\mathrm{W}} > n^{\mathrm{II}}$ holds and there is no one-to-one correspondence between waste types and treatment processes (Nakamura and Kondo 2002). The non-squareness of the WIOT does not pose any problem for merely descriptive purposes. For the purpose of developing an analytical model, however, this feature is quite inconvenient, and it is necessary to convert the matrix into a square one. The conversion is facilitated by an $n^{\mathrm{II}} \times n^{\mathrm{W}}$ matrix, $\mathbf{S}$, termed allocation matrix, the (i, j)-component of which refers to the share of waste j that is treated by treatment method i (Nakamura and Kondo 2002). By definition $s_{ij} \geq 0$ and $\sum_i s_{ij} = 1$.

Multiplication from the left by $\mathbf{S}$ converts the net waste generation in Table 27.1 into the net input of waste treatment services $\mathbf{X}_{\mathrm{II,I}} = \mathbf{S}\,\mathbf{W}_{\cdot,\mathrm{I}}$ and $\mathbf{X}_{\mathrm{II,II}} = \mathbf{S}\,\mathbf{W}_{\cdot,\mathrm{II}}$, and the net amount of waste treated into the n^{II}-vector of output of waste treatment sectors $\mathbf{x}_{\mathrm{II}} = \mathbf{S}\mathbf{w}$.

Denote by $\mathbf{A}$ the matrix of conventional input coefficients and by $\mathbf{G}$ the matrix of net waste generation coefficients. Adding appropriate suffixes referring to goods production and waste treatment, the flow of goods and net waste generation in Table 27.1 can then be given by

$$\begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{w} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathrm{I,I}} & \mathbf{A}_{\mathrm{I,II}} \\ \mathbf{G}_{\cdot,\mathrm{I}} & \mathbf{G}_{\cdot,\mathrm{II}} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} + \begin{bmatrix} \mathbf{X}_{\mathrm{I,F}} \\ \mathbf{W}_{\cdot,\mathrm{F}} \end{bmatrix}, \tag{27.2}$$

As mentioned above, the matrix inside the first square brackets on the right hand side is not square because $\mathbf{G}_{\cdot,\mathrm{II}}$ is not square. Multiplication of the lower half elements of Equation (27.2) from the left by $\mathbf{S}$ yields a square one, the WIO quantity model

$$\begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathrm{I,I}} & \mathbf{A}_{\mathrm{I,II}} \\ \mathbf{S}\mathbf{G}_{\cdot,\mathrm{I}} & \mathbf{S}\mathbf{G}_{\cdot,\mathrm{II}} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} + \begin{bmatrix} \mathbf{X}_{\mathrm{I,F}} \\ \mathbf{W}_{\cdot,\mathrm{F}} \end{bmatrix}, \tag{27.3}$$

which can be solved as usual provided the inverse matrix exists:

$$\begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} = \left(\mathbf{I} - \begin{bmatrix} \mathbf{A}_{\mathrm{I,I}} & \mathbf{A}_{\mathrm{I,II}} \\ \mathbf{S}\,\mathbf{G}_{\cdot,\mathrm{I}} & \mathbf{S}\,\mathbf{G}_{\cdot,\mathrm{II}} \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{X}_{\mathrm{I,F}} \\ \mathbf{S}\,\mathbf{W}_{\cdot,\mathrm{F}} \end{bmatrix}. \tag{27.4}$$

Let there be n^{E} environment loading factors. Write $\mathbf{R}_{\cdot,\mathrm{I}}$ and $\mathbf{R}_{\cdot,\mathrm{II}}$ for matrices of emission of these factors per unit of goods production and waste treatment. The vector of total emissions $\mathbf{e}$ is then given by

$$\mathbf{e} = \begin{bmatrix} \mathbf{R}_{\cdot,\mathrm{I}} & \mathbf{R}_{\cdot,\mathrm{II}} \end{bmatrix} \left(\mathbf{I} - \begin{bmatrix} \mathbf{A}_{\mathrm{I,I}} & \mathbf{A}_{\mathrm{I,II}} \\ \mathbf{S}\,\mathbf{G}_{\cdot,\mathrm{I}} & \mathbf{S}\,\mathbf{G}_{\cdot,\mathrm{II}} \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{X}_{\mathrm{I,F}} \\ \mathbf{S}\,\mathbf{W}_{\cdot,\mathrm{F}} \end{bmatrix} + \mathbf{E}_{\cdot,\mathrm{F}}. \tag{27.5}$$

The environmental IO (EIO) model of Leontief (1970, 1972) and Duchin (1990) corresponds to a special case of the WIO model where $\mathbf{S}$ is an identity matrix of order n^{II}. Implicit in the EIO model is the assumption that there exists for each pollutant (waste) one and only one abatement (treatment) method that treats no other pollutant (waste) but that pollutant (waste). This condition is hardly applicable to the reality of waste management because, in general, there is no one-to-one correspondence between a waste and its treatment method. It is usually the case that a multiplicity of treatment methods can be applied to a given solid waste, either separately or jointly. For instance, garbage can be composted, gasified, incinerated, and/or landfilled. Any of these methods can be applied separately or in combination. On the other hand, any solid waste can be landfilled.

The WIO represents a significant generalization over the EIO as regards its implications for waste management. First, because the allocation matrix **S** is not required to be square, the condition $n^{\mathrm{II}} = n^{\mathrm{W}}$ is no longer necessary. The number of waste types and that of treatment methods can be arbitrary. Secondly, it can handle the case where a single treatment method is applied to multiple types of waste, because each row of **S** can contain more than one non-zero element. Third, it can handle the case where several treatment methods are jointly applied to a single type of waste, because each column can contain more than one non-zero element. These cases were excluded in the EIO model (see Nakamura and Kondo 2002 for further details of the WIO quantity model).

The Price Model

We now turn to the aspect of cost and price of the WIO model. Let p_j be the price of output of sector j $(j \in N)$, p_k^{w} be the price of waste $k \in N^{\mathrm{w}}$, V_j be the cost for primary factors of production that includes depreciations as well as taxes less subsidies, and $U_{kj} > 0$ be the portion of $W_{kj}^{\oplus}$ that was used as input in sectors other than sector j. This explicit consideration of the sale and purchase of recovered waste materials distinguishes the definition of costs in the WIO from that of the conventional IOA. The sale of recovered waste materials is an important source of revenue for waste recyclers. A typical example is the disassembly of discarded automobiles, the major revenue source of which has been the sale of scrap metal to steel makers operating electric arc furnaces.

There are, however, cases where the price of waste materials is negative, that is, waste materials are "accepted" with a charge by the user. For instance, some Japanese steel makers operating blast furnaces accept waste plastics with a charge and use them as reduction agents together with pulverized coal. The price of waste can thus become negative. Based on its sign condition, three cases can be distinguished: the waste is valuable when $p_k^{\mathrm{w}} > 0$; it has no value but can be accepted by other sectors as input with no charge when $p_k^{\mathrm{w}} = 0$; and it has no value and its acceptance needs a positive charge when $p_k^{\mathrm{w}} < 0$. Henceforth, U_{kj} is called "sale of waste" regardless of whether the price of waste k is positive, zero, or negative.

In the input-output account system we have the identity that equates the value of output to the total cost. Considering the trade of waste, this identity can be given for sector j $(j \in N)$ by:

$$
\begin{aligned}
p_j x_j = {} & \underbrace{\sum_{i \in N^{\mathrm{I}}} p_i a_{ij} x_j}_{\text{(a)}} + \underbrace{\sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} \left(g_{kj}^{\oplus} x_j - U_{kj} \right)}_{\text{(b)}} + \underbrace{\sum_{k \in N^{\mathrm{w}}} p_k^{\mathrm{w}} g_{kj}^{\ominus} x_j}_{\text{(c)}} \\
& - \underbrace{\sum_{k \in N^{\mathrm{w}}} p_k^{\mathrm{w}} U_{kj}}_{\text{(d)}} + \underbrace{V_j}_{\text{(e)}} .
\end{aligned}
\tag{27.6}
$$

The cost can be decomposed into five parts: (a) the cost for the input of goods, (b) the cost for waste treatment, (c) the cost for the input of waste materials, (d) the revenue from the sale of waste materials, and (e) the cost for the input of primary factors. The terms (b), (c), and (d) are unique to the WIO price model. When there is no recycling, $U_{kj} = 0$ holds for all k and j, and the terms (c) and (d) vanish, while the term (b) reduces to the treatment cost of wastes generated in the sector. The term (b) indicates that the amount of waste for treatment is reduced by the amount of U_{kj}.

The sale of waste materials at positive prices can reduce the cost of production or treatment in two ways. First, it can reduce the cost directly by creating a new source of revenue other than the sale of "main" output. The term (d) refers to this component. Secondly, it can reduce the waste treatment cost that would have been necessary if the waste materials were not sold but had to be treated at a positive charge. The term (b) refers to this component. On the other hand, the sale of waste at negative prices reduces the production cost of the sectors that use the waste as input.

Rearranging the terms yields the following expression, which shows the contribution of the sale of waste materials to the cost in a more explicit way.

$$\begin{aligned} p_j x_j = & \underbrace{\sum_{i \in N^{\mathrm{I}}} p_i a_{ij} x_j}_{\text{(a)}} + \underbrace{\sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} g_{kj}^{\oplus} x_j}_{\text{(f)}} + \underbrace{\sum_{k \in N^{\mathrm{w}}} p_k^{\mathrm{w}} g_{kj}^{\ominus} x_j}_{\text{(c)}} \\ & - \underbrace{\sum_{k \in N^{\mathrm{W}}} \left(p_k^{\mathrm{w}} + p_l \sum_{k \in N^{\mathrm{W}}} s_{lk} \right) U_{kj}}_{\text{(g)}} + V_j, \end{aligned} \tag{27.7}$$

Here, the term (f) refers to the waste treatment cost that would have been necessary if no waste materials were sold. When waste is sold to other sectors, it can affect the cost via the term (g). The extent to which the cost can be reduced by the sale of waste depends on the sign condition of the expression inside the parentheses of (g). When $p_k^{\mathrm{w}} > 0$, the sale of waste certainly reduces the cost of production. It is important to note that even if $p_k^{\mathrm{w}} \leq 0$, the sale of waste could reduce the cost as long as the following condition is satisfied:

$$p_k^{\mathrm{w}} + \sum_{l \in N^{\mathrm{II}}} p_l s_{lk} > 0 \quad \Leftrightarrow \quad \left| p_k^{\mathrm{w}} \right| = -p_k^{\mathrm{w}} < \sum_{l \in N^{\mathrm{II}}} p_l s_{lk}. \tag{27.8}$$

This refers to the case where the sale of waste to other sectors at negative prices costs less than submitting it to waste treatment.

The term U_{kj} plays a vital role in "the cost equation (27.7)". It does not, however, occur in the systems of Equations (27.3) and (27.4) for the quantity model. It is necessary to establish the relationship between U_{kj} and the elements occurring in the quantity model. For this purpose, let r_k be the average rate of recycling of waste k defined as follows,

$$r_k := \sum_{l \in N \cup \{\mathrm{F}\}} W^{\ominus}_{kl} \Big/ \sum_{l \in N \cup \{\mathrm{F}\}} W^{\oplus}_{kl} = \sum_{l \in N \cup \{\mathrm{F}\}} U_{kl} \Big/ \sum_{l \in N \cup \{\mathrm{F}\}} W^{\oplus}_{kl}, \tag{27.9}$$

where the second equality follows from Equation (27.1), which implies $W^{\ominus}_{kj} = 0$ when $U_{kj} > 0$. We now assume that for a given waste its rate of recycling is the same across the sectors in N:

$$U_{kj} / W^{\oplus}_{kj} = r_k, \quad (W^{\oplus}_{kj} > 0,\ k \in N^{\mathrm{W}},\ j \in N). \tag{27.10}$$

Recalling the definition of $g^{\oplus}_{kj}$, we obtain

$$U_{kj} = W^{\oplus}_{kj} r_k = g^{\oplus}_{kj} x_j r_k. \tag{27.11}$$

Insertion of Equation (27.11) into (27.7) yields the following expression of the cost equation:

$$\begin{aligned} p_j x_j = & \sum_{i \in N^{\mathrm{I}}} p_i a_{ij} x_j + \sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} g^{\oplus}_{kj} x_j + \sum_{k \in N^{\mathrm{w}}} p^{\mathrm{w}}_k g^{\ominus}_{kj} x_j \\ & - \sum_{k \in N^{\mathrm{w}}} \left(p^{\mathrm{w}}_k + \sum_{l \in N^{\mathrm{II}}} p_l s_{lk} \right) r_k g^{\oplus}_{kj} x_j + V_j . \end{aligned} \tag{27.12}$$

Division of both the sides by x_j yields the following price equation:

$$\begin{aligned} p_j = & \sum_{i \in N^{\mathrm{I}}} p_i a_{ij} + \sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{W}}} s_{lk} g^{\oplus}_{kj} + \sum_{k \in N^{\mathrm{w}}} p^{\mathrm{w}}_k g^{\ominus}_{kj} \\ & - \sum_{k \in N^{\mathrm{w}}} \left(p^{\mathrm{w}}_k + \sum_{l \in N^{\mathrm{II}}} p_l s_{lk} \right) r_k g^{\oplus}_{kj} + v_j \\ = & \sum_{i \in N^{\mathrm{I}}} p_i a_{ij} + \sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} (1 - r_k) g^{\oplus}_{kj} \\ & + \sum_{k \in N^{\mathrm{w}}} p^{\mathrm{w}}_k (g^{\ominus}_{kj} - r_k g^{\oplus}_{kj}) + v_j , \end{aligned} \tag{27.13}$$

where v_j refers to the unit cost of primary inputs used in sector j.

Using obvious matrix notations, Equation (27.13) can be rewritten as

$$\begin{aligned} \begin{bmatrix} \mathbf{p}_{\mathrm{I}} & \mathbf{p}_{\mathrm{II}} \end{bmatrix} = & \begin{bmatrix} \mathbf{p}_{\mathrm{I}} & \mathbf{p}_{\mathrm{II}} \end{bmatrix} \begin{bmatrix} \mathbf{A}_{\mathrm{I,I}} & \mathbf{A}_{\mathrm{I,II}} \\ \mathbf{S}(\mathbf{I} - \mathbf{D})\mathbf{G}^{\oplus}_{\mathrm{I}} & \mathbf{S}(\mathbf{I} - \mathbf{D})\mathbf{G}^{\oplus}_{\mathrm{II}} \end{bmatrix} \\ & + \mathbf{p}^{\mathrm{w}} \begin{bmatrix} \mathbf{G}^{\ominus}_{\mathrm{I}} - \mathbf{D}\mathbf{G}^{\oplus}_{\mathrm{I}} & \mathbf{G}^{\ominus}_{\mathrm{II}} - \mathbf{D}\mathbf{G}^{\oplus}_{\mathrm{II}} \end{bmatrix} + \begin{bmatrix} \mathbf{v}_{\mathrm{I}} & \mathbf{v}_{\mathrm{II}} \end{bmatrix}, \end{aligned} \tag{27.14}$$

or in a more compact way as

$$\mathbf{p} = \mathbf{p}\begin{bmatrix} \mathbf{A}_{\mathrm{I},\cdot} \\ \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}^{\oplus} \end{bmatrix} + \mathbf{p}^{\mathrm{W}}(\mathbf{G}^{\ominus} - \mathbf{D}\mathbf{G}^{\oplus}) + \mathbf{v}, \tag{27.15}$$

where $\mathbf{p} = (\mathbf{p}_{\mathrm{I}}, \mathbf{p}_{\mathrm{II}}) = (p_1, \ldots, p_n)$, $\mathbf{v} = (\mathbf{v}_{\mathrm{I}}, \mathbf{v}_{\mathrm{II}}) = (v_1, \ldots, v_n)$, $\mathbf{p}^{\mathrm{W}} = (p_1^{\mathrm{W}}, \ldots, p_{n^{\mathrm{W}}}^{\mathrm{W}})$, $\mathbf{D}$ is a diagonal matrix whose k-th diagonal component is r_k, i.e., $\mathbf{D} = \mathrm{diag}(r_1, \ldots, r_{n^{\mathrm{W}}})$, and $\mathbf{I}$ is an identity matrix of an appropriate order. Provided it is possible to solve Equation (27.15) for $\mathbf{p}$, this solution can be given by

$$\mathbf{p} = \left\{ \mathbf{p}^{\mathrm{W}}(\mathbf{G}^{\ominus} - \mathbf{D}\mathbf{G}^{\oplus}) + \mathbf{v} \right\} \left(\mathbf{I} - \begin{bmatrix} \mathbf{A}_{\mathrm{I},\cdot} \\ \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}^{\oplus} \end{bmatrix} \right)^{-1}. \tag{27.16}$$

Comparing the inverse matrices occurring in Equation (27.16) and the quantity model Equation (27.4), we find that the former reduces to the latter if $\mathbf{G}^{\ominus} = 0$ (and hence $\mathbf{D} = 0$), that is, when there is no recycling of waste.

Application of WIO to LCA and LCC

WIO-LCA

LCA is concerned with the comparison of the level of environmental loading that results from alternative scenarios for a given functional unit. Elements of scenarios may include alternative waste treatment or recycling technologies, alternative institutional regulations, and alternative lifestyles with regard to the use of appliances. In the WIO model, the introduction of a new treatment and/or recycling technology occurs as a change in the coefficient matrices ($\mathbf{A}$, $\mathbf{G}$, $\mathbf{R}$), the introduction of a new regulation occurs as a change in $\mathbf{S}$, and a change in lifestyle occurs as a change in final demand vectors ($\mathbf{X}_{\mathrm{I,F}}$, $\mathbf{W}_{\cdot,\mathrm{F}}$). For instance, let Δa_{ij}, Δg_{ij} and Δr_{ij} be the incremental changes in input, waste generation, and emission coefficients associated with the introduction of a certain scenario (for simplicity, we ignore the suffixes “I” and “II”). The new set of corresponding input, waste generation, and emission coefficients matrices $\mathbf{A}'$, $\mathbf{G}'$ and $\mathbf{R}'$ are then given by $\mathbf{A}' = [a_{ij} + \Delta a_{ij}]$, $\mathbf{G}' = [g_{ij} + \Delta g_{ij}]$ and $\mathbf{R}' = [r_{ij} + \Delta r_{ij}]$. Furthermore, let $\mathbf{S}'$ be the allocation matrix corresponding to the scenario. We can evaluate the impact associated with the scenario by comparing the new solution for Equation (27.5) based on $\mathbf{A}'$, $\mathbf{G}'$, $\mathbf{S}'$ and $\mathbf{R}'$ with the reference solution based on the coefficients before the change.

Kondo and Nakamura (2004) conducted, among others, a WIO-LCA of the recycling of end-of-life electric home appliances (EoL-EHA), namely, TV sets, air conditioners, refrigerators, and washing machines, in Japan under the following three scenarios:

Table 27.2 Environmental Effects of EoL-EHA Recycling (Kondo and Nakamura 2004 with updated data)

Scenarios	Recycling	Recycling + DfD
GWP	−0.715	−0.721
Abiotic mineral resources	−0.184	−0.187
Landfill (weight)	−1.139	−1.214
Landfill (area)	−1.520	−1.677

Rate of change (%) relative to the case where all appliances are landfilled.

1. Landfilling (Lf): EoL-EHA are directly landfilled without any pretreatment, except for recovery and decomposition of chlorofluorocarbon (CFC) 12.
2. Recycling (Rc): EoL-EHA are subjected to an intensive material recovery process where aside from iron, plastics, glass, copper and aluminum are also recovered. Furthermore, the CFC11 contained in the urethane foam of refrigerators for insulation is also recovered and decomposed. Recovered iron, copper, aluminum, and glass are used respectively for electric arc steel making, copper elongation, aluminum rolling, and glass making as substitutes for virgin materials. Plastics are used as a reduction agent in blast furnaces in the iron and steel industry.
3. Recycling with design for disassembly (DfD): (Rc) is supplemented with additional implementation of DfD. This increases the efficiency of disassembling and the quality of recovered materials (plastics) as well, which makes possible a closed-loop recycling of some plastics.

Based on detailed technical information, alternative sets of **A**, **G** and **R** were obtained that correspond to each of these scenarios. For instance, material recovery under (Rc) refers to elements of $\mathbf{G}^{\oplus}$ of the EoL-EHA disassembling process, and the recycling of recovered materials refers to elements of $\mathbf{G}^{\ominus}$ and **A** of the corresponding goods-producing sectors. The allocation of EoL-EHA to alternative treatment scenarios is formulated by alternative sets of **S**. Table 27.2 gives the major results obtained by use of the Japanese WIO table for 1995 (Nakamura 2003). It is found that the recycling of EoL-EHA is effective in reducing environmental load, and that the implementation of DfD works to augment this tendency.

WIO-LCC

However excellent a product is environmentally, its potential for reducing environmental loading remains unexploited unless it is widely used in the economy. An important prerequisite for this is that the product be economically affordable as well. Life-cycle costing (LCC) is a means for evaluating the cost aspect of a product from the point of view of its whole life cycle including the use and EoL phases in addition to the manufacturing and distribution phases. In the following, the WIO price model is applied to an LCC of the recycling of EoL-EHA, which was found environmentally sound. Under the current Japanese EHA recycling law, consumers are to bear the EoL cost when they discard appliances. In view of this, our major concern consists in evaluating the effects of internalizing the EoL cost on the unit cost of appliances.

Compared with LCA, which is internationally standardized, there is no uniform understanding of the term life-cycle costing nor is there a standardized methodological framework that is commonly used in business (Rebitzer 2002). Because of its simplicity and close relationship to LCA, we have chosen to use the following definition of LCC (Rebitzer 2002):

$$LCC := R\&D + MAT + TRNS + MANF + USE + EoL + TC, \tag{27.17}$$

where $R\&D$, MAT, $TRNS$, $MANF$, USE, EoL, and TC refer to the costs for research and development, materials, transport/logistics, manufacturing, use, end-of-life, and transaction costs.

An IO table depicts all monetary flows of inputs and outputs including the items MAT, $TRNS$, $MANF$, and TC so far as they refer to current expenditures, that is the term (a) of Equation (27.7). In the Japanese IO table, the current expenditure for research and development is also recorded as an input item. To the extent that the current expenditure for research and development recorded in the IO table (including WIO) corresponds to the above concept of $R\&D$, implementation of the above LCC concept within an IO model is rather straightforward except for the terms USE and EoL.

Because the use pattern of EHA remained the same for each of the scenarios considered, only EoL (to be more specific, EoL per unit of appliance i, eol_i) needs to be additionally considered. In the following, the cost at the use phase is not considered. It is important to note that because Equation (27.16) encompasses the price (unit cost) of all the sectors including waste treatment, the price vector $\mathbf{p}$ actually includes eol_i as one of its elements. Inclusion of eol_i as an additional term to the right hand side of Equation (27.13) for appliance i then gives its life cycle cost per unit of output.

Some remarks on the characteristics of WIO-LCC may be due. Its functional unit is a unit of appliance from its production to the end of its life. As for the treatment of time, it is static, and the comparison among alternative scenarios is based on the method of comparative statics. The cost refers to static or average annual cost: discounting is not considered. As for space, it is limited to the territory of Japan, though the cost of import is taken into account.

Table 27.3 shows the results for two types of appliances for which detailed data were available (Nakamura and Kondo 2004). It is found that while internalization of the EoL cost in the manufacturing cost increases the unit cost of appliances by 4–5%, implementation of DfD can be effective to reduce the extent of cost increase. Recalling that DfD improves the environmental performance of recycling (Table 27.2), our results seem to indicate the effectiveness of an EcoDesign (DfD) strategy toward the realization of sustainable EHA manufacturing.

Table 27.3 Effects of Internalizing the EoL Cost on the Unit Cost of Appliances

	Recycling	Recycling + DfD
Television sets	3.61	3.07
Refrigerators	4.77	3.86

The figures refer to the rate of change (%) in the unit cost of *appliances* that results from internalizing the end-of-life cost of EHA relative to the case where the cost is external and borne by consumers. The cost at the use phase is not included.

Concluding Remarks

We close this chapter by introducing three recent applications/extensions of WIO. The analysis above has been static, and no aspect of the dynamic process, where goods are accumulated and then transformed into waste, was considered. Proper consideration of this dynamic aspect is of great importance for analyzing issues of durable waste such as buildings, structures, automobiles, and appliances. The issue of dynamics has been considered by Kazuyo Yokoyama (2004), who developed a dynamic version of the WIO quantity model and applied it to the life cycle of office buildings. Her major concern has been the effects on long-term recyclability of concretes which contain recycled materials.

The conventional IOA does not consider the issue of the choice of technology from among a set of alternatives. This applies to the above description of WIO as well. Kondo and Nakamura (2005) have proposed a decision analytic extension of the WIO model based on linear programming, and applied it to explore the extent to which a given measure of eco-efficiency can be maximized by an appropriate combination of existing (technological and resource) potentials. Their results indicate the presence of a substantial potential for reducing the volume of landfill in Japan that remains unutilized.

The final example of extension is concerned with our lifestyle, or the volume and composition of final demand, an issue which so far has been regarded as given. Our lifestyle (consumption pattern) is a major driving force of economic activity, and hence a major determinant of the associated environmental loading. In an attempt to evaluate the relationship between consumption patterns and waste generation, Koji Takase and Ayu Washizu 2004) have proposed a "Waste Score" for each consumer good, which refers to the ultimate landfill volume induced by the consumption per unit of the good.

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Chapter 28
Economy-Waste-Environment Input-Output Model: Effects of Portuguese Production and Consumption

Eduardo Barata

Introduction

The quantity and quality of wastes modern societies experience today is unparalleled in history. Additionally, a new awareness of the pollution and human health hazards caused by the disposal of waste has emerged.

Waste prevention strategies and careful management of waste have significant scope for limiting the waste flows damage and conserving scarce resources. However, successful prosecution of such policies would be possible only if concerted efforts are made to address the traditional partitioned perception of waste issues. Industry and final consumers have to become aware of their contribution to the problems associated with total waste flows generation (directly and indirectly), as well as their major role in delivering the needed solutions. Addressing this 'lack of perception' would ultimately change people's attitudes towards waste management as a whole and increase their involvement in 'sustainable integrated resource and waste management' practices. The increasing amounts of solid waste being generated show the necessity, and at the same time offer the opportunity, to look for new approaches.

An extended input-output model, capable of integrating economic and environmental issues is developed in this study, to give an analytical representation of these interdependences from the perspective of the Portuguese economic system. The input-output methodology appears appropriate for analysing waste generation and management problems, in that it provides a consistent framework encompassing the structure and level of final demand, the inter-sectoral relationships, and the factor inputs. The analysis is extended to take account of the waste flows attributable to a country's international trade. However, it must be acknowledged that

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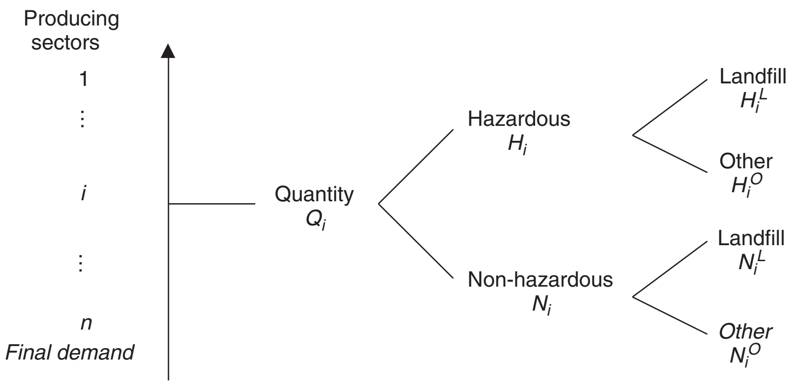
this modelling exercise is not explicitly concerned with making endogenous the generation of pollutants (as first suggested by Leontief 1970), neither considering the effects of potential abatement activities (Nakamura and Kondo 2002a).

The Different Dimensions of Waste Generation and Management Pressures

The major concerns resulting from waste generation and management processes can be associated with numerous policy fields which stress the significance of resource depletion issues and of different types of environmental pollution (e.g., the waste impacts on air pollution, climate change, ozone depletion, etc.).

Unfortunately, waste materials are less tractable than, for example, energy use. They cannot be satisfactorily reduced to single elementary indicators such as kilowatt-hours. To illustrate this point, a pound of biodegradable food waste cannot be simply compared with a pound of nuclear waste. Materials (including waste materials) possess unique properties, and these provide value, define uses, and have environmental consequences. To proceed with the evaluation of the main economic and environmental pressures of waste flows, both quantitative and qualitative aspects should be considered. However, the strong correlation between these is not always recognised. In this study, to capture these and other interactions, a set of three interdependent dimensions will be considered, as illustrated in Fig. 28.1.

Dimension (1) concerns the total solid waste generated (i.e., the weight of the materials that enter the solid waste streams, prior to treatment and recycling). Total solid waste generated can be regarded as a quantitative indicator of the resources



where: $\sum_i Q_i = \left(\sum_i (H_i^L + N_i^L)\right) + \left(\sum_i (H_i^O + N_i^O)\right)$

Fig. 28.1 Three Dimensions of the Waste Generation and Management Pressures use and of the environmental impact of production and consumption processes. Dimension (2) adds a qualitative feature to the analysis, by specifying the amount of hazardous waste generation, whose occurrence, even in small quantities, will decisively influence the potential threats to human health and the environment from waste generation and management. Dimension (3) relates to the amount of solid waste sent to landfill. Considering that, whatever the waste management solution implemented, at least partially, the solid residues usually end up in landfills for definitive final disposal (Nakamura and Kondo 2002b). So, waste landfilling would represent a sound direct measure of the environmental load from waste generation.[1]

Finally, the different waste generation and management processes in an economy are influenced by how efficiently natural resources and raw materials are used by the different producing sectors, and by the quantities of goods produced and consumed. With this recognition in mind, inter-sectoral analysis is a suitable framework for analysing the waste generation and management problems, since the structure of inter-industry relations, and the structure and level of the final demand are explicitly considered. Indeed, the more pervasive the generation of residuals, the more necessary is the inter-sectoral approach (Førsund 1985: 339).

The Environmental Input-Output Waste Model

According to the analytical requirements of input-output analysis and the research purposes of this study, the environmental input-output waste model comprises several blocks described below:

- Block 1 – intermediate supply and purchases: this comprises the transactions between the economic sectors regarding the supply and the purchase of commodities and services.
- Block 2 – primary inputs: primary inputs are reflected by the compensation paid for inputs other than intermediary inputs.
- Block 3 – final demand: final demand represents the output of the producing sectors that are sold to end-users.
- Block 4 – environmental output: solid waste emissions by the producing sectors. This block represents the volumes of total and hazardous solid waste generated, and the landfill consumption, by the producing sectors as a result of their producing activities.
- Block 5 – environmental output: solid waste emissions by final demand. This block represents the volumes of total and hazardous solid waste generated by final demand, as well as the landfill consumption by the final demand, as a result of final consumption activities.

[1] The main environmental pressures from landfilling of waste are land use (including loss of natural areas), contribution to the greenhouse effect, especially by emission of methane, and other pollution problems such as contamination of surface water and groundwater with toxic substances and nutrients leaching the waste.

The approach implemented in the modelling of 'environmental output' (Blocks 4 and 5) corresponds to the reconciliation of the goal of a comprehensive description of waste materials and management, with the restrictions resulting from the particular characteristics (theoretical and empirical) of this research subject. Again, and following standard input-output practice, there is assumed a constant proportional relationship between industry output and residuals generation (or landfilling consumption).

Waste Flows by the Producing Activities and by the Final Demand

We now define the following variables:

- Q_{ind}, H_{ind} and L_{ind} are the scalars representing the total amounts of solid waste emissions, hazardous waste emissions, and landfilling consumption by the producing sectors in the economy.
- Q_y, H_y and L_y are the scalars for the total solid waste emissions, total hazardous waste emissions, and total landfill consumption by the final demand.
- $\mathbf{q}_{\mathrm{ind}} = \{Q_{ind_i}\}$, $\mathbf{h}_{\mathrm{ind}} = \{H_{ind_i}\}$ and $\mathbf{l}_{\mathrm{ind}} = \{L_{ind_i}\}$ represent the vectors of total solid waste emissions, total hazardous waste emissions, and total landfill consumption by the producing sectors ($i = 1, 2, \ldots, n$).
- $\mathbf{q_y}$, $\mathbf{h_y}$ and $\mathbf{l_y}$ represent the vectors of total solid waste emissions, total hazardous waste emissions, and total landfill consumption by the final demand ($i = 1, 2, \ldots, n$).
- $\mathbf{r}' = \{Q_{ind_i}/X_i\}, \mathbf{o}' = \{H_{ind_i}/X_i\}$ and $\mathbf{p}' = \{L_{ind_i}/X_i\}$ are the transposed vectors of coefficients of solid waste emissions, hazardous waste emissions and landfilling consumption intensities by the producing sectors in the economy (i.e., each element of $\mathbf{r}'$, $\mathbf{o}'$ and $\mathbf{p}'$ tells us the 'intensity' with which each solid waste flow is generated).
- $\mathbf{r}'_{\mathbf{y}}$, $\mathbf{o}'_{\mathbf{y}}$ and $\mathbf{p}'_{\mathbf{y}}$ are the transposed vectors of coefficients of solid waste emissions, hazardous waste emissions and landfilling consumption intensities by the final demand.

Finally, considering the unit vector of order n as $\mathbf{i}' = (1, 1, \cdots, 1)$ the relationships in Blocks 4 and 5 can be formalised according to the following equations:

$$Q_{ind} = \mathbf{i}'\,\mathbf{q}_{\mathrm{ind}} = \mathbf{r}'\mathbf{x} \tag{28.1}$$

$$H_{ind} = \mathbf{i}'\,\mathbf{h}_{\mathrm{ind}} = \mathbf{o}'\mathbf{x} \tag{28.2}$$

$$L_{ind} = \mathbf{i}'\,\mathbf{l}_{\mathrm{ind}} = \mathbf{p}'\mathbf{x} \tag{28.3}$$

We now define $\mathbf{Z}$ as the $(n \times n)$ scaling matrix, where each element is simply the ratio of the domestic final demand (less stock building) to total final demand (including exports and stock building), for the sectors considered as directly generating solid waste by final demand consumption. Therefore, concerning the final demand total solid waste emissions (Q_y), total hazardous waste emissions (H_y), and total landfill consumption (L_y), we have:

$$Q_y = \mathbf{i}' \, \mathbf{q_y} = \mathbf{r}_\mathbf{y}' \mathbf{Z} \mathbf{y} \tag{28.4}$$

$$H_y = \mathbf{i}' \, \mathbf{h_y} = \mathbf{o}_\mathbf{y}' \mathbf{Z} \mathbf{y} \tag{28.5}$$

$$L_y = \mathbf{i}' \, \mathbf{l_y} = \mathbf{p}_\mathbf{y}' \, \mathbf{Z} \mathbf{y} \tag{28.6}$$

Concerning the matrix **Z** (and the resulting vector **Zy**) a more detailed explanation is required. The total final demand includes the output of the different sectors allocated to household and government consumption, investment (stock building), and exports. However, if the final demand for goods and services for household consumption is clearly associated to solid waste emissions, the final demand for goods and services corresponding to exports and stock building does not.[2] Therefore, the elements of **Z** are simply the ratios of the domestic final demand (less stock building) to total final demand (including exports and stock building), for the sectors considered as directly generating solid waste by final demand consumption. Finally, the elements of vector **Zy** are the modified values for final demand for goods and services whose consumption is directly associated with the different domestic waste flows to be analysed in this study.

Global Waste Flows by a Country's Economy

From the above, the global waste generation (Q_P), global hazardous waste generation (H_P) and global landfilling consumption (L_P), in the entire economy can be derived:

$$Q_P = \mathbf{i}'(\mathbf{q}_{\text{ind}} + \mathbf{q_y}) = \mathbf{r}' \, \mathbf{x} + \mathbf{r}_\mathbf{y}' \mathbf{Z} \mathbf{y} \tag{28.7}$$

$$H_P = \mathbf{i}'(\mathbf{h}_{\text{ind}} + \mathbf{h_y}) = \mathbf{o}' \mathbf{x} + \mathbf{o}_\mathbf{y}' \mathbf{Z} \mathbf{y} \tag{28.8}$$

$$L_P = \mathbf{i}'(\mathbf{l}_{\text{ind}} + \mathbf{l_y}) = \mathbf{p}' \mathbf{x} + \mathbf{p}_\mathbf{y}' \mathbf{Z} \mathbf{y} \tag{28.9}$$

We now recall the input-output fundamental equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \tag{28.10}$$

[2] Indeed, as these goods and services leave the country concerned, and are used elsewhere or not used at all, to analyse the solid waste flows resultant from final demand, it is useful to start by considering the final demand for goods and services, excluding exports and stock building.

Substitution for x as presented in Equation (28.10), into Equations (28.7)–(28.9), gives:

$$Q_P = \mathbf{i}'(\mathbf{q}_{\text{ind}} + \mathbf{q}_{\text{y}}) = \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{r}'_{\text{y}}\mathbf{Z}\mathbf{y} \tag{28.11}$$

$$H_P = \mathbf{i}'(\mathbf{h}_{\text{ind}} + \mathbf{h}_{\text{y}}) = \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{o}'_{\text{y}}\mathbf{Z}\mathbf{y} \tag{28.12}$$

$$L_P = \mathbf{i}'(\mathbf{l}_{\text{ind}} + \mathbf{l}_{\text{y}}) = \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{p}'_{\text{y}}\mathbf{Z}\mathbf{y} \tag{28.13}$$

Finally, factorisation of the above equations gives:

$$Q_P = \mathbf{i}'(\mathbf{q}_{\text{ind}} + \mathbf{q}_{\text{y}}) = [\mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1} + \mathbf{r}'_{\text{y}}\mathbf{Z}]\mathbf{y} \tag{28.14}$$

$$H_P = \mathbf{i}'(\mathbf{h}_{\text{ind}} + \mathbf{h}_{\text{y}}) = [\mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1} + \mathbf{o}'_{\text{y}}\mathbf{Z}\,]\,\mathbf{y} \tag{28.15}$$

$$L_P = \mathbf{i}'(\mathbf{l}_{\text{ind}} + \mathbf{l}_{\text{y}}) = [\mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1} + \mathbf{p}_{\text{y}}\mathbf{Z}]\mathbf{y} \tag{28.16}$$

To interpret these equations one could recall the matrix expansion of $(\mathbf{I} - \mathbf{A})^{-1}$:

$$Q_P = \mathbf{i}'(\mathbf{q}_{\text{ind}} + \mathbf{q}_{\text{y}}) = \mathbf{r}'_{\text{y}}\mathbf{Z}\mathbf{y} + \mathbf{r}'\mathbf{y} + \mathbf{r}'(\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots)\mathbf{y} \tag{28.17}$$

$$H_P = \mathbf{i}'(\mathbf{h}_{\text{ind}} + \mathbf{h}_{\text{y}}) = \mathbf{o}'_{\text{y}}\mathbf{Z}\mathbf{y} + \mathbf{o}'\mathbf{y} + \mathbf{o}'(\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots)\mathbf{y} \tag{28.18}$$

$$L_P = \mathbf{i}'(\mathbf{l}_{\text{ind}} + \mathbf{l}_{\text{y}}) = \mathbf{p}'_{\text{y}}\mathbf{Z}\mathbf{y} + \mathbf{p}\mathbf{y} + \mathbf{p}'(\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots)\mathbf{y} \tag{28.19}$$

Here $(\mathbf{r}'_{\text{y}}\mathbf{Z}\,\mathbf{y}), (\mathbf{o}'_{\text{y}}\mathbf{Z}\,\mathbf{y})$, and $(\mathbf{p}'_{\text{y}}\mathbf{Z}\mathbf{y})$ represent the solid waste generation, hazardous waste generation and landfilling consumption because of 'direct consumption demand', i.e., the solid and hazardous waste generation, and landfilling consumption, directly attributable to final demand consumption. The corresponding effects from the 'direct production demand' for the different commodities associated with interindustry economic activity are represented by $(\mathbf{r}'\mathbf{y}), (\mathbf{o}'\mathbf{y})$, and $(\mathbf{p}'\mathbf{y})$. Finally, $\mathbf{r}'(\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots)\mathbf{y}$, $\mathbf{o}'(\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots)\mathbf{y}$ and $\mathbf{p}'(\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots)\mathbf{y}$ represent the waste generation, hazardous waste generation and landfilling consumption attributable to 'indirect production demand' for the different commodities included in the intermediate demand purchases throughout the economy.

Equations (28.17)–(28.19) form the basis for all of the analysis of solid waste flows in this study. These equations stress that the solid waste flows by an economy are entirely attributed to final demand. This is a very desirable feature of this modelling approach because it is final demand (especially consumer behaviour and government expenditure) that policy makers can hope to influence reasonably directly.[3]

[3] Additionally, these equations provide an excellent basis for scenario analysis. They include factors reflecting the mix of different goods and services used by final demand and in production, and their efficiency (reflected by **r'**, **p'** and **o'**; and by $\mathbf{r}_{\text{y}}$', $\mathbf{p}_{\text{y}}$' and $\mathbf{o}_{\text{y}}$'), the structure of interindustry trading (**A**), and the structure and level of final demand (**y**). These can be varied separately or together, to give estimates of the various total waste flows by an economy under a variety of assumptions on technological change in waste generation, the nature of interindustry trading, and consumer and government behaviour.

The Waste Flows Attributable to a Country's International Trade

The above extensions to the basic input-output model will allow the identification of the waste flows attributable to an economy[4] (i.e., Q_P, H_P, and L_P), but nothing has been said about the specific role of exports (and imports) on the waste flows in the economy.

However, the solid waste flows in Portugal are partly related to production of goods and services for consumption abroad. On the other hand, consumption by Portuguese residents causes environmental pressures in other countries.

Hence, there should be evaluated the waste generation and the landfilling consumption by the Portuguese economic activities to meet the demand for goods and services by foreign consumers and producing activities. Also needed are the waste flows taking place in foreign countries to satisfy the Portuguese demand for imports (either for intermediate or final consumption). Indeed, associated with exports there are waste flows taking place within Portugal which may not be entirely its responsibility, and the opposite happens with imports.

The input-output approach can be further extended, to include the analysis of the significance of exports and imports for the different waste flows. This will allow the calculation of a country's true responsibility for the respective waste flows (that is waste flows attributable to a country's economy, less waste flows attributable to the production of final demand for goods and services exported, plus waste flows attributable to the production (by foreign countries) of imported goods and services).

Waste Flows Attributable to Exports of Goods and Services

Considering that exports of goods and services are a component of final demand, the assessment of the related waste flows would follow a similar methodology to the one used to estimate the waste flows attributable to the production of domestic final demand. Indeed, taking into account that the goods and services that are exported are produced using the same technology as the ones that are destined for domestic final demand, then the waste flows intensities corresponding to (direct and indirect) production demand should be the same.

Therefore, recalling that, for the producing activities in one country, the intensities for total waste generation, hazardous waste generation and landfilling consumption are given by the column vectors $\mathbf{r}'$, $\mathbf{o}'$ and $\mathbf{p}'$, we now define $\mathbf{y}_X$ as the vector of exports, and $\mathbf{q}_X = \{Q_{X_i}\}$, $\mathbf{h}_X = \{H_{X_i}\}$ and $\mathbf{l}_X = \{L_{M_i}\}$ as the vectors of total solid waste emissions, total hazardous waste emissions, and total landfill

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[4] Indeed, what effectively these initial calculations would allow one to assess are the waste flows attributable to the producing activities in a country's economy, whether the goods and services produced are demanded by residents or by non-resident final consumers (i.e., $Q_{ind} = \mathbf{i}'\,\mathbf{q}_{ind}$, $H_{ind} = \mathbf{i}'\,\mathbf{h}_{ind}$, and $L_{ind} = \mathbf{i}'\,\mathbf{l}_{ind}$) plus the waste flows attributable to the final demand consuming activities for goods and services domestically produced (i.e., $Q_y = \mathbf{i}'\,\mathbf{q}_\mathbf{y}$, $H_y = \mathbf{i}'\,\mathbf{h}_\mathbf{y}$, and $L_y = \mathbf{i}'\,\mathbf{l}_\mathbf{y}$).

consumption, embodied in exports of goods and services from the various sectors ($i = 1, 2, \ldots, n$). Hence, one could calculate the total amounts of solid and hazardous waste generation, and landfilling consumption, attributable to exports (i.e., Q_X, H_X and L_X), that is:

$$Q_X = \mathbf{i}'\,\mathbf{q}_{\mathrm{X}} = \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \tag{28.20}$$

$$H_X = \mathbf{i}'\,\mathbf{h}_{\mathrm{X}} = \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \tag{28.21}$$

$$L_X = \mathbf{i}'\,\mathbf{l}_{\mathrm{X}} = \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \tag{28.22}$$

The waste flows attributable to exports ($Q_X = \mathbf{i}'\,\mathbf{q}_{\mathrm{X}}$, $H_X = \mathbf{i}'\,\mathbf{h}_{\mathrm{X}}$ and $L_X = \mathbf{i}'\,\mathbf{l}_{\mathrm{X}}$), should be subtracted from the country's economy total waste flows ($Q_P = \mathbf{i}'(\mathbf{q}_{\mathrm{ind}} + \mathbf{q}_{\mathbf{y}})$, $\mathrm{H}_P = \mathbf{i}'(\mathbf{h}_{\mathrm{ind}} + \mathbf{h}_{\mathbf{y}})$, and $L_P = \mathbf{i}'(\mathbf{l}_{\mathrm{ind}} + \mathbf{l}_{\mathbf{y}})$), as responsibility for these flows should be attributed to the importing countries.

Waste Flows Attributable to Imports of Goods and Services

Turning now to the treatment of waste flows because of imports, one additional difficulty has to be considered. One might argue that the exact calculation of these waste flows would require the consideration of the waste intensity coefficients based on input-output tables of the relevant countries where the goods and services imported had been produced. Considering the potentially huge variety of countries involved, this would be a major task, especially for very open economies, as happens with the generality of the economies of the European Union countries, including Portugal.

In this research, for the calculation of the waste flows attributable to imports, one additional hypothesis will be assumed, i.e., that overseas technology is the same as domestic technology, or in other words, that the waste flows pattern that characterises the economic activities in countries of imports origin is the same as the one in importing country. This is almost certainly not the case. However, one major objective of this analysis is to evaluate the waste generation prevented and the landfilling space 'saved' by one country, resulting from the option of importing goods and services instead of producing them. If this is the case, the proper waste flows intensity coefficients to be used in assessing the waste flows embodied in imports are precisely those given by the domestic technology (and which were also used to estimate the waste flows embodied in exports) (Proops et al. 1993: 138).

Therefore, the total waste generation, hazardous waste generation and landfilling consumption embodied in Portuguese imports will be achieved through the sum of two components: the waste flows embodied in the matrix of imports for use in further production (in order to satisfy domestic final demand), plus the waste flows embodied in $\mathbf{y}_{\mathrm{M}}$, i.e., the vector of imports for use by consumers directly. Thus, designating $\mathbf{y}_{\mathrm{D}}$ as the domestic final demand (i.e., $\mathbf{y}_{\mathrm{D}} = \mathbf{y} - \mathbf{y}_{\mathrm{X}}$), and h_{ij} as the intermediate demand of domestic sector j for imports from foreign countries sector i, one could define the technological coefficients matrix $\mathbf{B} = \{b_{ij}\} = \{h_{ij}/X_j\}$ as the imports coefficient matrix for imports to intermediate demand. Finally, Q_M,

H_M, and L_M, i.e., the levels for total waste generation, hazardous waste generation and landfilling consumption, that occurs in foreign countries in order to meet the domestic final demand, are given by:

$$Q_M = \mathbf{i}'\mathbf{q}_{\mathrm{M}} = \mathbf{r}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{r}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \tag{28.23}$$

$$H_M = \mathbf{i}'\mathbf{h}_{\mathrm{M}} = \mathbf{o}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{o}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \tag{28.24}$$

$$L_M = \mathbf{i}'\,\mathbf{l}_{\mathrm{M}} = \mathbf{p}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{p}'(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \tag{28.25}$$

In the above equations, $\mathbf{q}_{\mathrm{M}} = \{Q_{M_{\mathrm{i}}}\}$, $\mathbf{h}_{\mathrm{M}} = \{H_{M_i}\}$ and $\mathbf{l}_{\mathrm{M}} = \{L_{M_i}\}$ represent the vectors of total solid waste emissions, total hazardous waste emissions, and total landfill consumption, embodied in the imports of the various goods and services $(i = 1, 2, \ldots, n)$.

The first term on the right hand side of Equations (28.23)–(28.25) corresponds to waste flows attributable to domestic imports that will be used as intermediate consumption, i.e., which are attributable to imported products used in the domestic production processes in order to meet $\mathbf{y}_D$ (domestic final demand).[5] The second term correspond to the foreign waste flows to meet the imported final demand $\mathbf{y}_{\mathrm{M}}$ (i.e., imports for use by consumers directly).

The waste flows attributable to imports (Q_M, H_M, and L_M), should be added to the country's economy total waste flows ($Q_P = \mathbf{i}'(\mathbf{q}_{\mathrm{ind}} + \mathbf{q}_{\mathbf{y}})$, $H_P = \mathbf{i}'(\mathbf{h}_{\mathrm{ind}} + \mathbf{h}_{\mathbf{y}})$, and $L_P = \mathbf{i}'(\mathbf{l}_{\mathrm{ind}} + \mathbf{l}_{\mathbf{y}})$), as responsibility for these flows should be attributed to the importing country.

Waste Flows Attributable to International Trade and Waste Flows Responsibility

The analysis of the waste flows embodied in international trade make it possible to distinguish between the 'nationally produced' waste flows, the 'domestically produced' waste flows and the 'nationally attributable' waste flows.

[5] To make clear the meaning of this expression one must take into account that one country's imports of goods and services (to be used as intermediate consumption in the country) are final demand in the foreign countries from which they came. Therefore, the foreign sectoral outputs necessary for producing these imports must be considered; this is why we premultiply $\mathbf{B}$ by $(\mathbf{I}\text{-}\mathbf{A})^{-1}$. This mean that the solid waste flows generation intensities in foreign countries, for each sector, are given by $[\mathbf{r}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$, $[\mathbf{o}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$, $[\mathbf{p}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$. We use the same intensities vectors ($\mathbf{r}'$, $\mathbf{o}'$, and $\mathbf{p}'$) and the same technical coefficients matrix ($\mathbf{A}$) for the foreign countries as for the country analysed, as we assume that foreign technologies are the same as those estimated for domestic production. Then, as usual, one multiplies those waste flows intensities by the final demand ($\mathbf{y}_D$) to achieve total waste flows generation. Hence, as these imported goods and services will be used as inputs in the country's production processes, the amounts that will be necessary to import are given by the direct and indirect production demand for these goods and services in order satisfy (the country's) domestic final demand, as indicated by the post-multiplication of $[\mathbf{r}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$, $[\mathbf{o}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$ and $[\mathbf{p}'(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{B}]$ by $[(\mathbf{I}\text{-}\mathbf{A})^{-1}\mathbf{y}_D]$.

The 'nationally produced' waste flows, or the total waste flows generated by a country's economy, correspond to the emissions attributable to the production of the economy, whether demanded by national or by foreign final consumers and industries. These waste flows form the basis for all of the analysis in this study, and the methodology for their calculations was shown above. We recall Equation (28.11) (concerning the nationally produced solid waste ($Q_P = \mathbf{i}'(\mathbf{q}_{\mathrm{ind}} + \mathbf{q}_{\mathbf{y}})$), Equation (28.12) (concerning the nationally produced hazardous solid waste ($H_P = \mathbf{i}'(\mathbf{h}_{\mathrm{ind}} + \mathbf{h}_{\mathbf{y}})$), and Equation (28.13) (concerning the nationally produced landfilling consumption ($L_P = \mathbf{i}'(\mathbf{l}_{\mathrm{ind}} + \mathbf{l}_{\mathbf{y}})$).

The 'domestically produced' waste flows, that is, the total solid waste, total hazardous waste and total landfilling consumption, attributable to a country's domestic final demand, can be obtained from the total waste flows generated by a country's economy (i.e., Q_P, H_{P} and L_P) and subtracting the waste flows attributable to production of final demand for export (i.e., Q_X, H_X and L_X). Thus, combining Equations (28.11–28.13) with Equations (28.20–28.22), one can derive:

$$\begin{aligned} Q_D &= (Q_P - Q_{\mathrm{X}}) = \mathbf{i}'(\mathbf{q}_{\mathrm{ind}} + \mathbf{q}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{q}_{\mathrm{X}} \\ &= \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{r}'_{\mathbf{y}}\mathbf{Zy} - \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \end{aligned} \tag{28.26}$$

$$\begin{aligned} H_D &= (H_P - H_{\mathrm{X}}) = \mathbf{i}'(\mathbf{h}_{\mathrm{ind}} + \mathbf{h}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{h}_{\mathrm{X}} \\ &= \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{o}'_{\mathbf{y}}\mathbf{Zy} - \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \end{aligned} \tag{28.27}$$

$$\begin{aligned} L_D &= (L_P - L_{\mathrm{X}}) = \mathbf{i}'(\mathbf{l}_{\mathrm{ind}} + \mathbf{l}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{l}_{\mathrm{X}} \\ &= \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{p}'_{\mathbf{y}}\mathbf{Zy} - \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \end{aligned} \tag{28.28}$$

Finally, the consideration of the net waste flows embodied in international trade (i.e., the balance between the waste flows embodied in imports (see Equations (28.23)–(28.25)) minus those embodied in exports) make possible the derivation of the equations concerning a country's 'nationally attributable' waste flows Q_R, H_R and L_R (the 'nationally attributable' waste flows correspond to the waste flows that a nation must be held responsible for, and for this reason they are also referred to as 'waste flows responsibility'), that is:

$$\begin{aligned} Q_R &= (Q_P - Q_{\mathrm{X}} + Q_M) = (Q_D + Q_M) = \mathbf{i}'(\mathbf{q}_{\mathrm{ind}} + \mathbf{q}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{q}_{\mathrm{X}} + \mathbf{i}'\mathbf{q}_{\mathrm{M}} \\ &= \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{r}'_{\mathbf{y}}\mathbf{Zy} - \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \\ &\quad + \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \end{aligned} \tag{28.29}$$

$$\begin{aligned} H_R &= (H_P - H_{\mathrm{X}} + H_M) = (H_{\mathrm{D}} - H_{\mathrm{M}}) \\ &= \mathbf{i}'(\mathbf{h}_{ind} + \mathbf{h}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{h}_{\mathrm{X}} + \mathbf{i}'\mathbf{h}_{\mathrm{M}} \\ &= \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{o}'_{\mathbf{y}}\mathbf{Zy} - \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \\ &\quad + \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{o}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \end{aligned} \tag{28.30}$$

$$\begin{aligned} L_R &= (L_P - L_{\mathrm{X}} + L_M) = (L_{\mathrm{D}} - L_{\mathrm{M}}) \\ &= \mathbf{i}'(\mathbf{l}_{ind} + \mathbf{l}_{\mathbf{y}}) - \mathbf{i}'\,\mathbf{l}_{\mathrm{X}} + \mathbf{i}'\,\mathbf{l}_{\mathrm{M}} \\ &= \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} + \mathbf{p}_{\mathbf{y}}'\mathbf{Z}\mathbf{y} - \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{X}} \\ &\quad + \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{D}} + \mathbf{p}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}_{\mathrm{M}} \end{aligned} \tag{28.31}$$

The Empirical Data

To apply this modelling approach to the study of the waste-economy-environment interactions, an input-output table for Portugal was estimated, concerning the Portuguese economic structure in 1992. Details about the data collection and processing undertaken (i.e., the economic and environmental output data sources used and some of the simplifying hypothesis that was necessary to consider) can be found in Barata (2002).

An Input-Output Assessment of Portuguese Solid Waste Flows

A description of the application of the environmental input-output waste model to Portugal will now be presented.

The Waste Flows Intensities

The tables presented in this section contain the basic data and some of the results from applying the model. Table 28.1 contains the data on total solid waste intensities. Columns (1) and (4) represent the direct total waste generation by industry, per unit of total output ($\mathbf{r}'$) and per unit of consumer's final demand ($\mathbf{r}_{\mathbf{y}}$), i.e., the waste coefficients of production (or interindustry) activities and final demand (or household consumption) activities. Column (2) shows the total solid waste indirectly generated by each industry's producing activities, per million of PTE of final demand for the output of that industry ($\mathbf{r}'(\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots)$). In Column (3) are reported the waste generation intensities of producing activities by industry (i.e., the sum of direct plus indirect production intensities), by each industry ($\mathbf{r}'(\mathbf{I} - \mathbf{A})^{-1}$). Finally, column (5) shows the global total waste generation intensities for the whole economy, (i.e., considering the producing activities (directly and indirectly) and the household consumption). Tables 28.2 and 28.3 offer a similar results breakdown for hazardous waste generation intensities (Table 28.2) and landfilling consumption intensities (Table 28.3).

Taking into consideration the global results for the total waste generation intensities (Table 28.1), the sectors with the highest intensities are: Sector 22

Table 28.1 Total Solid Waste Generation Intensities

unit: *tonnes of waste/million PTE*	Corresponding to direct production demand	+	Corresponding to indirect production demand	=	Corresponding to total production demand	+ Corresponding to direct consumption demand	=	Corresponding to total final demand	*Tt. waste generation intensities ranking*
	r'	(1) / (5) (%)	**r' (A+A²+...)**	(2) / (5) (%)	**r' (I-A)⁻¹**	**r_y**	(4) / (5) (%)		
	(1)		(2)=(3)–(1)		(3)	(4)		(5)=(3)+(4)	
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	9.70	68.1	2.25	15.8	11.96	2.29	16.1	14.25	3
04 Mining and Manufacture of Coal By-Products	4.26	39.1	0.79	7.3	5.05	5.85	53.7	10.90	5
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	0.08	21.6	0.27	78.4	0.35	–	–	0.35	33
06 Electricity Production, Transport and Distribution	1.04	59.9	0.69	40.1	1.73	–	–	1.73	18
07 Gas Production and Distribution	0.58	30.4	1.33	69.6	1.91	–	–	1.91	16
08 Water Supply	0.35	35.2	0.64	64.8	0.99	–	–	0.99	28
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	4.81	78.5	1.32	21.5	6.13	–	–	6.13	7
10 Extraction and Manuf. of Non-Metallic Minerals	4.09	51.3	1.36	17.1	5.45	2.52	31.6	7.97	6
11 Manuf. of Chemicals and Chemical Products	0.28	26.2	0.78	73.8	1.06	–	–	1.06	27
12 Manufacture of Fabricated Metal Products	0.99	24.6	1.22	30.2	2.20	1.82	45.2	4.02	11
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	0.67	34.5	0.56	28.8	1.24	0.72	36.7	1.95	15
14 Manufacture of Transport Equipment	0.58	52.4	0.49	44.6	1.07	0.03	3.0	1.10	25
15 Manufacture of Food Products and Beverages	1.56	29.1	3.68	68.7	5.24	0.12	2.2	5.36	8
16 Manufacture of Tobacco and Tobacco Products	0.00	0.1	0.32	99.9	0.32	–	–	0.32	34
17 Manufacture of Textiles and Clothing	1.46	57.5	0.81	32.1	2.27	0.26	10.4	2.53	13
18 Manufacture of Leather and Footwear	0.04	5.4	0.66	94.4	0.70	0.00	0.2	0.70	31
19 Other Manuf. Prod. (including wood, cork and furniture)	2.88	54.2	2.26	42.4	5.14	0.18	3.3	5.31	9
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	2.72	22.4	2.31	19.0	5.03	7.11	58.6	12.14	4
21 Manufacture of Rubber and Plastic Products	0.22	0.8	0.64	2.3	0.86	26.53	96.9	27.39	2
22 Construction	6.40	17.4	1.53	4.1	7.93	28.93	78.5	36.86	1
23 Recycling, Recovery and Repair Services	2.44	90.6	0.25	9.4	2.70	–	–	2.70	12
24 Wholesale and Retail Trade	1.69	69.8	0.73	30.2	2.42	–	–	2.42	14
25 Hotel and Restaurant Services	2.00	42.9	2.67	57.1	4.67	–	–	4.67	10
26 Land Transport and Transport Via Pipeline Services	0.64	48.8	0.67	51.2	1.32	–	–	1.32	22
27 Water and Air Transport Services	0.14	11.6	1.04	88.4	1.18	–	–	1.18	24
28 Supporting and Auxiliary Transport Services	0.35	32.2	0.74	67.8	1.09	–	–	1.09	26
29 Post and Telecommunication Services	0.40	54.5	0.33	45.5	0.72	–	–	0.72	30
30 Financial Intermediation Serv. (except insurance & pension...)	0.27	44.6	0.33	55.4	0.60	–	–	0.60	32
31 Insurance and Pension Funding Services	0.26	15.6	1.39	84.4	1.64	–	–	1.64	20
32 Real Estate Services and Other Renting Services	0.92	51.6	0.87	48.4	1.79	–	–	1.79	17
33 Education and R & D Services	1.02	82.1	0.22	17.9	1.24	–	–	1.24	23
34 Health and Veterinary Market Services	1.20	73.5	0.43	26.5	1.63	–	–	1.63	21
35 Other Services (Market and Non-Market)	0.38	44.2	0.47	55.8	0.85	–	–	0.85	29
36 Public Administration Non-Market Services	0.99	58.6	0.70	41.4	1.69	–	–	1.69	19

Table 28.2 Hazardous Waste Intensities

unit: tonnes of waste/million PTE	Corresponding to direct production demand	+	Corresponding to indirect production demand	=	Corresponding to total production demand	+ Corresponding to direct consumption demand	=	Corresponding to total final demand	*Tt. haz. waste intensities ranking*
	o'	(1) / (5) (%)	$o'(A+A^2+...)$	(2) / (5) (%)	$o'(I-A)^{-1}$	o_y	(4) / (5) (%)		
	(1)		(2)=(3)−(1)		(3)	(4)		(5)=(3)+(4)	
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	0.015	58.0	0.011	42.0	0.025	–	–	0.025	13
04 Mining and Manufacture of Coal By-Products	0.014	62.9	0.008	37.1	0.022	–	–	0.022	15
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	0.018	75.3	0.006	24.7	0.023	–	–	0.023	14
06 Electricity Production, Transport and Distribution	0.040	62.4	0.024	37.6	0.064	–	–	0.064	5
07 Gas Production and Distribution	0.040	59.9	0.027	40.1	0.066	–	–	0.066	4
08 Water Supply	0.040	73.2	0.015	26.8	0.054	–	–	0.054	8
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	0.014	40.4	0.020	59.6	0.034	–	–	0.034	10
10 Extraction and Manuf. of Non-Metallic Minerals	0.014	48.4	0.015	51.6	0.028	–	–	0.028	11
11 Manuf. of Chemicals and Chemical Products	0.050	82.7	0.011	17.3	0.061	–	–	0.061	6
12 Manufacture of Fabricated Metal Products	0.158	89.7	0.018	10.3	0.176	–	–	0.176	3
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	0.017	4.1	0.013	3.1	0.030	0.382	92.8	0.412	2
14 Manufacture of Transport Equipment	0.033	78.8	0.009	21.2	0.042	–	–	0.042	9
15 Manufacture of Food Products and Beverages	0.001	9.2	0.014	90.8	0.015	–	–	0.015	23
16 Manufacture of Tobacco and Tobacco Products	0.001	43.2	0.002	56.8	0.003	–	–	0.003	33
17 Manufacture of Textiles and Clothing	0.002	16.6	0.010	83.4	0.012	–	–	0.012	29
18 Manufacture of Leather and Footwear	0.001	9.2	0.007	90.8	0.008	–	–	0.008	31
19 Other Manuf. Prod. (including wood, cork and furniture)	0.040	68.4	0.018	31.6	0.058	–	–	0.058	7
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	0.005	24.0	0.014	76.0	0.019	–	–	0.019	19
21 Manufacture of Rubber and Plastic Products	0.006	0.3	0.012	0.7	0.018	1.670	98.9	1.687	1
22 Construction	0.006	26.2	0.016	73.8	0.021	–	–	0.021	17
23 Recycling, Recovery and Repair Services	0.010	73.7	0.004	26.3	0.014	–	–	0.014	25
24 Wholesale and Retail Trade	0.004	30.6	0.008	69.4	0.012	–	–	0.012	28
25 Hotel and Restaurant Services	0.002	15.4	0.012	84.6	0.014	–	–	0.014	24
26 Land Transport and Transport Via Pipeline Services	0.005	36.7	0.008	63.3	0.013	–	–	0.013	26
27 Water and Air Transport Services	0.005	32.1	0.010	67.9	0.015	–	–	0.015	22
28 Supporting and Auxiliary Transport Services	0.005	38.6	0.008	61.4	0.013	–	–	0.013	27
29 Post and Telecommunication Services	0.005	57.8	0.004	42.2	0.008	–	–	0.008	30
30 Financial Intermediation Serv. (except insurance & pension...)	0.013	79.4	0.003	20.6	0.016	–	–	0.016	21
31 Insurance and Pension Funding Services	0.013	47.2	0.014	52.8	0.027	–	–	0.027	12
32 Real Estate Services and Other Renting Services	0.013	65.8	0.007	34.2	0.019	–	–	0.019	18
33 Education and R & D Services	0.000	16.2	0.002	83.8	0.002	–	–	0.002	34
34 Health and Veterinary Market Services	0.016	75.7	0.005	24.3	0.022	–	–	0.022	16
35 Other Services (Market and Non-Market)	0.013	70.0	0.006	30.0	0.018	–	–	0.018	20
36 Public Administration Non-Market Services	0.001	13.0	0.005	87.0	0.005	–	–	0.005	32

Table 28.3 Landfilling Consumption Intensities

unit: tonnes of waste/million PTE	Corresponding to direct production demand	+	Corresponding to indirect production demand	=	Corresponding to total production demand	+ Corresponding to direct consumption demand	=	Corresponding to total final demand	Tt. Landfilling consumption intensities ranking
	p'	(1) / (5) (%)	p' (A+A^2+...)	(2) / (5) (%)	p' (I-A)$^{-1}$	p_y	(4) / (5) (%)		
	(1)		(2)=(3)–(1)		(3)	(4)		(5)=(3)+(4)	
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	7.08	67.8	1.44	13.8	8.52	1.92	18.4	10.44	3
04 Mining and Manufacture of Coal By-Products	3.60	38.4	0.45	4.8	4.05	5.33	56.8	9.38	4
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	0.06	31.7	0.14	68.3	0.20	–	–	0.20	33
06 Electricity Production, Transport and Distribution	0.44	58.8	0.31	41.2	0.74	–	–	0.74	21
07 Gas Production and Distribution	0.24	21.6	0.89	78.4	1.13	–	–	1.13	16
08 Water Supply	0.15	28.3	0.37	71.7	0.52	–	–	0.52	28
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	4.07	82.8	0.85	17.2	4.91	–	–	4.91	7
10 Extraction and Manuf. of Non-Metallic Minerals	3.46	52.1	0.89	13.4	4.34	2.29	34.5	6.63	6
11 Manuf. of Chemicals and Chemical Products	0.14	23.6	0.45	76.4	0.58	–	–	0.58	25
12 Manufacture of Fabricated Metal Products	0.49	16.8	0.76	26.2	1.25	1.65	56.9	2.90	10
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	0.33	25.4	0.33	24.9	0.66	0.65	49.7	1.31	14
14 Manufacture of Transport Equipment	0.28	49.2	0.26	45.7	0.55	0.03	5.1	0.58	26
15 Manufacture of Food Products and Beverages	0.77	22.7	2.51	74.1	3.28	0.11	3.2	3.39	8
16 Manufacture of Tobacco and Tobacco Products	0.00	0.0	0.20	100.0	0.20	–	–	0.20	34
17 Manufacture of Textiles and Clothing	0.72	52.8	0.40	29.5	1.12	0.24	17.6	1.36	13
18 Manufacture of Leather and Footwear	0.02	4.9	0.36	94.7	0.38	0.00	0.4	0.38	30
19 Other Manuf. Prod. (including wood, cork and furniture)	1.43	47.6	1.41	47.0	2.84	0.16	5.4	3.00	9
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	1.35	15.1	1.35	15.2	2.70	6.19	69.6	8.88	5
21 Manufacture of Rubber and Plastic Products	0.11	0.4	0.34	1.4	0.45	24.15	98.2	24.60	2
22 Construction	1.92	6.6	1.05	3.6	2.97	26.33	89.9	29.29	1
23 Recycling, Recovery and Repair Services	2.20	94.4	0.13	5.6	2.33	–	–	2.33	12
24 Wholesale and Retail Trade	0.80	67.2	0.39	32.8	1.19	–	–	1.19	15
25 Hotel and Restaurant Services	0.95	35.9	1.69	64.1	2.64	–	–	2.64	11
26 Land Transport and Transport Via Pipeline Services	0.30	47.0	0.34	53.0	0.65	–	–	0.65	22
27 Water and Air Transport Services	0.06	11.1	0.52	88.9	0.58	–	–	0.58	24
28 Supporting and Auxiliary Transport Services	0.17	31.5	0.36	68.5	0.53	–	–	0.53	27
29 Post and Telecommunication Services	0.19	55.1	0.15	44.9	0.34	–	–	0.34	31
30 Financial Intermediation Serv. (except insurance & pension...)	0.13	44.3	0.16	55.7	0.29	–	–	0.29	32
31 Insurance and Pension Funding Services	0.12	15.3	0.67	84.7	0.79	–	–	0.79	20
32 Real Estate Services and Other Renting Services	0.44	51.7	0.41	48.3	0.84	–	–	0.84	17
33 Education and R & D Services	0.48	81.6	0.11	18.4	0.59	–	–	0.59	23
34 Health and Veterinary Market Services	0.57	71.1	0.23	28.9	0.80	–	–	0.80	19
35 Other Services (Market and Non-Market)	0.18	41.5	0.25	58.5	0.43	–	–	0.43	29
36 Public Administration Non-Market Services	0.47	58.1	0.34	41.9	0.81	–	–	0.81	18

(Construction), Sector 21 (Manufacture of Rubber and Plastics), and Sector (1 + 2 + 3) (Agriculture, Forestry, Fishing and Related Service Activities).

These results confirm the major relative significance of carefully considering these activities (and their corresponding products) when envisaging strategies to promote the goals of waste prevention and reduction. Conversely, business service sectors such as Sector 29 (Post and Telecommunication Services) and Sector 30 (Financial Intermediation Services) are among the less waste generation intensive. It is worth mentioning that for a significant number of industries, the indirect waste generation intensities are higher than the direct intensities. A paradigmatic example of this situation is given by Sector 16 (Manufacture of Tobacco and Tobacco Products), where the indirect total waste generation intensity represents 99.9% of the global waste generation intensity of this sector, against only 0.1% for the direct waste generation intensity (of tobacco producing activity). This indicates how crucial it is to use an approach which takes economic interrelationships into account when analysing waste generation intensities.

In Table 28.2, the highest global hazardous waste generation intensities are found in Sectors 21 (Manufacture of Rubber and Plastics), and 13 (Manufacture of Electrical and Non-Electrical Machinery and Equipment).

The landfilling consumption intensities are presented in Table 28.3. Sectors 22 (Construction), 21 (Manufacture of Rubber and Plastics), and (1 + 2 + 3) (Agriculture, Forestry, Fishing and Related Service Activities) occupy the first three positions in the ranking of total landfilling consumption intensities, indicating that this waste management option tends to be heavily influenced by the activities within these sectors.

The Waste Flows Attributable to the Portuguese Economy

The interpretation of the results presented in Tables 28.1–28.3 can be combined with the results presented in Tables 28.4–28.6. There, the above described different waste flows intensities have been multiplied by the final demand vector using our input-output approach, to obtain waste flows (that is: tons of hazardous waste, and kilotons of total waste generation and landfilling consumption) by the Portuguese economy, for each sector.

Below each of these columns are the total waste flows attributable to direct and indirect production demand, and direct consumption demand. Differences in the relative significance of each industry, between these two analyses, can be explained by what might be described as a ‘scale effect’, resulting from the specific relative significance of a particular industry (or a particular product) in the context of the Portuguese economic structure, which is the basis of the input-output model.

In Table 28.4, the global solid waste generation of about 48,940 kt is attributed to direct and indirect production demand (60.4% and 35.7%), and to direct consumption demand (4.0%). Construction (Sector 22), Manufacture of Food Products and Beverages (Sector 15), Agriculture, Forestry, Fishing and Related Service Activities

Table 28.4 Total Solid Waste Generation Flows

unit: 10^3 tonnes of waste/million PTE	Corresponding to direct production demand $r'\,y$ (1)	+ (1) / (5) (%)	Corresponding to indirect production demand $r'(A+A^2+...)\,y$ (2)=(3)–(1)	= (2) / (5) (%)	Corresponding to total production demand $r'(I-A)^{-1}y$ (3)	+ Corresponding to direct consumption demand $r_y Z\,y$ (4)	= (4) / (5) (%)	Corresponding to total final demand (5)=(3)+(4)	*Relative distribution of Tt. Waste generation flows by industry (%)*	*Tt .Waste generation flows ranking*
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	4,242	70.5	985	16.4	5,227	793	13.2	6,020	12.3	3
04 Mining and Manufacture of Coal By-Products	2	69.0	0	12.8	2	0	18.2	2	0.0	34
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	8	21.6	30	78.4	39	–	–	39	0.1	31
06 Electricity Production, Transport and Distribution	176	59.9	118	40.1	294	–	–	294	0.6	20
07 Gas Production and Distribution	6	30.4	13	69.6	19	–	–	19	0.0	33
08 Water Supply	9	35.2	17	64.8	27	–	–	27	0.1	32
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	301	78.5	83	21.5	384	–	–	384	0.8	19
10 Extraction and Manuf. of Non-Metallic Minerals	580	71.5	194	23.9	774	37	4.6	811	1.7	13
11 Manuf. of Chemicals and Chemical Products	71	26.2	199	73.8	269	–	–	269	0.5	23
12 Manufacture of Fabricated Metal Products	225	41.4	277	51.0	502	41	7.6	544	1.1	16
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	372	54.0	311	45.2	683	5	0.8	688	1.4	14
14 Manufacture of Transport Equipment	226	53.6	193	45.6	419	3	0.7	422	0.9	18
15 Manufacture of Food Products and Beverages	1,849	29.1	4,367	68.8	6,216	129	2.0	6,345	13.0	2
16 Manufacture of Tobacco and Tobacco Products	0	0.1	47	99.9	47	–	–	47	0.1	28
17 Manufacture of Textiles and Clothing	1,513	62.1	844	34.6	2,357	80	3.3	2,437	5.0	6
18 Manufacture of Leather and Footwear	13	5.4	222	94.5	235	0	0.1	235	0.5	24
19 Other Manuf. Prod. (including wood, cork and furniture)	862	55.5	674	43.4	1,536	16	1.0	1,552	3.2	9
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	517	36.1	439	30.6	956	477	33.3	1,434	2.9	10
21 Manufacture of Rubber and Plastic Products	14	4.9	41	14.2	55	231	80.9	286	0.6	21
22 Construction	9,527	79.9	2,276	19.1	11,803	127	1.1	11,930	24.4	1
23 Recycling, Recovery and Repair Services	605	90.6	63	9.4	668	–	–	668	1.4	15
24 Wholesale and Retail Trade	2,911	69.8	1,262	30.2	4,173	–	–	4,173	8.5	4
25 Hotel and Restaurant Services	1,490	42.9	1,984	57.1	3,474	–	–	3,474	7.1	5
26 Land Transport and Transport Via Pipeline Services	138	48.8	144	51.2	282	–	–	282	0.6	22
27 Water and Air Transport Services	20	11.6	154	88.4	175	–	–	175	0.4	25
28 Supporting and Auxiliary Transport Services	37	32.2	77	67.8	114	–	–	114	0.2	26
29 Post and Telecommunication Services	52	54.5	43	45.5	95	–	–	95	0.2	27
30 Financial Intermediation Serv. (except insurance & pension...)	18	44.6	22	55.4	41	–	–	41	0.1	30
31 Insurance and Pension Funding Services	6	15.6	35	84.4	41	–	–	41	0.1	29
32 Real Estate Services and Other Renting Services	892	51.6	838	48.4	1,730	–	–	1,730	3.5	8
33 Education and R & D Services	867	82.1	189	17.9	1,056	–	–	1,056	2.2	11
34 Health and Veterinary Market Services	679	73.5	245	26.5	924	–	–	924	1.9	12
35 Other Services (Market and Non-Market)	224	44.2	283	55.8	507	–	–	507	1.0	17
36 Public Administration Non-Market Services	1,099	58.6	778	41.4	1,878	–	–	1,878	3.8	7
Total	**29,551**	**60.4**	**17,447**	**35.7**	**46,998**	**1,942**	**4.0**	**48,940**	**100**	

Table 28.5 Hazardous Waste Flows

unit: tonnes of waste/million PTE	Corresponding to direct production demand	+	Corresponding to indirect production demand	=	Corresponding to total production demand	+ Corresponding to Direct Consumption Demand	=	Corresponding to total final demand	*Relative distribution of Haz. Waste generation flows by industry (%)*	*Tt. Haz. Waste generation flows ranking*
	o' y	(1) / (5) (%)	o' (A+A²+...) y	(2) / (5) (%)	o' (I-A)⁻¹ y	o_y Z y	(4) / (5) (%)			
	(1)		(2)=(3)−(1)		(3)	(4)		(5)=(3)+(4)		
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	6,441	58.0	4,667	42.0	11,108	–	–	11,108	3.5	13
04 Mining and Manufacture of Coal By-Products	5	62.9	3	37.1	8	–	–	8	0.0	34
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	1,938	75.3	637	24.7	2,574	–	–	2,574	0.8	23
06 Electricity Production, Transport and Distribution	6,738	62.4	4,066	37.6	10,804	–	–	10,804	3.4	15
07 Gas Production and Distribution	402	59.9	268	40.1	670	–	–	670	0.2	32
08 Water Supply	1,070	73.2	391	26.8	1,461	–	–	1,461	0.5	27
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	854	40.4	1,262	59.6	2,116	–	–	2,116	0.7	25
10 Extraction and Manuf. of Non-Metallic Minerals	1,938	48.4	2,064	51.6	4,002	–	–	4,002	1.3	18
11 Manuf. of Chemicals and Chemical Products	12,775	82.7	2,675	17.3	15,449	–	–	15,449	4.8	10
12 Manufacture of Fabricated Metal Products	36,055	89.7	4,141	10.3	40,196	–	–	40,196	12.6	1
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	9,378	48.6	7,024	36.4	16,402	2,913	15.1	19,315	6.1	4
14 Manufacture of Transport Equipment	13,075	78.8	3,511	21.2	16,586	–	–	16,586	5.2	8
15 Manufacture of Food Products and Beverages	1,649	9.2	16,192	90.8	17,841	–	–	17,841	5.6	6
16 Manufacture of Tobacco and Tobacco Products	205	43.2	270	56.8	476	–	–	476	0.1	33
17 Manufacture of Textiles and Clothing	2,032	16.6	10,179	83.4	12,212	–	–	12,212	3.8	12
18 Manufacture of Leather and Footwear	242	9.2	2,394	90.8	2,636	–	–	2,636	0.8	22
19 Other Manuf. Prod. (including wood, cork and furniture)	11,807	68.4	5,453	31.6	17,260	–	–	17,260	5.4	7
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	860	24.0	2,731	76.0	3,592	–	–	3,592	1.1	19
21 Manufacture of Rubber and Plastic Products	356	2.3	777	4.9	1,132	14,565	92.8	15,697	4.9	9
22 Construction	8,282	26.2	23,339	73.8	31,621	–	–	31,621	9.9	2
23 Recycling, Recovery and Repair Services	2,481	73.7	887	26.3	3,368	–	–	3,368	1.1	20
24 Wholesale and Retail Trade	6,253	30.6	14,193	69.4	20,446	–	–	20,446	6.4	3
25 Hotel and Restaurant Services	1,586	15.4	8,726	84.6	10,312	–	–	10,312	3.2	16
26 Land Transport and Transport Via Pipeline Services	1,039	36.7	1,795	63.3	2,834	–	–	2,834	0.9	21
27 Water and Air Transport Services	718	32.1	1,523	67.9	2,241	–	–	2,241	0.7	24
28 Supporting and Auxiliary Transport Services	507	38.6	806	61.4	1,313	–	–	1,313	0.4	28
29 Post and Telecommunication Services	639	57.8	467	42.2	1,106	–	–	1,106	0.3	29
30 Financial Intermediation Serv. (except insurance & pension...)	867	79.4	226	20.6	1,093	–	–	1,093	0.3	30
31 Insurance and Pension Funding Services	324	47.2	362	52.8	686	–	–	686	0.2	31
32 Real Estate Services and Other Renting Services	12,414	65.8	6,449	34.2	18,862	–	–	18,862	5.9	5
33 Education and R & D Services	314	16.2	1,627	83.8	1,941	–	–	1,941	0.6	26
34 Health and Veterinary Market Services	9,264	75.7	2,969	24.3	12,233	–	–	12,233	3.8	11
35 Other Services (Market and Non-Market)	7,640	70.0	3,277	30.0	10,916	–	–	10,916	3.4	14
36 Public Administration Non-Market Services	746	13.0	5,011	87.0	5,756	–	–	5,756	1.8	17
Total	**160,894**	**50.5**	**140,360**	**44.0**	**301,254**	**17,478**	**5.5**	**318,732**	**100**	

Table 28.6 Landfilling Consumption Flows

unit: 10^3 tonnes of waste/million PTE	Corresponding to direct production demand **p' y** (1)	+ (1) / (5) (%)	Corresponding to indirect production demand **p' (A+A^2+...) y** (2)=(3)–(1)	= (2) / (5) (%)	Corresponding to total production demand **p' (I-A)$^{-1}$ y** (3)	+ Corresponding to direct consumption demand **p_y Z y** (4)	= (4) / (5) (%)	Corresponding to total final demand (5)=(3)+(4)	*Relative distribution of Tt. Landfilling consumption flows by industry (%)*	*Tt. Landfilling consumption flows ranking*
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	3,097	70.6	629	14.3	3,726	663	15.1	4,389	16.6	2
04 Mining and Manufacture of Coal By-Products	1	70.9	0	8.9	2	0	20.2	2	0.0	34
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	7	31.7	15	68.3	22	–	–	22	0.1	29
06 Electricity Production, Transport and Distribution	74	58.8	52	41.2	126	–	–	126	0.5	24
07 Gas Production and Distribution	2	21.6	9	78.4	11	–	–	11	0.0	33
08 Water Supply	4	28.3	10	71.7	14	–	–	14	0.1	32
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	254	0.0	53	0.0	307	–	–	307	1.2	17
10 Extraction and Manuf. of Non-Metallic Minerals	490	75.4	126	19.4	617	34	5.2	650	2.5	11
11 Manuf. of Chemicals and Chemical Products	35	23.6	113	76.4	148	–	–	148	0.6	21
12 Manufacture of Fabricated Metal Products	111	34.5	174	53.8	285	38	11.7	323	1.2	16
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	184	49.9	180	48.8	364	5	1.3	369	1.4	15
14 Manufacture of Transport Equipment	112	51.1	104	47.6	216	3	1.3	219	0.8	20
15 Manufacture of Food Products and Beverages	915	22.8	2,977	74.3	3,892	118	2.9	4,009	15.2	3
16 Manufacture of Tobacco and Tobacco Products	0	0.0	30	100.0	30	–	–	30	0.1	28
17 Manufacture of Textiles and Clothing	748	60.4	419	33.8	1,167	73	5.9	1,240	4.7	6
18 Manufacture of Leather and Footwear	6	4.9	121	94.9	127	0	0.1	127	0.5	23
19 Other Manuf. Prod. (including wood, cork and furniture)	426	49.4	421	48.9	848	14	1.7	862	3.3	9
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	256	27.6	257	27.7	513	415	44.7	929	3.5	7
21 Manufacture of Rubber and Plastic Products	7	2.9	22	9.0	29	211	88.1	239	0.9	19
22 Construction	2,858	63.1	1,558	34.4	4,416	116	2.6	4,531	17.1	1
23 Recycling, Recovery and Repair Services	545	94.4	32	5.6	577	–	–	577	2.2	12
24 Wholesale and Retail Trade	1,377	67.2	673	32.8	2,050	–	–	2,050	7.8	4
25 Hotel and Restaurant Services	705	35.9	1,260	64.1	1,965	–	–	1,965	7.4	5
26 Land Transport and Transport Via Pipeline Services	65	47.0	73	53.0	138	–	–	138	0.5	22
27 Water and Air Transport Services	10	11.1	77	88.9	86	–	–	86	0.3	25
28 Supporting and Auxiliary Transport Services	17	31.5	38	68.5	55	–	–	55	0.2	26
29 Post and Telecommunication Services	25	55.1	20	44.9	45	–	–	45	0.2	27
30 Financial Intermediation Serv. (except insurance & pension...)	9	44.3	11	55.7	19	–	–	19	0.1	31
31 Insurance and Pension Funding Services	3	15.3	17	84.7	20	–	–	20	0.1	30
32 Real Estate Services and Other Renting Services	422	51.7	395	48.3	817	–	–	817	3.1	10
33 Education and R & D Services	410	81.6	92	18.4	502	–	–	502	1.9	13
34 Health and Veterinary Market Services	321	71.1	130	28.9	451	–	–	451	1.7	14
35 Other Services (Market and Non-Market)	106	41.5	150	58.5	256	–	–	256	1.0	18
36 Public Administration Non-Market Services	520	58.1	375	41.9	895	–	–	895	3.4	8
Total	**14,123**	**53.4**	**10,612**	**40.2**	**24,736**	**1,690**	**6.4**	**26,425**	**100**	

(Sector $(1 + 2 + 3)$) and Wholesale and Retail Trade (Sector 24), explain 58.2% of the global waste generation flows. As such, waste surveys concerning final demand for these sectors output would be of extreme utility for waste policy purposes.

In Table 28.5, the hazardous waste generation of 318,732 t can be decomposed into direct and indirect production demand (50.5% and 44.0%), and the direct consumption demand (5.5%). The top three hazardous waste generators are Sectors 12 (Manufacture of Fabricated Metal Products), 22 (Construction), and 24 (Wholesale and Retail Trade). The high proportion of hazardous waste corresponding to indirect production explains the above results for Sectors 22 and 24; on the other hand, the effect corresponding to the direct consumption demand justifies the result for Sector 12.

Finally, in Table 28.6, the solid waste landfilling consumption of 26,425 kt correspond to the combination of the direct and indirect production demand (53.5% and 40.2%), and the direct consumption demand (6.4%). The hierarchy of the different sectors according to their landfilling consumption flows, highlights the major contributions from final demand for the outputs from Construction (Sector 22), Agriculture, Forestry, Fishing and Related Service Activities (Sector $1 + 2 + 3$), Manufacture of Food Products and Beverages (Sector 15), Wholesale and Retail Trade (Sector 24), and Hotel and Restaurant Services (Sector 25). Together they make up approximately 64% of waste sent to landfill. It would be interesting to conduct more detailed research on the characteristics of the waste resulting from these sectors output final demand.

The data up to this point illustrates some of the most significant empirical details on waste generation and management for the Portuguese economy. However, the analysis so far developed does not consider the potential significance of the waste flows attributable to imports and exports. It is this issue that will be introduced into to our analysis in the following section.

The Waste Flows Attributable to Portuguese International Trade

This section describes the effects of international trade on the various waste flows using the input-output model presented above.

The Waste Flows Resulting from Portuguese Exports

In Table 28.7, the 'total waste flows attributable to Portuguese exports', i.e., the tons of solid waste (column (7)) and hazardous waste generation (column (8)), and landfilling consumption (column (9)) attributable to Portuguese exports, are decomposed according to the effects attributable to direct production demand (columns (1) to (3)) and those attributable to indirect production demand (columns (4) to (6)).

Table 28.7 Waste Flows Attributed to Portuguese Exports

unit: 10^3 tonnes of waste; tonnes of hazardous waste	Attrib. to Direct Prod. Demand			+ Attributable to Indirect Production Demand			= Total waste flows attributable to Portuguese exports					
	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Relative dist. of SW by sector (%)	Hazardous waste	Relative dist. of HW by sector (%)	Landfilling consumtpion	Relative dist. of LC by sector (%)
	$r' y_X$	$o' y_X$	$p' y_X$	$r' (A+A^2+...) y_X$	$o' (A+A^2+...) y_X$	$p' (A+A^2+...) y_X$	$q_X=r' (I-A)^{-1} y_X$		$h_X=o'(I-A)^{-1} y_X$		$l_X=p' (I-A)^{-1} y_X$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)=(1)+(4)		(8)=(2)+(5)		(9)=(3)+(6)	
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	601	912	439	140	661	89	740	9.8	1,573	1.8	528	11.9
04 Mining and Manufacture of Coal By-Products	1	4	1	0	3	0	2	0.0	7	0.0	1	0.0
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	5	1,223	4	19	402	10	24	0.3	1,625	1.9	14	0.3
06 Electricity Production, Transport and Distribution	8	295	3	5	178	2	13	0.2	473	0.6	6	0.1
07 Gas Production and Distribution	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
08 Water Supply	0	2	0	0	1	0	0	0.0	3	0.0	0	0.0
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	256	725	216	70	1,072	45	326	4.3	1,797	2.1	261	5.9
10 Extraction and Manuf. of Non-Metallic Minerals	492	1,642	416	164	1,749	107	656	8.7	3,391	3.9	522	11.8
11 Manuf. of Chemicals and Chemical Products	32	5,744	16	89	1,203	51	121	1.6	6,946	8.1	67	1.5
12 Manufacture of Fabricated Metal Products	97	15,463	48	119	1,776	74	216	2.9	17,239	20.1	122	2.8
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	209	5,273	103	175	3,950	101	384	5.1	9,223	10.7	204	4.6
14 Manufacture of Transport Equipment	138	7,998	68	118	2,148	64	256	3.4	10,145	11.8	132	3.0
15 Manufacture of Food Products and Beverages	195	174	96	460	1,707	314	655	8.7	1,881	2.2	410	9.3
16 Manufacture of Tobacco and Tobacco Products	0	1	0	0	1	0	0	0.0	1	0.0	0	0.0
17 Manufacture of Textiles and Clothing	1,067	1,434	528	596	7,184	295	1,663	22.0	8,618	10.0	823	18.6
18 Manufacture of Leather and Footwear	8	161	4	148	1,598	80	157	2.1	1,759	2.0	85	1.9
19 Other Manuf. Prod. (including wood, cork and furniture)	549	7,522	272	430	3,474	269	978	12.9	10,996	12.8	540	12.2
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	337	561	167	286	1,780	168	623	8.2	2,341	2.7	334	7.6
21 Manufacture of Rubber and Plastic Products	8	195	4	22	426	12	30	0.4	621	0.7	16	0.4
22 Construction	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
23 Recycling, Recovery and Repair Services	25	101	22	3	36	1	27	0.4	137	0.2	24	0.5
24 Wholesale and Retail Trade	12	26	6	5	60	3	18	0.2	86	0.1	9	0.2
25 Hotel and Restaurant Services	31	33	15	41	180	26	72	0.9	212	0.2	40	0.9
26 Land Transport and Transport Via Pipeline Services	23	177	11	25	305	12	48	0.6	482	0.6	24	0.5
27 Water and Air Transport Services	18	621	8	133	1,317	66	151	2.0	1,938	2.3	75	1.7
28 Supporting and Auxiliary Transport Services	12	162	6	25	257	12	36	0.5	419	0.5	18	0.4
29 Post and Telecommunication Services	12	143	6	10	105	4	21	0.3	248	0.3	10	0.2
30 Financial Intermediation Serv. (except insurance & pension...)	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
31 Insurance and Pension Funding Services	1	74	1	8	83	4	9	0.1	157	0.2	5	0.1
32 Real Estate Services and Other Renting Services	171	2,381	81	161	1,237	76	332	4.4	3,617	4.2	157	3.5
33 Education and R & D Services	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
34 Health and Veterinary Market Services	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
35 Other Services (Market and Non-Market)	1	28	0	1	12	1	2	0.0	40	0.0	1	0.0
36 Public Administration Non-Market Services	0	0	0	0	0	0	0	0.0	0	0.0	0	0.0
Total	**4,308**	**53,076**	**2,540**	**3,252**	**32,901**	**1,887**	**7,560**	**100**	**85,977**	**100**	**4,427**	**100**

The results achieved show that there were 7,560 kt of solid waste attributable to 1992 Portuguese exports, of which 85,977 t correspond to hazardous waste, and 4,427 kt would have been sent to landfilling.

Concerning the total amount of solid waste generation attributable to Portuguese exports, the sectors that contributed the most to these results were Manufacture of Textiles and Clothing (Sector 17) (22%) and Other Manufacturing Products (including wood, cork and furniture) (Sector 19) (12.9%). In spite of the relatively modest waste generation intensities that characterise the output of these Sectors 17 (see Table 28.1), the significance of these activities in terms of the solid waste attributable to exports is remarkable. Indeed, these results confirm the major contribution of the above sectors to Portuguese exports.

The results concerning the landfilling consumption attributable to Portuguese exports are closely related to the above regarding solid waste generation flows, which indicates that the composition of Portuguese exports is most influential to the relative significance of landfilling flows.

Concerning the relative distribution of hazardous waste flows attributable from Portuguese exports, the top sectors are: Sector 12 (Manufacture of Fabricated Metal Products) and Sector 19 (Manufacture of Textiles and Clothing), reflecting both the combination of the relatively significant hazardous waste generation intensities and the amounts of these goods and services that are exported.

The Waste Flows Resulting from Portuguese Imports

The results on the waste flows attributable to Portuguese imports (see Equations (28.23)–(28.25)), are given in Table 28.8. The 'total waste flows attributable to Portuguese imports', i.e., the tons of solid waste (column (7)) and hazardous waste generation (column (8)), and landfilling consumption (column (9)), resulting from foreign production activities to satisfy the domestic final demand for goods and services, are distributed according to the effects attributable to imports for use in further production (columns (1)–(3)), and imports for use by final consumers directly (columns (4)–(6)). Globally, these results show that there were 8,590 kt of solid waste generation associated with the production of the 1992 Portuguese imports, of which 128,660 t correspond to hazardous waste, and 6,732 kt correspond to landfilling consumption. Typically, the waste flows attributable to imports for use in further production represent about three quarters of the global waste flows attributable to Portuguese imports, the remaining being attributable to imports for use directly by final consumers. All of these waste flows can be interpreted as physical amounts whose direct generation was 'avoided' by Portugal when importing the corresponding goods and services, instead of producing them domestically. According to this interpretation, the impacts from waste generation and management harm the ecological system of the country where production takes place, rather than the ecological system of the importing country (where direct and indirect consumption occurs). In this sense, it might be possible for one country, to 'save' its own carrying capacity by shifting away from more waste intensive activities (Munksgaard and Pedersen 2001).

Table 28.8 Waste Flows Attributed to Portuguese Imports

unit: 10^3 tonnes of waste; tonnes of hazardous waste	Attrib. to Imports for use in further prod.			+ Attrib. to Imp. for use by cons. directly			= Total waste flows attributable to Portuguese imports					
	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Relat. dist. of SW by sector (%)	Hazardous waste	Relat. dist. of HW by sector (%)	Landfilling consumtpion	Relat. dist. of LC by sector (%)
	$r'(I-A)^{-1}B(I-A)^{-1}y_D$	$o'(I-A)^{-1}B(I-A)^{-1}y_D$	$p'(I-A)^{-1}B(I-A)^{-1}y_D$	$r'(I-A)^{-1}y_M$	$o'(I-A)^{-1}y_M$	$p'(I-A)^{-1}y_M$	$q_M=r'(I-A)^{-1}B(I-A)^{-1}y_D + r'(I-A)^{-1}y_M$		$h_M=o'(I-A)^{-1}B(I-A)^{-1}y_D + o'(I-A)^{-1}y_M$		$l_M=p'(I-A)^{-1}B(I-A)^{-1}y_D + p'(I-A)^{-1}y_M$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)=(1)+(4)		(8)=(2)+(5)		(9)=(3)+(6)	
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	269	1,932	183	680	1,445	485	948	11.0	3,377	2.6	668	9.9
04 Mining and Manufacture of Coal By-Products	0	3,796	575	0	0	0	0	0.0	3,796	3.0	575	8.5
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	16	8,589	84	4	285	2	20	0.2	8,873	6.9	86	1.3
06 Electricity Production, Transport and Distribution	44	1,584	73	0	0	0	44	0.5	1,584	1.2	73	1.1
07 Gas Production and Distribution	4	4,162	101	0	0	0	4	0.0	4,162	3.2	101	1.5
08 Water Supply	5	1,514	43	0	0	0	5	0.1	1,514	1.2	43	0.6
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	14	4,840	416	0	0	0	14	0.2	4,840	3.8	416	6.2
10 Extraction and Manuf. of Non-Metallic Minerals	11	2,221	130	62	319	49	72	0.8	2,540	2.0	179	2.7
11 Manuf. of Chemicals and Chemical Products	122	7,186	211	70	3,999	38	192	2.2	11,186	8.7	250	3.7
12 Manufacture of Fabricated Metal Products	170	4,931	370	41	3,245	23	210	2.4	8,176	6.4	393	5.8
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	182	4,830	187	157	3,764	83	338	3.9	8,594	6.7	271	4.0
14 Manufacture of Transport Equipment	138	7,825	216	207	8,182	107	345	4.0	16,007	12.4	322	4.8
15 Manufacture of Food Products and Beverages	1,594	2,741	389	734	2,107	460	2,328	27.1	4,848	3.8	848	12.6
16 Manufacture of Tobacco and Tobacco Products	39	432	68	0	4	0	40	0.5	436	0.3	68	1.0
17 Manufacture of Textiles and Clothing	316	2,596	237	342	1,771	169	658	7.7	4,367	3.4	406	6.0
18 Manufacture of Leather and Footwear	57	2,040	113	14	162	8	71	0.8	2,202	1.7	121	1.8
19 Other Manuf. Prod. (including wood, cork and furniture)	156	4,154	359	292	3,277	161	448	5.2	7,431	5.8	520	7.7
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	44	2,376	145	145	546	78	189	2.2	2,922	2.3	223	3.3
21 Manufacture of Rubber and Plastic Products	17	8,385	131	21	434	11	38	0.4	8,819	6.9	142	2.1
22 Construction	876	3,657	152	0	0	0	876	10.2	3,657	2.8	152	2.3
23 Recycling, Recovery and Repair Services	47	1,772	42	1	8	1	49	0.6	1,779	1.4	44	0.6
24 Wholesale and Retail Trade	391	1,105	51	0	0	0	391	4.6	1,105	0.9	51	0.8
25 Hotel and Restaurant Services	605	1,668	209	0	0	0	605	7.0	1,668	1.3	209	3.1
26 Land Transport and Transport Via Pipeline Services	31	1,413	38	1	15	1	32	0.4	1,428	1.1	39	0.6
27 Water and Air Transport Services	8	2,236	81	11	139	5	19	0.2	2,375	1.8	86	1.3
28 Supporting and Auxiliary Transport Services	13	844	38	0	0	0	13	0.1	844	0.7	38	0.6
29 Post and Telecommunication Services	10	636	21	4	44	2	14	0.2	680	0.5	23	0.3
30 Financial Intermediation Serv. (except insurance & pension...)	7	456	21	0	0	0	7	0.1	456	0.4	21	0.3
31 Insurance and Pension Funding Services	19	4,120	186	0	0	0	19	0.2	4,120	3.2	186	2.8
32 Real Estate Services and Other Renting Services	131	839	37	0	0	0	131	1.5	839	0.7	37	0.6
33 Education and R & D Services	44	242	12	0	0	0	44	0.5	242	0.2	12	0.2
34 Health and Veterinary Market Services	103	1,469	41	0	0	0	103	1.2	1,469	1.1	41	0.6
35 Other Services (Market and Non-Market)	139	1,403	50	0	5	0	139	1.6	1,408	1.1	50	0.7
36 Public Administration Non-Market Services	184	916	39	0	0	0	184	2.1	916	0.7	39	0.6
Total	**5,805**	**98,911**	**5,048**	**2,785**	**29,749**	**1,683**	**8,590**	**100**	**128,660**	**100**	**6,732**	**100**

(continued)

Balance of the Waste Flows Attributable to Portuguese International Trade

In global terms it can be said that Portugal faced a negative balance respecting the waste flows relating to Portuguese international trade in 1992. That is, in most cases the waste flows attributable to Portuguese imports exceed the corresponding waste flows relating to Portuguese exports. The analysis of Table 28.9 gives a deficit of 1,030 kt of solid waste, 42,683 t of hazardous waste, and 2,305 kt of landfilling consumption (i.e., domestic landfilling potentially 'avoided' in consequence of international trade). Interestingly, according to these results, the landfilling consumption deficit is bigger than the total solid waste generation deficit. This outcome can be explained by the different sectoral composition of imports and exports, i.e., the imports are typically more landfilling consumption intensive (about 78% of the total solid waste generation attributed to imports) than exports (about 59%). In other words, there is a surplus for the non-landfilling solid waste management flows incorporated in Portuguese exports, indicating that exports are relatively more concentrated on goods and services for which alternatives to landfilling are more practised in Portugal.

The Waste Flows Attributable to Portuguese Domestic Final Demand and Portugal's Total Waste Flows Responsibility

Finally, the calculations of waste flows attributable to Portuguese international trade make it possible to distinguish between the Portuguese 'nationally produced' waste flows, the 'domestically produced' waste flows and the 'nationally attributable' waste flows.[6]

By applying these concepts, one can divide the total solid waste flows by the Portuguese economy (or the 'nationally produced' waste flows) into the waste flows due to its demand for its own domestic goods (the total waste flows attributable to domestic final demand), and due to foreign countries final demand (exports). That is, as can be seen from Table 28.10, Portuguese exports represent 15.5% of the solid waste generation (7,560 kt), 27.0% of the hazardous waste generation (85,977 t), and 16.8% of the landfilling consumption (4,427 kt).

These figures mean that 84.6% of the solid waste produced by the Portuguese economy, 73.0% of the hazardous waste generated, and 83.3% of the landfilling consumption, occurred to satisfy the final demand by Portuguese consumers, while the remaining resulted from the satisfaction of foreign final demand.

[6] According to Equations (28.26)–(28.28), the Portuguese 'domestically produced' waste flows, that is, the total waste flows attributable to domestic final demand, can be estimated from the total waste flows by the Portuguese economy and subtracting the amounts of waste flows attributable to production of final demand for export. On the other hand, according to Equations (28.29)–(28.31), the 'domestically produced' waste flows plus the waste flows attributable to imports gives the Portuguese 'nationally attributable' waste flows or the 'waste flows responsibility' (i.e., Portugal's total 'nationally attributable' waste flows can be calculated from the nationally produced waste flows by adding the flows attributable to imports, and subtracting those attributable to exports).

Table 28.9 Balance of Waste Flows Attributed to Portuguese International Trade

unit: 10^3 tonnes of waste; tonnes of hazardous waste	Tt. waste flows attrib. to Portuguese exports			- Tt. waste flows attrib. to Port. Imports			= Balance of Port. Inter. trade waste flows		
	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion
	$q_X=r'(I-A)^{-1}y_X$	$h_X=o'(I-A)^{-1}y_X$	$l_X=p'(I-A)^{-1}y_X$	$q_M=r'(I-A)^{-1}B(I-A)^{-1}y_D + r'(I-A)-1\ y_M$	$h_M=o'(I-A)^{-1}B(I-A)^{-1}y_D + o'(I-A)-1\ y_M$	$l_M=p'(I-A)^{-1}B(I-A)^{-1}y_D + p'(I-A)-1\ y_M$	q_X-q_M	h_X-h_M	l_X-l_M
	(1)	(2)	(3)	(4)	(5)	(6)	(7)=(1)–(4)	(8)=(2)–(5)	(9)=(3)–(6)
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	740	1,573	528	948	3,377	668	−208	−1,804	−140
04 Mining and Manufacture of Coal By-Products	2	7	1	0	3,796	575	1	−3,789	−574
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	24	1,625	14	20	8,873	86	4	−7,249	−72
06 Electricity Production, Transport and Distribution	13	473	6	44	1,584	73	−32	−1,112	−67
07 Gas Production and Distribution	0	0	0	4	4,162	101	−4	−4,162	−101
08 Water Supply	0	3	0	5	1,514	43	−5	−1,510	−43
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	326	1,797	261	14	4,840	416	312	−3,043	−155
10 Extraction and Manuf. of Non-Metallic Minerals	656	3,391	522	72	2,540	179	584	851	344
11 Manuf. of Chemicals and Chemical Products	121	6,946	67	192	11,186	250	−71	−4,239	−183
12 Manufacture of Fabricated Metal Products	216	17,239	122	210	8,176	393	5	9,062	−270
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	384	9,223	204	338	8,594	271	45	628	−66
14 Manufacture of Transport Equipment	256	10,145	132	345	16,007	322	−89	−5,861	−190
15 Manufacture of Food Products and Beverages	655	1,881	410	2,328	4,848	848	−1,672	−2,967	−438
16 Manufacture of Tobacco and Tobacco Products	0	1	0	40	436	68	−40	−435	−68
17 Manufacture of Textiles and Clothing	1,663	8,618	823	658	4,367	406	1,005	4,251	418
18 Manufacture of Leather and Footwear	157	1,759	85	71	2,202	121	85	−443	−37
19 Other Manuf. Prod. (including wood, cork and furniture)	978	10,996	540	448	7,431	520	531	3,566	20
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	623	2,341	334	189	2,922	223	434	−582	111
21 Manufacture of Rubber and Plastic Products	30	621	16	38	8,819	142	−8	−8,198	−126
22 Construction	0	0	0	876	3,657	152	−876	−3,657	−152
23 Recycling, Recovery and Repair Services	27	137	24	49	1,779	44	−22	−1,642	−20
24 Wholesale and Retail Trade	18	86	9	391	1,105	51	−374	−1,019	−42
25 Hotel and Restaurant Services	72	212	40	605	1,668	209	−534	−1,456	−168
26 Land Transport and Transport Via Pipeline Services	48	482	24	32	1,428	39	16	−945	−15
27 Water and Air Transport Services	151	1,938	75	19	2,375	86	132	−437	−11
28 Supporting and Auxiliary Transport Services	36	419	18	13	844	38	24	−425	−20
29 Post and Telecommunication Services	21	248	10	14	680	23	7	−432	−13
30 Financial Intermediation Serv. (except insurance & pension...)	0	0	0	7	456	21	−7	−456	−21
31 Insurance and Pension Funding Services	9	157	5	19	4,120	186	−10	−3,964	−181
32 Real Estate Services and Other Renting Services	332	3,617	157	131	839	37	201	2,778	120
33 Education and R & D Services	0	0	0	44	242	12	−44	−242	−12
34 Health and Veterinary Market Services	0	0	0	103	1,469	41	−103	−1,469	−41
35 Other Services (Market and Non-Market)	2	40	1	139	1,408	50	−137	−1,368	−50
36 Public Administration Non-Market Services	0	0	0	184	916	39	−184	−916	−39
Total	**7,560**	**85,977**	**4,427**	**8,590**	**128,660**	**6,732**	**−1,030**	**−42,683**	**−2,305**

Table 28.10 Waste Flows attributed to Domestic Final Demand

unit: 10^3 tonnes of waste; tonnes of hazardous waste

	Total waste flows by the Port. economy			- Waste flows attrib. to prod. of final demand for exp.			= Total waste flows attributable to domestic final demand								
	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Relat. dist. of SW by sector (%)	Dist. of SW by sector rank.	Hazardous waste	Relat. dist. of HW by sector (%)	Dist. of HW by sector rank.	Landfilling consumtpion	Relat. dist. of LC by sector (%)	Dist. of LC by sector rank.
	$q_p=r'(I-A)^{-1}y + r_y Z y$	$h_p=o'(I-A)^{-1}y + o_y Z y$	$l_p=p'(I-A)^{-1}y + p_y Z y$	$q_X=r'(I-A)^{-1}y_X$	$h_X=o'(I-A)^{-1}y_X$	$l_X=p'(I-A)^{-1}y_X$	$q_D=q_P-q_X$			$h_D=h_P-h_X$			$l_D=l_P-l_X$		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)=(1)+(4)			(8)=(2)+(5)			(9)=(3)+(6)		
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	6,020	11,108	4,389	740	1,573	528	5,280	12.8	3	9,535	4.1	12	3,861	17.6	2
04 Mining and Manufacture of Coal By-Products	2	8	2	2	7	1	1	0.0	34	2	0.0	34	1	0.0	34
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	39	2,574	22	24	1,625	14	14	0.0	33	950	0.4	24	8	0.0	33
06 Electricity Production, Transport and Distribution	294	10,804	126	13	473	6	281	0.7	17	10,332	4.4	9	120	0.5	19
07 Gas Production and Distribution	19	670	11	0	0	0	19	0.0	32	670	0.3	28	11	0.1	32
08 Water Supply	27	1,461	14	0	3	0	27	0.1	30	1,457	0.6	21	14	0.1	30
09 Extr. and Manuf. of Ferrous and Non-Ferrous Ores and Metals	384	2,116	307	326	1,797	261	58	0.1	26	319	0.1	32	46	0.2	23
10 Extraction and Manuf. of Non-Metallic Minerals	811	4,002	650	656	3,391	522	155	0.4	21	611	0.3	29	128	0.6	18
11 Manuf. of Chemicals and Chemical Products	269	15,449	148	121	6,946	67	148	0.4	22	8,503	3.7	13	81	0.4	22
12 Manufacture of Fabricated Metal Products	544	40,196	323	216	17,239	122	328	0.8	15	22,957	9.9	2	201	0.9	16
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	688	19,315	369	384	9,223	204	304	0.7	16	10,093	4.3	11	164	0.7	17
14 Manufacture of Transport Equipment	422	16,586	219	256	10,145	132	166	0.4	20	6,441	2.8	14	87	0.4	21
15 Manufacture of Food Products and Beverages	6,345	17,841	4,009	655	1,881	410	5,690	13.8	2	15,960	6.9	4	3,599	16.4	3
16 Manufacture of Tobacco and Tobacco Products	47	476	30	0	1	0	47	0.1	27	475	0.2	31	30	0.1	27
17 Manufacture of Textiles and Clothing	2,437	12,212	1,240	1,663	8,618	823	773	1.9	11	3,594	1.5	17	416	1.9	12
18 Manufacture of Leather and Footwear	235	2,636	127	157	1,759	85	78	0.2	23	877	0.4	26	42	0.2	24
19 Other Manuf. Prod. (including wood, cork and furniture)	1,552	17,260	862	978	10,996	540	573	1.4	13	6,263	2.7	15	322	1.5	13
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	1,434	3,592	929	623	2,341	334	811	2.0	10	1,251	0.5	22	594	2.7	8
21 Manufacture of Rubber and Plastic Products	286	15,697	239	30	621	16	256	0.6	18	15,076	6.5	6	224	1.0	15
22 Construction	11,930	31,621	4,531	0	0	0	11,930	28.8	1	31,621	13.6	1	4,531	20.6	1
23 Recycling, Recovery and Repair Services	668	3,368	577	27	137	24	641	1.5	12	3,231	1.4	18	553	2.5	9
24 Wholesale and Retail Trade	4,173	20,446	2,050	18	86	9	4,155	10.0	4	20,360	8.7	3	2,042	9.3	4
25 Hotel and Restaurant Services	3,474	10,312	1,965	72	212	40	3,403	8.2	5	10,100	4.3	10	1,925	8.7	5
26 Land Transport and Transport Via Pipeline Services	282	2,834	138	48	482	24	234	0.6	19	2,352	1.0	19	115	0.5	20
27 Water and Air Transport Services	175	2,241	86	151	1,938	75	24	0.1	31	303	0.1	33	12	0.1	31
28 Supporting and Auxiliary Transport Services	114	1,313	55	36	419	18	78	0.2	24	894	0.4	25	38	0.2	25
29 Post and Telecommunication Services	95	1,106	45	21	248	10	74	0.2	25	858	0.4	27	35	0.2	26
30 Financial Intermediation Serv. (except insurance & pension...)	41	1,093	19	0	0	0	41	0.1	28	1,093	0.5	23	19	0.1	28
31 Insurance and Pension Funding Services	41	686	20	9	157	5	32	0.1	29	529	0.2	30	15	0.1	29
32 Real Estate Services and Other Renting Services	1,730	18,862	817	332	3,617	157	1,399	3.4	7	15,245	6.5	5	660	3.0	7
33 Education and R & D Services	1,056	1,941	502	0	0	0	1,056	2.6	8	1,941	0.8	20	502	2.3	10
34 Health and Veterinary Market Services	924	12,233	451	0	0	0	924	2.2	9	12,233	5.3	7	451	2.1	11
35 Other Services (Market and Non-Market)	507	10,916	256	2	40	1	505	1.2	14	10,876	4.7	8	255	1.2	14
36 Public Administration Non-Market Services	1,878	5,756	895	0	0	0	1,878	4.5	6	5,756	2.5	16	895	4.1	6
Total	**48,940**	**318,732**	**26,425**	**7,560**	**85,977**	**4,427**	**41,380**	**100**		**232,755**	**100**		**21,998**	**100**	

(continued)

Table 28.10 (continued)

unit: 10[3] tonnes of waste; tonnes of hazardous waste	Tt. w.f. attrib. dom. final demand			+ Total waste flows attributable to imports			= Portugal's total waste flows responsibility								
	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Hazardous waste	Landfilling consumtpion	Solid waste	Relat. dist. of SW by sector (%)	Dist. of SW by sector rank.	Hazardous waste	Relat. dist. of HW by sector (%)	Dist. of HW by sector rank.	Landfilling consumtpion	Rela. dist. of LC by sector (%)	Dist. of LC by sector rank.
	$q_D=q_P-q_X$	$h_D=h_P-h_X$	$l_D=l_P-l_X$	$q_M=r'(I-A)^{-1}B(I-A)^{-1}y_D+r'(I-A)^{-1}y_M$	$h_M=o'(I-A)^{-1}B(I-A)^{-1}y_D+o'(I-A)^{-1}y_M$	$l_M=p'(I-A)^{-1}B(I-A)^{-1}y_D+p'(I-A)^{-1}y_M$	$q_R=q_D+q_M$			$h_R=h_D+h_M$			$l_R=l_D+l_M$		
	(7)=(1)+(4)	(8)=(2)+(5)	(9)=(3)+(6)	(10)	(11)	(12)	(13)=(7)+(10)			(14)=(8)+(11)			(15)=(9)+(12)		
01+02+03 Agriculture, Forestry, Fishing and Related Serv. Act.	5,280	9,535	3,861	948	3,377	668	6,228	12.5	3	12,912	3.6	12	4,529	15.8	2
04 Mining and Manufacture of Coal By-Products	1	2	1	0	3,796	575	1	0.0	34	3,797	1.1	24	576	2.0	13
05 Extr. of Crude Petroleum..., & Manuf. of Refined Petroleum Prod.	14	950	8	20	8,873	86	34	0.1	31	9,823	2.7	16	95	0.3	30
06 Electricity Production, Transport and Distribution	281	10,332	120	44	1,584	73	325	0.7	19	11,916	3.3	14	193	0.7	24
07 Gas Production and Distribution	19	670	11	4	4,162	101	23	0.0	33	4,832	1.3	21	112	0.4	27
08 Water Supply	27	1,457	14	5	1,514	43	31	0.1	32	2,971	0.8	28	57	0.2	33
09 Extr. and Manuf. of Ferrous and Non-ferrous Ores and Metals	58	319	46	14	4,840	416	71	0.1	27	5,159	1.4	19	463	1.6	16
10 Extraction and Manuf. of Non-metallic Minerals	155	611	128	72	2,540	179	227	0.5	22	3,151	0.9	26	307	1.1	21
11 Manuf. of Chemicals and Chemical Products	148	8,503	81	192	11,186	250	340	0.7	18	19,689	5.4	7	331	1.2	20
12 Manufacture of Fabricated Metal Products	328	22,957	201	210	8,176	393	538	1.1	16	31,133	8.6	2	593	2.1	12
13 Manuf. of Elect. and Non-Elect. Machinery and Equipment	304	10,093	164	338	8,594	271	643	1.3	15	18,687	5.2	8	435	1.5	17
14 Manufacture of Transport Equipment	166	6,441	87	345	16,007	322	510	1.0	17	22,448	6.2	4	409	1.4	18
15 Manufacture of Food Products and Beverages	5,690	15,960	3,599	2,328	4,848	848	8,018	16.0	2	20,808	5.8	6	4,447	15.5	3
16 Manufacture of Tobacco and Tobacco Products	47	475	30	40	436	68	87	0.2	26	911	0.3	34	98	0.3	28
17 Manufacture of Textiles and Clothing	773	3,594	416	658	4,367	406	1,431	2.9	8	7,961	2.2	17	822	2.9	8
18 Manufacture of Leather and Footwear	78	877	42	71	2,202	121	150	0.3	23	3,079	0.9	27	164	0.6	25
19 Other Manuf. Prod. (including wood, cork and furniture)	573	6,263	322	448	7,431	520	1,021	2.0	11	13,694	3.8	11	842	2.9	7
20 Manufacture of Pulp, Paper, Paper Prod. and Printing Prod.	811	1,251	594	189	2,922	223	1,000	2.0	12	4,174	1.2	23	817	2.8	9
21 Manufacture of Rubber and Plastic Products	256	15,076	224	38	8,819	142	294	0.6	20	23,895	6.6	3	365	1.3	19
22 Construction	11,930	31,621	4,531	876	3,657	152	12,806	25.6	1	35,278	9.8	1	4,683	16.3	1
23 Recycling, Recovery and Repair Services	641	3,231	553	49	1,779	44	690	1.4	13	5,010	1.4	20	597	2.1	11
24 Wholesale and Retail Trade	4,155	20,360	2,042	391	1,105	51	4,547	9.1	4	21,465	5.9	5	2,092	7.3	5
25 Hotel and Restaurant Services	3,403	10,100	1,925	605	1,668	209	4,008	8.0	5	11,767	3.3	15	2,133	7.4	4
26 Land Transport and Transport Via Pipeline Services	234	2,352	115	32	1,428	39	266	0.5	21	3,780	1.0	25	154	0.5	26
27 Water and Air Transport Services	24	303	12	19	2,375	86	42	0.1	30	2,678	0.7	29	98	0.3	29
28 Supporting and Auxiliary Transport Services	78	894	38	13	844	38	90	0.2	24	1,738	0.5	31	76	0.3	31
29 Post and Telecommunication Services	74	858	35	14	680	23	88	0.2	25	1,538	0.4	33	58	0.2	32
30 Financial Intermediation Serv. (except insurance & pension...)	41	1,093	19	7	456	21	47	0.1	29	1,549	0.4	32	40	0.1	34
31 Insurance and Pension Funding Services	32	529	15	19	4,120	186	51	0.1	28	4,649	1.3	22	201	0.7	23
32 Real Estate Services and Other Renting Services	1,399	15,245	660	131	839	37	1,530	3.1	7	16,084	4.5	9	697	2.4	10
33 Education and R & D Services	1,056	1,941	502	44	242	12	1,099	2.2	9	2,183	0.6	30	514	1.8	14
34 Health and Veterinary Market Services	924	12,233	451	103	1,469	41	1,026	2.1	10	13,701	3.8	10	492	1.7	15
35 Other Services (Market and Non-Market)	505	10,876	255	139	1,408	50	644	1.3	14	12,284	3.4	13	305	1.1	22
36 Public Administration Non-Market Services	1,878	5,756	895	184	916	39	2,062	4.1	6	6,672	1.8	18	934	3.3	6
Total	**41,380**	**232,755**	**21,998**	**8,590**	**128,660**	**6,732**	**49,970**	**100**		**361,415**	**100**		**28,730**	**100**	

In spite of the relatively significant figures for the waste flows resulting from non-domestic final demand (i.e., exports), the relative distribution by sector of the different waste flows only attributable to domestic final demand is not significantly changed from the one already offered concerning the total waste flows by the Portuguese economy (which includes non-domestic final demand as well). These results are indicative that the exports distribution by sector is closely related to the national economic structure.

The Portuguese total waste flows responsibility can also be decomposed to distinguish the relative significance of total waste flows attributable to domestic final demand and to the waste flows attributable to imports. According to the data presented in Table 28.10, of the waste flows for which the Portuguese economy is responsible, only 82.8% of the solid waste generation, 64.4% of the hazardous waste generation, and 76.6% of the landfilling consumption, had taken place on Portuguese territory, while the remaining waste flows occurred in the foreign countries from the which the Portuguese imports come.

Consistently, this study emphasises the major contribution to Portuguese waste flows responsibility that arises from Sector 22 (Construction), which confirms this sector as one of the most relevant solid waste generators in Portugal. Taking into account the increasing scarcity of landfill space, and the rising costs involved in modern solid waste management practices, and considering the amounts of solid waste generated by this economic activity, as well as the significant proportion of it that is landfilled, the potential for actions envisaging to increase prevention, re-use or recycling this particular waste category, are of enormous importance. However, until now the Portuguese national waste authorities have not given any particular attention to this waste stream, and relatively little is known about the nature or volumes of the flows concerned. The results presented in this study strongly suggest that this status should be changed, and detailed research should be carried out in Portugal on the waste arisings and practices within this sector, and their economic impacts, addressing, e.g., the relationships between its origins and characteristics. The results here presented additionally indicate that it would be interesting to evaluate whether, for certain components of construction waste, separate collection should be implemented.

Conclusions

In this research, an environmental input-output analysis has been implemented, based on an extended conventional input-output framework, to explore the economic and environmental significance of three major dimensions from waste generation and management processes, namely: solid waste generation, hazardous waste generation and landfilling consumption. This analysis combines, as explanatory variables for the global waste flows, the significance of each sector's economic size, with the related economic structures reflected in the waste flows intensity coefficients (concerning the inter-industrial structure and the final consumption patterns).

From the application of this environmental input-output waste model to Portugal, both direct consumption demand and direct plus indirect production demand effects of waste generation and landfilling consumption have been assessed.

A critical strength of the input-output approach lies in its ability to integrate different economic and environmental dimensions in one coherent model. For example, the structure of inter-industry relations (Block 1) and the structure and level of final demand (Block 3) were linked with total waste generation, hazardous waste generation and landfilling consumption. Such linking efforts would in themselves increase the awareness of environmental and socio-economic repercussions of economic activities.

The assessment of environmental waste flows attributable to goods traded internationally is a significant additional contribution of this study, to a more comprehensive analysis of waste generation and management implications from the domestic manufacturing, use and disposal practices. Therefore, it is appropriate to reflect on its meaning.

The allocation of a country's waste flows responsibility allows one to define the shares of responsibility, and hence the costs that should be attributed to different countries, and to individual sectors within those countries. This assessment is of crucial importance to a more transparent definition of the roles that should be played by the different economic actors (e.g., producers and users, enterprises and public authorities, researchers and education systems), in improving the overall sustainability of economies ('If you cannot (or have not) measured it, how can you manage or intend to change it?').

However, it is appropriate to emphasise that an important limitation of this modelling approach results from the considerable requirements for detailed and comprehensive data. The vast data sources used, and the simplifying assumptions considered, involve various levels of error. Therefore, the results here presented are intended to be only indicative of the broad trends for each industry, and final demand components, rather than exact estimates of the waste generation and landfilling consumption quantities. In future, with better information, greater accuracy could be achieved.

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Chapter 29
Environmental Household Accounts with Waste Discharge Using the Waste Input-Output Table

Ayu Washizu and Koji Takase

Introduction

It seems that there is a trade-off between our everyday life and ecology.

Japanese national energy consumption increased 3.4 times from FY1965 (1,085 peta cal) to FY2001 (3,676 peta cal). During the same period, household energy consumption increased by 4.9 times, from 107 to 522 peta cal (The Energy Data and Modeling Center (EDMC) 2003). One major cause of such a rapid increase in household consumption is electric appliances, that is household electricity consumption has increased 9.3 times from 24 to 227 peta cal; our convenient everyday life is based on increasing energy consumption, inevitably linked with ecological degradation. Therefore, when we talk about ecology, our lifestyle must also be reviewed in that context. Recently, UNEP (United Nations Environmental Programme) has proposed the concept of "Sustainable Consumption" besides "Sustainable Production." (United Nations Environmental Programme (UNEP) 2002) It says that sustainable consumption "is the final step in progressive widening of the horizons of pollution prevention," and that "action focused on consumption has highlighted the need to address the creation of new systems of production and consumption." Supplier's efforts towards ecological products will be meaningless if people do not use them and stick to their consumption habits.

In our life, there are several ways to do the same thing, but one of them can be more ecological than the others. However, no method has yet been developed to enable quantitative evaluation of the ecological effect of household activities. We need a methodology to analyze consumers' behavior.

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

In this chapter, we review our consumption life from the view of waste discharge. The approach from this view point has its own difficulties. A typical example is as follows: The final volume of general waste disposal decreased from 16.38 million tons in FY1991 to 10.51 million tons in FY2000, with the increase in the recycling ratio from 6.1% to 14.3%. However, the cost of waste disposal increased from 1.59 to 2.37 trillion yen during the same period. This means the cost of waste disposal per ton increased from 969,00 yen up to 225,600 yen (Japan Environmental Sanitation Center 2001). Can we say that the ecological issue regarding waste is getting better? Another example may be this. Some people say "the more convenient our living is, the more disposal goods we use and the more waste we emit," while others say "we spend more portion of income for service, and we emit less waste." Which is more likely to happen? These problems are somewhat complicated, because wastes emitted in various ways must be taken into account. The waste input-output table (WIO) originally developed by Shinichiro Nakamura provides a way for a quantitative analysis for such problems. (For the details of WIO, see Chapter 39.) Using the WIO we tried to evaluate the ecological effect of our everyday life concretely and quantitatively.

On the Conventional "Environmental Household Accounting (EHA)" in Japan

Environmental Household Accounting (EHA) is a method which enables the quantitative evaluation of the ecological effect of household activities. It was originally offered in early 1990s by engineers. Morioka and others developed the new computer software for consumers to self-check, self-evaluate, and self-improve the ecological effects of their lifestyle (Morioka et al. 1992). They say that it is insufficient only to recommend frugality in our ecological life, and that people have to more positively take the opportunities to choose our ecological lifestyles.

After the original invention of EHA, several institutions, including the Ministry of Environment, have developed their versions of EHA. According to the web-site of the ministry (Ministry of the Environment Government, Japan), there are now 31 kinds of EHA in Japan. They are classified into the following three types:

1. Those which list ecologically desirable activities for consumers
2. Those which express the ecological effect of consumers' activity numerically
3. And those which include both elements of 1 and 2

But all of them evaluate direct effect only, for instance how much electricity is saved, or how much waste is reduced or recycled.

However, there should be a way to indirectly save energy or waste generation, for instance by choosing a product which requires less energy or less waste emission to manufacture. For example, steel products made of recycled materials may use less energy or emit less waste than those made of new materials. Note that both kinds of steel products are almost equivalent for consumers, but their environmental loading to manufacture is much different from each other. Consumers must be conscious of the differences and choose the bundle of consumption goods that induce the least environmental loading to manufacture. But a limitation with the conventional EHA cannot incorporate such indirect environmental loading of consumption goods.

On the Life Cycle Assessment (LCA) of Consumption Goods

The Life Cycle Assessment (LCA) is a self-check system for manufacturers and it can estimate the ultimate environmental loading of each consumer product. By the LCA we can know the secondary and higher order ecological effects, or the effects from cradle to grave, induced by consumption goods. And in Japan input-output analysis is often used to carry out the LCA.

By combining the LCA method with the traditional (monetary) household accounting, we can incorporate the induced ecological effects into conventional EHA. An ordinary consumer enters the names of goods that he purchased in one column of his accounting book and then the expenditure value of the goods in the corresponding column. Suppose that he adds one more column and enters the ecological effects induced by his purchased goods, namely the ecological effects evaluated from the view point of LCA. Then he can know how many ecological effects were induced by his consumption activity. If he knows the total is somewhat large, he will reconsider his consumption activity.

We have multiple numbers of goods in the consumption basket, and we choose the bundle of goods to maximize the satisfaction we can achieve, given the limited budget available to us. Generally, keeping (traditional) household accounts to manage our expenditure is helpful for such maximization. But in order to achieve an ecologically efficient lifestyle, consumers will have to choose consumption goods considering not only budget constraints but also ecological constraints.

To think about such a problem, Hayami et al. (1996) have proposed “Ecological Household Accounting Using Environmental Input-Output Table (EHA using IO)”, which takes Japanese CO_2 emission as the index to evaluate ecological issues and applies input-output analysis to the evaluation of ecological effects from the view point of LCA. In this chapter, using the 1995 Waste Input-Output Table (WIO) (Nakamura 2003) we look at the same problem from the view of waste discharge, because the shortage of landfill is one of the most serious problems in Japan, which has limited space for that purpose.

Other studies have also analyzed the environmental load induced by household using input-output table and including information on household characteristics (Duchin 1998; Duchin and Lange 1994; Wier et al. 2001). These studies did from sociological point of view, while our study focused on rather technological problem.

The “Waste Score Table”

In this section we propose the use of a Waste Score for each product in order to keep EHA. The Waste Score is defined as the ultimate landfill volume induced by the consumption of 10,000 yen for each product. This score is obtained by WIO and the LCA index for the evaluation of the environmental loading of each commodity. The waste scores of all 80 products of WIO are listed in the “Waste Score Table” (see Appendix). Using this waste score table, the ordinary consumer can easily keep his EHA.

The calculation method of each waste score is as follows.

Nakamura and Kondo (2002) and also Chapter 39 presented the WIO quantity model as

$$\begin{bmatrix} \boldsymbol{x_I} \\ \boldsymbol{x_{II}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A_{I,I}} & \boldsymbol{A_{I,II}} \\ \boldsymbol{SG_{\cdot,I}} & \boldsymbol{SG_{\cdot,II}} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_I} \\ \boldsymbol{x_{II}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{X_{I,F}} \\ \boldsymbol{SW_{\cdot,F}} \end{bmatrix} \tag{29.1}$$

$\boldsymbol{A}$: matrix of input coefficients,
$\boldsymbol{G}$: matrix of net waste generation coefficients,
$\boldsymbol{S}$: allocation matrix the (i, j)-component of which refers to the share of waste j that is treated by treatment method i,
$\boldsymbol{X_{I,F}}$: vector of final demand goods,
$\boldsymbol{W_{\cdot,F}}$: vector of waste generated from the final demand sector.

Write $\boldsymbol{R_{\cdot,I}}$ and $\boldsymbol{R_{\cdot,II}}$ for matrices of emission coefficients of environmental loading factor. The vector of total emissions $\boldsymbol{e}$ is then given by

$$\boldsymbol{e} = \left[\boldsymbol{R_{\cdot,I}}\ \boldsymbol{R_{\cdot,II}}\right]\left(\boldsymbol{I} - \begin{bmatrix} \boldsymbol{A_{I,I}} & \boldsymbol{A_{I,II}} \\ \boldsymbol{SG_{\cdot,I}} & \boldsymbol{SG_{\cdot,II}} \end{bmatrix}\right)^{-1} \begin{bmatrix} \boldsymbol{X_{I,F}} \\ \boldsymbol{SW_{\cdot,F}} \end{bmatrix} + \boldsymbol{E_{\cdot,F}} \tag{29.2}$$

$\boldsymbol{E_{\cdot,F}}$ refers to direct emission from the final demand sector.

We extend this model to calculate waste score. The vector $\boldsymbol{Y_{(i)}}$ below represents household consumption of ith product or services. It has the consumption of the product itself in ith position, and the other cross-terms are zero, below which are added the margin and the freight to the market.

$$Y_{(i)} = \begin{pmatrix} 0 \\ \vdots \\ (Y_{(i)})_i \\ \vdots \\ 0 \\ \vdots \\ (Y_{(i)})_{m\arg in} \\ (Y_{(i)})_{freight} \end{pmatrix} \tag{29.3}$$

Here

$$(\hat{Y}_{(i)})_i = (Y_{(i)})_i + (Y_{(i)})_{m\arg in} + (Y_{(i)})_{freight} \tag{29.4}$$

The scalar $(\hat{\boldsymbol{Y}}_{(i)})_i$ means the Japanese consumption value of ith good expressed in purchaser's price.

Denote by $\boldsymbol{U}_{(i)}$ the vector of emission of environmental loading factor from the consumption of ith good, and by $\boldsymbol{F}_{(i)}$ direct emission which arise with the consumption of it. Then the household consumption of ith good $\boldsymbol{Y}_{(i)}$ induces emissions $\boldsymbol{Q}_i$, which is

$$Q_i = \begin{bmatrix} R_{.,I} & R_{.,II} \end{bmatrix} \left(I - \left(I - \begin{bmatrix} M_{I,I} & 0 \\ 0 & 0 \end{bmatrix} \right) \begin{bmatrix} A_{I,I} & A_{I,II} \\ SG_{.,I} & SG_{.,II} \end{bmatrix} \right)^{-1} \begin{bmatrix} Y_{(i)} \\ SU_{(i)} \end{bmatrix} + F_{(i)} \tag{29.5}$$

$\boldsymbol{M}$ is the import coefficient matrix, and here we use the Leontief inverse which takes account of leakage through import. $\boldsymbol{Q}_i$ represents the total emission of environmental loading factor directly and indirectly induced through consumption and production of each product or service. And the results can be regarded as LCA indices of waste emission resulting from consumption. There are several choices in how we evaluate the environmental loading factor emission, but in this study, we use the landfill volume that is needed for the disposal of the waste. And the corresponding element $(\boldsymbol{Q}_i)_{landfill}$ of vector $\boldsymbol{Q}_i$ shows total landfill volume directly and indirectly induced through consumption and production of ith good.

Dividing $(\boldsymbol{Q}_i)_{landfill}$ by the scalar $(\hat{\boldsymbol{Y}}_{(i)})_i$, we get the waste score of ith good, which is the induced landfill volume for 1 yen of consumption of ith good. We made such $\boldsymbol{Y}_{(i)}$ vectors for all goods and services, and calculated the induced waste emission per 1 yen of their consumption. (In the "Waste Score Table" we presented figures changed into induced landfill volume per 10,000 yen of consumption of goods and services.)

For further discussions about this model, see Takase et al. (2004).

Using the 1995 WIO, we have derived the "Waste Score Table" (see Appendix) in this way, whose typical results are summarized in Table 29.1 by consumption category of governmental statistics in "The Survey of Household Expenditure." The figures in the tables show how many liters of landfill volume are induced by 10,000 yen of expenditure for each product or service. For example, 10,000 yen of expenditure for eggs and milk induced direct and indirect wastes corresponding to 10.9 l of landfill volume. Minus 4.8 l of landfill volume for vegetables and fruits might sound rather strange, but what it says is that consumption has provided a market for compost, and reduced the direct disposal of agricultural waste.

These minus figures in Table 29.1 show the important features of WIO. In WIO, the rows of wastes describe the physical balance of waste emission and its disposal. Recycling is treated as a negative quantity in the disposal row. In ordinary IO analysis, negative quantities are difficult to explain; however, in WIO, negative quantities as a result of computation imply that there are some inducements for recycling activities.

Table 29.1 Waste Score Table (Unit: liter per 10,000 Yen)

1. Food	
Eggs and dairy products	10.9
Eating and drinking places	2.0
Foods	1.9
Beverages	1.8
Fishery	1.3
Mushrooms	1.1
Vegetables and Fruits	−4.8
2. Housing	
Gravel and crushed stones	24.0
Metal products for repairs	8.5
Cast and forged steel products	4.2
Clay	2.9
Tatami mats	2.1
Plastic products for repairs	1.6
Glass products for repairs	−1.2
Misc. stone and clay products for repairs	−2.6
Non-ferrous metal castings and forgings	−7.2
Rolled and drawn aluminum for repairs	−24.8
Cement	−131.4
3. Fuel, light and water charges	
Heat supply	38.0
Sewage disposal	15.5
Water supply	5.4
Electric power	4.4
Coal	2.9
LPG and kerosene	2.3
Coal products	1.6
Gas supply	1.4
4. Furniture and household utensils	
Tissue	17.1
Gas rings and stoves	8.5
Furniture	2.1
Carpets	2.0
Refrigerators, washing machines, etc.	2.0
Wooden products for decoration	1.9
Plastic products for table	1.6
Sewing machines	0.8
Glass products for table	−1.2
Enameled ware	−2.6
Tinfoil	−24.8
5. Clothes and footwear	
Texture and thread	2.0
Rubber shoes	1.9
Leather shoes	1.4
Textile clothes	1.1
6. Medical care	
Paper diapers	17.1
Medicines	2.5
Textiles for hygiene	2.0
Medical services	1.0
Glasses	0.9
7. Transportation and communication	
Boats and bicycles	16.3
Passenger motor cars	6.8
Motorcycles	6.3
Gasoline and light oil	2.3
Railway transport	1.0
Repair of motor vehicles	0.8
Road transport	0.7
8. Education	
School textbooks	4.7
9. Reading and recreation	
Notebooks	17.1
Pets	10.9
Newspaper and magazines	4.7
Paper and paperboard	4.3
Stationery	2.1
Televisions and Stereos	2.0
PCs and word processors	0.8
Garden plants	−4.8
10. Other living expenditure	
Cosmetics	2.5
Wholesale trade	0.7
Retail trade	0.6
Bags	1.4
Public administration	0.5
Other non-ferrous metals	−3.0

According to Table 29.1, the waste scores of livestock and related products, mining products, heat supply, sewage disposal, paper products, passenger motor cars, and boats are large. However, the scores of vegetables and fruits, cement, metal products show negative quantities. In the production process of these products, there are large inducements for recycling activities.

All waste scores are provided in the Appendix, by the sector of WIO.

Induced Waste Emission from Household Consumption

In this section we combine our "Waste Score Table" with Japanese household consumption data and show how much landfill volume on average is induced from per capita consumption expenditure, based on the statistics of 1995.

Figure 29.1 shows the induced landfill volume per capita per year consumption classified into the ten categories of the household survey, calculated using the 1995 WIO. The consumption expenditure per capita is 2.1 million yen, and this expenditure induced 285 l of landfill volume. Among them the expenditure for foods and transportation induced a large landfill volume, 25% and 26% respectively. This is because the consumption of food and the disposal of private cars produce a large waste emission.

Let us compare this result with our previous study which examined the induced CO_2 emission per capita consumption. Figure 29.2 shows the induced CO_2 emission per capita consumption classified into the eight consumption categories of the System of National Accounts (SNA). According to Fig. 29.2, the induced CO_2 emission was calculated to be 5.2 t per capita. Among the eight categories in the graph, the expenditure for fuel, light and transportation induced the largest CO_2 emission, 30% and 26% respectively. The induced emission from food expenditure is relatively small, 14%. Therefore, for reduction of the CO_2 emission from household consumption, energy saving is of primary importance. However, as we saw in Fig. 29.1, if we use a different measure for minimizing landfill volume, we get a different view.

Figure 29.3 shows the result when Fig. 29.1 is further divided into various consumption goods. It shows that per capita consumption of processed foods has induced 45.5 l of landfill volume directly and indirectly. 29.1 l out of 45.5 are the "direct effect," which means that waste discharge accompanied with a person's consumption of processed foods needed 29.1 l of landfill volume. The remaining 19.4 l out of 45.5 show the "indirect effect," namely the landfill volume which is needed by wastes emitted in the production stage of processed foods and their materials. In the case of beverages, feeds and tobacco, the direct effect is 33.8 l whereas the

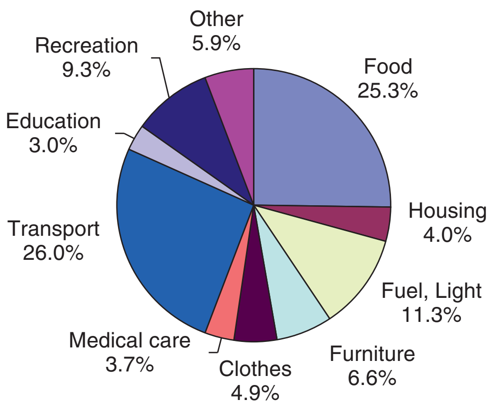

Fig. 29.1 Induced Landfill Volume from Household Consumption (285.3 l Per Capita)

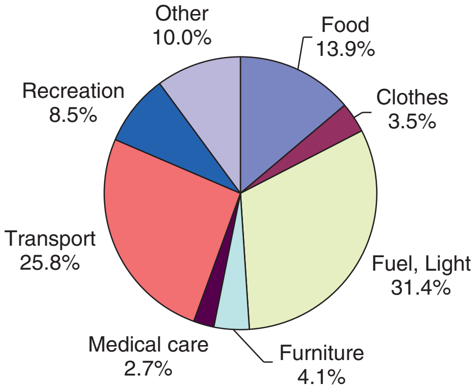

Fig. 29.2 Induced CO_2 Emission from Household Consumption (5.24t-CO_2 Per Capita)

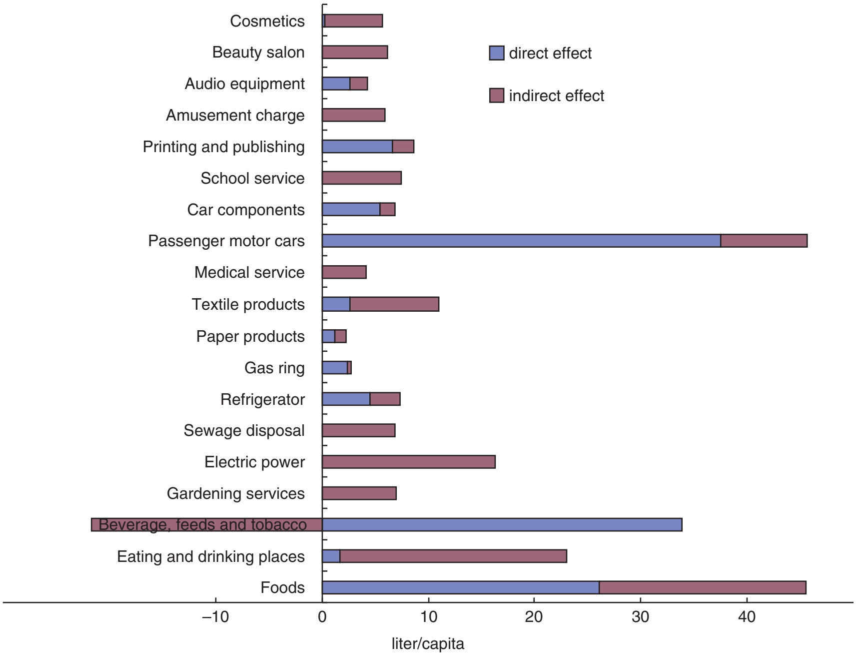

Fig. 29.3 Induced Landfill Volume from Per Capita Consumption

indirect effect is minus 17.1 l. This minus figure shows the recycling activity, such as composting, on the production process of beverages, feeds and tobacco.

Next, we combined our "Waste Score Table" with governmental statistics in "The Survey of Household Expenditure," and constructed the EHA using the WIO for a typical Japanese family. From that survey, we know the typical household's consumption patterns based on the nature of the householder, that is to say, based on the income bracket, the age bracket, and the residential area. We can calculate our EHA by such householder's property.

Figure 29.4 shows one of the results. Households in the high income brackets induced more landfill volume than those in the low income brackets. According to the governmental survey, households in the fifth bracket expended 2.1 times more than those in the first bracket. But this figure shows that they induced a landfill volume 1.7 times larger. The composition of landfill volume induced by households in the low income brackets is quite different from the one induced by households in the high income brackets. Three consumption categories, food, housing and medical care, induced a larger portion of landfill volume for households in the low income brackets than in the high brackets.

Figure 29.5 shows the result based on the householder's age bracket. According to this figure, households in the 40–44 years old bracket induced most landfill volume. It is because households in this age bracket have relatively large families on average 4.16 persons. The induced landfill volume per family member is 148.5 l for

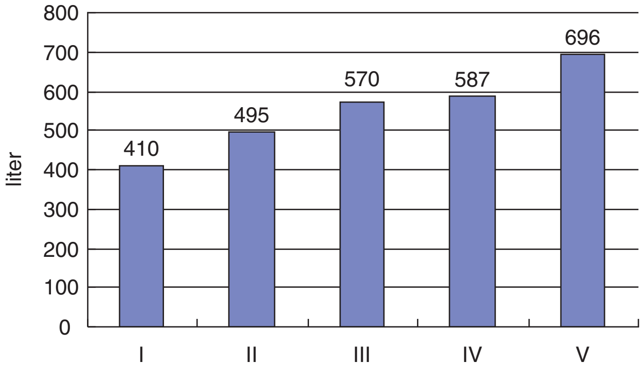

Fig. 29.4 Induced Landfill Volume per Household/Year by Income Bracket

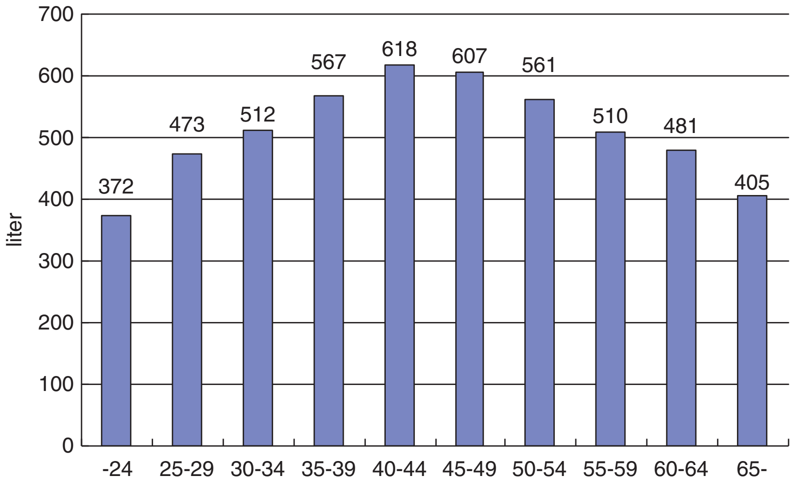

Fig. 29.5 Induced Landfill Volume per Household/Year by Age Bracket

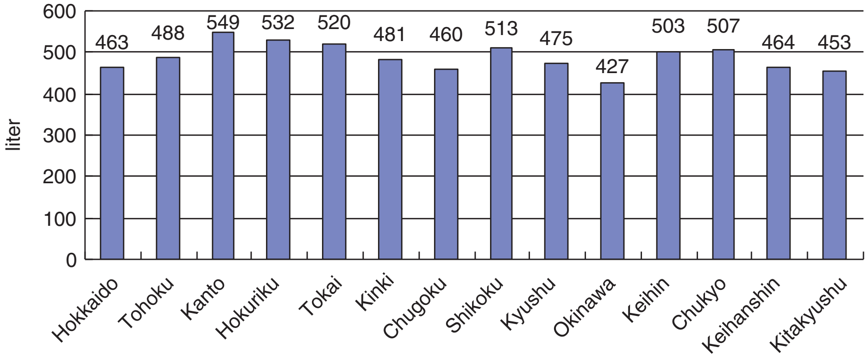

Fig. 29.6 Induced Landfill Volume per Household/Year by Region

households in the 40–44 year old bracket, compared to 175.4 l for the 60–64 year old bracket. As the householder's age is increased, the induced landfill volume per family member tends to increase.

Figure 29.6 shows the result based on region. Households in the Kanto (including the metropolitan area) and Hokuriku areas induced large landfill volume. This is attributable to the fact that they used cars more than in any other areas. The degree of motorization and the condition of public traffic system in each area may affect its induced landfill volume. Residents in the Kinki and Chugoku areas induced smaller landfill volume than others. In their case, a larger part of their total induced landfill volume is caused by expenditure for foods.

The Effects of Diversity of Lifestyle on Induced Waste Emission

In this section we discuss the effect of consumption diversity in our lifestyle on induced waste emission.

First, we show that individual's time allocation pattern has large effect on the induced landfill volume, based on time use survey in Japan. According to the governmental statistics, "the Survey on Time Use and Leisure Activities", we can know each person's time allocation pattern. In the survey individuals are classified according to age, marital status, usual economic activity (working or not working), occupation, usual working hours per week, and characteristics of their households, that is to say, family type (with child(ren) or not), usual economic activities of a married couple, type of residence, number of residence rooms, possession of car(s). This survey is conducted every 5 years, and we have been able to use 1996 survey. The survey shows that, for example, time allocation pattern of housewives who have small children is much different from them who have no children. Such variation in time allocation pattern will affect waste emission.

The first column of Table 29.2 shows the 20 types of activities in"The Survey on Time Use and Leisure Activities." And the second column shows the time allocation pattern of an average individual based on that survey. By re-classifying the average results of EHA according to type of activity in the time use survey (Box 29.1), we can obtain induced landfill volume per capita by the type of activity (which is presented in the third column of Table 29.2) and then the corresponding quantity per minute (which is given in the forth column). For example, the average individual spends 1.7% of his time "moving," and the "moving" is related to 17.7% of total landfill inducement. Thus we can calculate that a minute of "Moving" induced 3.11 l of landfill volume on average. This is because the average person often uses cars to move around. According to WIO the households' spending on cars induced much waste emission, including scrapped cars and various industrial wastes in the production process of cars. Assuming that the induced landfill volume per minute for each kind of activity is the same for every individual, we examined how the variation in time allocation pattern between individuals affects waste emission. However, because the assumption is too strict, we will have to adjust it in our future research.

Table 29.2 Induced Landfill Volume per Minute by Type of Activity

	Type of activity	Time allocation ratio (weekly average) (%)	Composition of induced landfill volume (%)	Induced landfill volume per minute (cm$^{3)}$
1	Sleep	32.4	19.6	0.18
2	Personal care	4.8	5.1	0.31
3	Meals	6.9	0.8	0.04
4	Commuting to and from school or work	2.3	0.6	0.07
5	Work	16.3	5.7	0.10
6	Schoolwork	3.1	3.5	0.34
7	Housekeeping	6.0	19.7	0.96
8	Nursing	0.2	0.5	0.64
9	Child care	0.8	2.7	1.03
10	Shopping	1.5	4.5	0.85
11	Moving	1.7	17.7	3.11
12	Watching TV, listening to radio, reading newspapers or magazines	10.6	5.5	0.15
13	Rest and relaxation	5.2	3.0	0.17
14	Study and research	0.8	0.6	0.21
15	Hobbies and amusements	2.5	1.8	0.21
16	Sports	0.9	1.4	0.44
17	Social activities	0.3	0.5	0.56
18	Social life	1.9	2.4	0.38
19	Medical examination or treatment	0.5	3.9	2.33
20	Other activities	1.4	0.6	0.13
		100.0	100.0	

Box 29.1 Time Use Survey in Japan

In Japan there are two surveys on time use. One is published by the government, and the other by Nippon Hoso Kyokai (NHK; Japan Broadcasting Corporation).

The governmental survey, "A Survey of Time Use and Leisure Activities," has the purpose of clarifying the actual state of people's social life in order to obtain basic data for several kinds of administrative measures. This survey has been conducted every 5 years since 1976, and the most recent one was done in 2001. In the 2001 survey, in addition to the traditional survey method (Questionnaire A: pre-coding system), a new method (Questionnaire B: after-coding system) was introduced in order to obtain more detailed results. About 77,000 households were selected, and about 2,000,000 household members 10 years old and above were surveyed.

The reports are published in this way:

<Questionnaire A>
Volume 1: Time Use for Japan
by individual property, such as sex, age, and economic activity
by family type of household
Volume 2: Leisure Activities for Japan
Internet use/Study and Research/Sports/Hobbies and Amusements/Volunteer Activities/Travel and Excursions
Volume 3: Time Use for Prefectures
Volume 4: Leisure Activities for Prefectures
Volume 5: Activities by Time of the Day for Japan and Prefectures
Daily Time Allocation by Time of the Day
Volume 6: Summary and Analyses
<Questionnaire B>
Volume 7: Time Use for Japan by Detailed Activity Coding

For the results of time use (Volumes 1 and 3), daily activities were classified into the 20 categories given in Tables 29.2 and 29.3, and time per day used for each category was reported. There are two measures for the average time use for each of the 20 activity categories: one is "average for all persons" and the other is "average for participants in the activity." The former is computed for all persons whether they did the activity or not, and the latter is for only the persons who did it. And such measures are prepared for weekdays, Saturday, Sunday, and a weekly average, as well as for each characteristic of individuals or households.

In Volumes 2 and 4 experiences for some selected leisure activities are reported. Frequency, purpose of activities, and the people involved are also surveyed.

For Questionnaire B, respondents recorded their activities for 15-min time slot. Their activities were classified into 62 categories, and the results were tabulated in Volume 7.

The NHK survey, "A Survey of Japanese Time Use" has been conducted every 5 years since 1960 and the most recent survey was for 2000. The purpose of this survey is to describe the Japanese life-style from the aspect of time use as basic data for broadcasting. The survey covered 45,120 Japanese people aged 10 and above and asked about their time use for activities which were classified into 28 items. The 28 items of surveyed activities are as follows:

Necessary Activities:

Sleep, Meals, Personal Chores, Medical Treatment or Recuperation

Obligatory Activities:

Work, Work-Related Association, Classes and School Activities, Learning Activities Outside School, Cooking, Cleaning, Laundry, Shopping, Caring for Children, Miscellaneous Housework, Commuting to Work, Commuting to School, Social Obligations

Free-time Activities:

Conversation/Personal Association, Exercise and Sports, Outings and Walks, Hobbies, Entertainment, Cultural Activities, TV, Radio, Newspapers, Magazines, Comic Books, Books, CDs, tapes, Videos, Rest

Other activities

The survey results have been averaged for weekdays, Saturday, Sunday based of sex, age bracket, occupation, and residential district. For 2000, the survey for each of the 47 prefectures, as well as national inquiry, has been also conducted.

Figure 29.7 shows the results. Individuals who work over 35 h per week induced less landfill volume than others. (In this calculation, however, the volume induced at the workplace is not included.) And younger housewives induced especially large volumes.

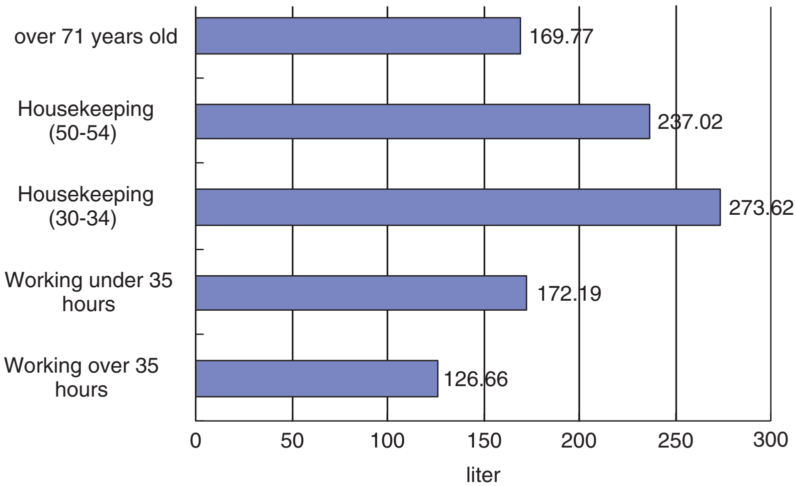

Fig. 29.7 Induced Landfill Volume Per Capita by Individual Property

Table 29.3 Induced Landfill Volume Composition by Individual Time Spending Category for Wives (%)

	Detached house	Condo-minium	Not working	Working	With kids (50–59)	With kids (30–39)
Sleep	13.78	12.51	11.21	17.02	13.90	11.62
Personal care	4.06	3.67	3.29	5.18	4.32	3.21
Meals	0.67	0.59	0.55	0.74	0.70	0.52
Commuting to and from school or work	0.18	0.19	0.00	0.64	0.20	0.13
Work	3.21	2.08	0.07	8.31	3.53	1.74
Schoolwork	0.00	0.00	0.00	0.00	0.00	0.00
Housekeeping	41.13	38.32	41.10	33.80	42.73	37.97
Nursing	0.68	0.50	0.63	0.30	0.71	0.29
Child care	3.66	7.35	10.20	3.46	0.39	14.99
Shopping	6.06	6.65	6.49	5.53	7.06	5.38
Moving	13.24	15.61	13.79	13.93	13.16	14.00
Watching TV, reading newspapers	3.69	3.40	3.50	3.29	4.12	2.58
Rest and relaxation	1.94	1.96	1.78	2.06	1.91	1.69
Study and research	0.19	0.34	0.21	0.19	0.20	0.19
Hobbies and amusements	1.07	1.07	1.10	0.70	1.07	0.65
Sports	0.62	0.70	0.56	0.50	0.73	0.53
Social activities	0.49	0.53	0.47	0.38	0.51	0.50
Social life	1.47	1.46	1.56	1.35	1.60	1.42
Medical examination or treatment	3.31	2.60	2.97	2.13	2.59	2.10
Other activities	0.55	0.45	0.52	0.48	0.59	0.50
Total induced landfill volume (liter)	205.51	224.11	253.50	163.71	198.69	243.05

Table 29.3 shows the breakdown of wives' induced landfill volume. According to the table, sleeping, housekeeping, child care and moving are the major activities inducing waste emission. The person who has a large waste emission spends longer time for these activities. For example, wives who are living in a condominium have induced more landfill volume those who are living in a detached house. This is because the former spend more time moving than the latter. And wives who are not working have induced a larger volume than working wives, because the former spend longer time for housekeeping and child care. Working wives induced a larger portion of the landfill volume by sleeping, but their induced total is not large. Furthermore, among the wives who have child(ren), younger ones (who are supposed to have small children) induced a large landfill volume, because they spend longer time for nursing.

Second, to examine the effects of diversity of lifestyle on induced waste emission, we have done a simulation analysis. In our simulation, we assume that on the whole 10% of Japanese give up using private cars and rely on the public railway system.

Table 29.4 Shifting of Transportation from Cars and Trains

WIO sector		Changes from the current consumption	
No.	Name	(Billion yen)	(%)
18	Petroleum refinery products	−242.90	−8.27
35	Passenger motor cars	−515.60	−10.00
36	Trucks, buses and other cars	−86.80	−10.00
45	Wholesale trade	−253.20	−1.37
46	Retail trade	−286.80	−0.90
47	Railway transport	714.10	20.25
48	Road transport	−11.80	−0.17
49	Other transport and communication	−9.00	−0.10
52	Repair of motor vehicles	−278.70	−10.00
		10^3 t	
	Scrapped cars from households	−502.00	−10.00

According to the governmental statistics in "The Trend of Traffic (Ministry of Land, Infrastructure and Transport)," in 1995 Japanese demand for car transportation was 820 billion persons-kilometer, while the demand for railway transportation was 400 billion persons-kilometer. The 10% of car transportation (82 billion persons-kilometer) was equivalent to 20.5% of railway transportation (82/400 = 20.5%). As a result, such changes affect the household consumption vector of WIO in the way showed in Table 29.4. Our simulation results show that by shifting from private cars to the public railway system or by the changes of consumption pattern showed in Table 29.4, Japanese induced landfill volume is reduced $633,000\mathrm{m}^3$ in all, or 5 l per capita (see Hayami et al. 1996 for details).

The Effects of Technological Change on Induced Waste Emission

We also examined the effect of technological change. Nakamura and others have developed a linear programming model using the WIO (WIO-LP model) and calculated the effect of technological optimization. They consider the five technologies for production of iron, steel, copper, aluminum, and glass products. And also they consider two waste management strategies for incineration plants and shredding methods. Then they have used the WIO-LP model and provided the least-CO_2-emitting or least-landfill-demanding technologies/strategies (see Kondo and Takase 2003; Nakamura and Kondo 2004 for details).

The question we have is how the technologies/strategies affect our waste scores of goods and services. Is the combination of technologies for minimum CO_2 emission the same as that for minimum landfill demand?

Figure 29.8 summarizes the results. The waste scores of many goods and services diminished as a result of minimizing induced CO_2 emission or landfill demand, while some of them increased. Thirty-two of 80 waste scores increased in the case

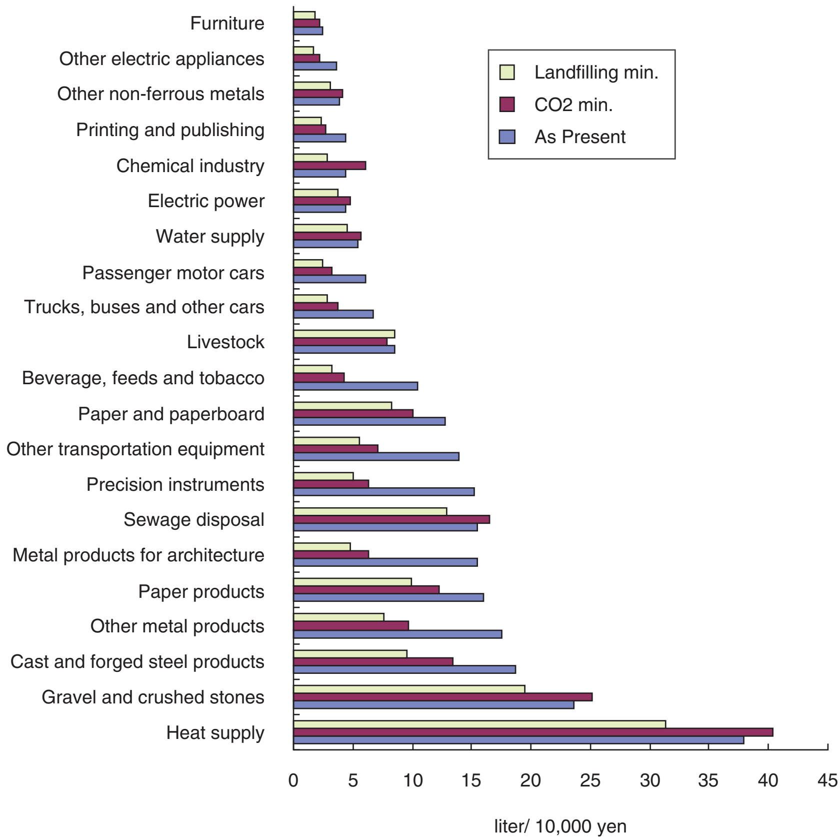

Fig. 29.8 Waste Scores Under the Alternative Technologies

of CO_2 minimizing and 7 waste scores in the case of landfill minimizing. Examples of the former are heat supply, gravel and crushed stones, sewage disposal, and an example of the latter is general machinery. For 27 waste scores such as heat supply, electric power, and chemical industry, the direction of changes by CO_2 minimizing is the opposite to that by landfill minimizing. The technologies/strategies for minimum CO_2 and minimum landfill do not always seem compatible.

Concluding Remarks

This chapter can be summarized as follows:

- We proposed the use of "landfill volume" as an indicator of the waste emission from consumption of various goods and showed the "Waste Score Table."
- We evaluated each household's or person's consumption activity using the indicator and recommended keeping on "Environmental Household Accounts (EHA)."

- We have shown the effects of technological change and lifestyle shifting on waste emission.

Now is the time when we must reconsider our lifestyle from the viewpoint of environment. Our EHA may be one of the most useful analytical tools for that purpose. We hope that the EHA will not only be used for academic purposes but also come into wide use in the near future.

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Appendix

Table 29.5 The Waste Score by Sector of WIO (Unit: liter per 10,000 Yen)

	Sector name of WIO	Waste score	Item examples
1	Agriculture (excl. livestock)	−4.80	Vegetables, fruits, flowers
2	Livestock	10.85	Eggs, airy products, pets
3	Forestry	1.15	Mushrooms
4	Fishery	1.31	Fish
5	Materials for ceramics		
6	Gravel and crushed stones	24.04	
7	Other mining	2.90	Clay, coal
8	Foods	1.89	Foods, supplements
9	Beverage, feeds and tobacco	1.78	
10	Textile	2.04	Carpets, cloth, thread, bandages
11	Textile products	1.11	Bedclothes, clothes
12	Timber and wooden products	1.88	
13	Furniture	2.07	
14	Pulp		
15	Paper and paperboard	4.27	
16	Paper products	17.07	Tissue, paper diaper, packages
17	Printing and publishing	4.69	Text books, newspapers
18	Chemical fertilizer	0.06	
19	Chemical industry	2.48	Salt, soap, medicine, cosmetics,
20	Petroleum refinery products (inc. greases)	2.32	Kerosene, lubricants, gasoline
21	Coal products	1.61	
22	Paving materials		
23	Plastic products	1.65	Tableware, toys
24	Rubber products	1.88	Boots, tires, erasers
25	Leather and fur products	1.35	Shoes, bags
26	Glass products	−1.24	Window glass, tableware
27	Cement	−131.43	
28	Misc. stone and clay products	−2.62	Brick
29	Pig iron		
30	Ferroalloys		
31	Crude steel (converters)		
32	Crude steel (electric furnaces)		
33	Hot rolled steel		
34	Steel pipes and tubes		
35	Cold-finished and coated steel		
36	Cast and forged steel products	4.23	Pipes
37	Other steel products		
38	Copper		
39	Lead and zinc (inc. regenerated lead)		

(continued)

Table 29.5 (continued)

40	Aluminum (inc. regenerated aluminum)		
41	Other non-ferrous metals	−3.01	Gold
42	Electric wires and cables		
43	Optical fiber cable		
44	Rolled and drawn copper and copper alloys		
45	Rolled and drawn aluminum	−24.80	Foil
46	Non-ferrous metal castings and forgings	−7.15	Pipes, leads
47	Nuclear fuels		
48	Other non-ferrous metal products		
49	Metal products for construction		
50	Metal products for architecture	−0.15	
51	Other metal products	8.47	Gas rings, stoves
52	General machinery	0.83	Sewing machines, calculators, copying machines
53	Household electric appliances	1.95	Refrigerators, washing machines, TV sets
54	Other electric appliances	0.76	Electric bulbs, PC
55	Passenger motor cars	6.78	
56	Trucks, buses and other cars	6.32	
57	Other transportation equipment	16.27	Boats, bicycles
58	Precision instruments	0.93	Clocks, watches, glasses, cameras
59	Misc. manufacturing products	2.14	Tatami, vacuum bottles, stationeries, umbrellas
60	Construction		
61	Civil engineering		
62	Electric power	4.45	
63	Gas supply	1.44	
64	Heat supply	37.96	
65	Water supply	5.38	
66	Sewage disposal	15.48	
67	Wholesale trade	0.72	
68	Retail trade	0.62	
69	Railway transport	0.96	
70	Road transport	0.66	Bus, taxi
71	Other transport and communication	0.53	Air or water transport
72	Public administration	0.50	
73	Scientific research institutions		
74	Medical service	1.04	
75	Repair of motor vehicles	0.82	
76	Repair of machine	0.41	
77	Eating and drinking places	2.04	
78	Other services	0.40	Housekeeper, beauty shop, health facilities
79	Office supplies		
80	Activities not elsewhere classified	0.06	

Part VIII
National Accounts, Statistics and Databases

Chapter 30
SEEA-2003 and the Economic Relevance of Physical Flow Accounting at Industry and National Economy Level

Ole Gravgård Pedersen and Mark de Haan

This year the international handbook on integrated Environmental and Economic Accounting (SEEA-2003) will be published. This handbook provides a detailed overview of environmental accounting approaches that have been developed in parallel with the System of National (economic) Accounts. In addition to natural resource stock accounts, and environmental protection expenditure accounts, SEEA-2003 pays considerable attention to physical flow accounting. Expanding the national economic accounts with physical data sets facilitates the joint analysis of environmental and economic policy issues. This article discusses the main characteristics of national accounts-oriented physical flow accounting approaches and provides an overview of the kind of indicators they may put forward. Also the analytical advantages of national accounts oriented physical flow accounts are illustrated. The article is not an attempt to provide a comprehensive review of macro-oriented physical flow accounting approaches. For such reviews in this Journal we would like to refer to Daniels (2002) and Daniels and Moore (2002).

National Accounts and SEEA-2003

The System of National Accounts (SNA 1993) provides the world-wide internationally standardized macroeconomic accounting standards. The national accounts provide coherent and consistent data sets and indicators for economic policy analysis. However, the standard SNA-1993 is too restricted with respect to environmental research questions. Since environmental functions are in many cases available

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without direct monetary costs incurred to their users, monetary accounting will usually not reflect the social costs of depleting or deteriorating natural resources.

As a solution to this problem the international Handbook on Integrated Environmental and Economic Accounting 2003, commonly referred to as SEEA-2003, is developed as a coherent and comprehensive accounting framework for measuring objectively and consistently how environmental functions contribute to the economy and, subsequently, how the economy exert pressures on the environment. As a satellite accounting system, the SEEA-2003 extends the coverage of the SNA by way of several supplementary environmental accounting modules. Satellite accounting systems have also been developed in other fields of interest such as public health, transportation and tourism, but the SEEA-2003 represents probably one of the most well-developed satellite systems to SNA.

SEEA-2003 is jointly published by the EC/Eurostat, IMF, OECD, UN and World Bank and can be regarded as an international environmental accounting reference book for statistical offices, national governments and international organizations.

SEEA-2003 expands the system of national accounts (SNA 1993). This means that national accounts concepts and definitions are used as the basis for the environmental accounting in SEEA-2003. One big advantage of linking environmental statistics to the national accounts is the consistency and direct comparability of (physical-oriented) environmental indicators and mainstream (monetary-oriented) national accounts indicators. This is for example shown in the National Accounting Matrix including Environmental Accounts (NAMEA), one of the main building blocks of the SEEA-2003.

Although focus in this article is on the physical flow accounts it should be mentioned that SEEA-2003 includes, in addition to physical flow accounts, also accounts (in money terms) for environmental protection activities such as waste and waste water treatment, accounts for environmental taxes and subsidies and natural resource stock accounts. The system also presents valuation techniques for measuring in money terms environmental depletion of natural resources as well as degradation of nature assets and ways to adjust the national income figures of SNA for depletion and degradation (i.e. "green GDP"-type figures). Finally, SEEA-2003 describes various applications and uses of the environmental accounts and related modeling approaches.

The physical accounts of the SEEA-2003 specifically focus on the material, energy and spatial requirements and flows of production and consumption processes rather than on the consequences on the availability of natural resources and the services provided by the natural environment. There are at least two reasons for this. Firstly, policy decisions often primarily focus on changing the environmental consequences of human behavior by addressing the causes. This requires information on 'who is doing what?' Secondly, an accounting-wise description of changes in environmental assets, such as ecosystems or species, face limitations due to the multidimensional and non-linear nature of cause-effect interactions within the environmental sphere. If at all possible, changes in the state of such environmental assets can only be described by combining accounts with ecological models.

SEEA-2003's Basic Building Blocks

Physical Supply-Use Tables

SEEA-2003 distinguishes four main types of physical matter: natural resources, ecosystem inputs, products (e.g. classified by HS, SITC or CPC) and residuals.[1] *Ecosystem inputs* are substances withdrawn from ecosystems for purposes of production and consumption such as gases needed for combustion and production processes as well as air and water for living things. *Residuals* are the unintended and undesired outputs from production and consumption processes. They include the usual types of solid waste and emissions to land, air and water, but also all other materials left behind from production and consumption processes. Thus, surplus N and P from using fertilizers, road salt and grit are ultimately included in the residuals concept just as so-called dissipative flows from car brakes, erosion and corrosion of infrastructures. An important residual in terms of volume is water evaporation. Thus, the residual concept includes in principle all material outputs whether regarded harmful or not.

In order to categorize the origin and destination of flows, the SEEA-2003 distinguishes between the economy and the environment. The economy is divided into three main entities: *Producers* (e.g. classified by ISIC, NACE), *Households* (e.g. the Classification of Individual Consumption According to Purpose, COICOP) and *Capital*. The latter covers traditional economic assets (e.g. building and machines) but also other physical stocks like controlled landfills, which are still under the control of human beings. Capital related flows of residuals include for instance the disposal of capital equipment (scrap), leakages from landfills and infrastructure and waste stocked in landfills. A *Rest of the World* (ROW) entry is added to describe the physical interactions with foreign economies. These include airborne pollution transfers such as acid rain and pollution transferred via river systems, the cross-border transportation of (solid) waste and residuals transferred via internationally operating activities such as transport and tourism.

SEEA-2003 structures the presentation of physical flows in so-called supply (origin) and use (destination) tables. The structure of supply–use tables is shown by Tables 30.1 and 30.2. Ton is often used as the unit for the physical supply–use tables, but also alternative units (e.g. Joule for energy) can be applied.

The supply table shows the origin of flows while the use table shows their destination. At later stages in the process of accounting and analysis, the origin and destination of physical flows can be interconnected in so-called physical input-output tables described below.

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[1] HS Harmonized Commodity Description and Coding Systems – SITC Standard International Trade Classification – CPC Central Product Classification. SEEA-2003 contains a classification of assets and subsequently asset inputs (cf. SEEA-2003: Annex 2), material throughputs (Annex 3) and residual outputs (Annex 4). A detailed classification of material flows is an important precondition for indicating the wide variety of environmental impacts associated with different material flows.

Table 30.1 Schematic Outline of Supply Tables

		Industries 1 2 3 … n	Capital	Consumption 1 2 3 … c	Rest of the world imports	National environment	Total supply
Products	1 2 3 . . . p Total	Output by product and by industry			Imports by products		Total supply of products
Residuals	1 2 3 . . . r Total	Residuals generated by type and by industry	Scrap of capital goods Leakages from landfills etc. by residual type	Residuals generated by type and by household consumption groups	Residuals from non-residents on national territory and cross-boundary inflows		Total supply of residuals by type

Supply tables for products can be presented in physical (tons) or monetary units. Supply tables for residuals can be presented in physical units (tons, cubic meters, energy units, etc.

Table 30.2 Schematic Outline of Use Tables

		Industries 1 2 3 . . . n	Capital	Consumption 1 2 3 . . . c	Rest of the world exports	National environment	Total use
Natural resources	1 2 3 . . . n Total	Use of natural resources by type and by industry		Use of natural resources by type and by household consumption groups	Use of natural resources by type and by non-residents on national territory		Total use of resources by type
Ecosystem inputs	1 2 3 . . . e Total	Use of ecosystem inputs by type and by industry		Use of ecosystem inputs by type and by household consumption groups	Use of ecosystem inputs by type and by non-residents on national territory		Total use of ecosystem inputs by type

(continued)

Table 30.2 (continued)

		Industries 1 2 3 … n	Capital	Consumption 1 2 3 … c	Rest of the world exports	National environment	Total use
Products	1 2 3 . . . p Total	Use of products as intermediate inputs by products and by industry	Use of products for capital formation by products	Use of products for private consumption by household consumption groups	Exports by products		Total use of products (= total supply of products)
Residuals	1 2 3 . . . r Total	Absorption (reuse and treatment) of residuals by type and by industry	Accumulati-on of residuals in economy (e.g. controlled landfills)		Residuals generated by residents in the rest of the world and cross-boundary outflows	Residuals ending up in the national environment by type	Total use ("dis-appearance" of residuals) by type (=total supply of residuals)

Use tables for products can be presented in physical (tons) or monetary units. Supply tables for natural resources, ecosystem inputs and residuals can be presented in physical units (tons, cubic meters, energy units etc.)

For products the supply table shows the amounts of various products (e.g. animal and vegetable products, stone, gravel, energy, metals) supplied by domestic industries or imported from abroad. The use tables for products show how products are used by industries for intermediate consumption or, alternatively, for final consumption by government or households, as fixed capital formation or for foreign use (exports).

For each residual type (emissions to air and water and solid wastes) the supply table records how much each industry or household emits. In addition, the supply table records residuals originating from the capital stock (e.g. scrapping and leakages). The use table of residuals shows what happens to all residuals generated: whether these residuals have been re-absorbed and converted to other materials and substances, for example, in connection with waste treatment, whether they are accumulated within the economy, e.g. in controlled landfills or whether they have been disposed of in the environment. The system boundary between the economy and the environment refers to the extent to which materials can be regarded as being under the control or not of economic entities.

For each category, e.g. subsoil assets, non-cultivated biological assets, water, air, oxygen, the use tables for natural resources and ecosystem inputs show the extraction by industries, households and the rest of the world. Extractions by non-residents may occur, for example, when foreigners fish on national territorial waters. The supply of natural resources and ecosystem inputs are not shown explicitly.

Material Balances and Bookkeeping Identities

The accounting identities that structure the physical flow accounts in the SEEA-2003 are based on the material balance principle. This law on the conservation of mass states that 'what goes in must come out'. In the SEEA-2003 the material balance principle is applied to the various categories of flows as well as to the various entities.

For a physical *flow* of a given type or group of materials the material balance principle can be expressed as:

$$\textbf{Supply} \equiv \textbf{use} \text{ (or } \textbf{origin} \equiv \textbf{destination}\text{)}$$

So, the accounts reflect that total supply in mass terms must by definition correspond to the total use. An example from the Netherlands may illustrate this accounting principle for residuals. Table 30.3 shows the supply and use of acidifying and eutrophicating substances. These substances may first of all be emitted by Dutch residents (from industries, households and leakages from capital), however, they may also originate from the rest of the world, via both non-residents operating in the Netherlands, as well as by transfers into domestic territory via water and air. On the use side, part of the substances is reabsorbed by producers, or transferred to the rest of the world, while the remaining part accumulates on Dutch territory.

Table 30.3 Acid and Nutrient Pollution in the Dutch Physical Flow Accounts, 1997 (de Haan 2004: Table 3.1)

		NO_x	SO_2	NH_3	P	N
				1,000 t		
Supply	Emission by residents	701	236	188	100	1,034
	From the rest of the world					
	Non-residents in The Netherlands	41	12	–	–	11
	Transfer by surface water or air	60	70	22	15	313
	Total supply (origin)	**801**	**319**	**210**	**115**	**1,359**
Use	Absorption by producers (waste water treatment)				21	118
	To the rest of the world					
	Residents in the rest of the world	282	131	–	–	79
	Transfer by surface water or air	414	92	34	16	425
	Accumulation in the Netherlands					
	Acidification	108	96	176		
	Eutrophication				77	736
	Total use (destination)	**801**	**319**	**210**	**115**	**1,359**

For a given entity, e.g. a producer, a household or a capital stock, the material balance principle leads to the following identity:

$$\textbf{Total inputs} \equiv \textbf{total outputs} + \textbf{net accumulation}$$

In other words, what goes into a system is either accumulated in the system or leaves the system again as an output. In this case, the balance is based on an aggregation of different types of materials. Table 30.4 illustrates the application of this identity in the SEEA-2003.

Total material input of the *production* system equals 831 million tons. This breaks down to 442 million tons of products supplied and used for the production processes, 261 million tons of natural resources and 121 million tons of ecosystem inputs extracted by the industries from nature, and finally 7 million tons of residuals released but, subsequently, reabsorbed by the industries (for recycling and reuse after cleaning or processing). These 831 million tons of materials are transformed by the production system into 551 millon tons of products and 280 million tons of residuals. No accumulation enters the balance for production. This is due to the fact that accumulation is explicitly accounted for via the capital account. Similar balances are presented in the table for the other entities. In the case of households, the accounts include accumulation entries for consumer durables.

The presented identities can only be applied in the accounts when the underlying statistics are well developed and sufficiently cover both the input and the output side. In practice, data are often missing. This does not mean, however, that the balancing principle and the bookkeeping identities are without relevance. The identities can often be used to compare existing, and in some cases, contradictory pieces of

Table 30.4 Physical Input-Output Relationships for Economic Activities (SEEA-2003: Table 3.18)

	Inputs		Outputs
	(Million tones)		(Million tones)
Production			
Intermediate consumption of products	442	Output of products	551
Extraction of natural resources	261	Generation of residuals	280
Ecosystem inputs	121		
Re-absorption of residuals	7		
Total material inputs	*831*	*Total material outputs*	*831*
Capital formation			
Capital formation and changes in inventories	119	Generation of residuals	73
Waste to landfill sites (absorption of residuals)	26	Net material accumulation in the economy	72
Total material inputs	*145*	*Total material outputs*	*145*
Consumption			
Household consumption of products	39	Generation of residuals	48
Extraction of natural resources	2	Net material accumulation of products (consumer durables)	17
Ecosystem inputs	24		
Total material inputs	*65*	*Total material outputs*	65
Rest of the world			
Exports	101	Imports	150
		Net material accumulation of products in the rest of the world	−49
Total inputs of products to ROW	*101*	*Total outputs of products from ROW*	*101*
Residuals generated by residents in ROW	5	Residuals by non residents in national territory	6
Cross boundary flows to ROW	4	Cross boundary flows from ROW	8
Natural resources and ecosystem inputs to ROW	3	Natural resources and ecosystem inputs from the rest of the world	10
		Net accumulation of natural resources, ecosystem inputs and residuals in ROW	−12
Total inputs of natural resources, ecosystem inputs and residuals to ROW	*12*	*Total outputs of natural resources, ecosystem inputs and residuals from ROW*	*12*

The figures are fictitious and do not relate to any specific country.

information. Thus, the accounting principles are instrumental in checking data, to find erroneous data, to fill gaps in data and ensure a better quality of the information provided. In relation to this it should be observed that the accounting identities must hold at all levels, i.e. for the total economy level, for industry groups, for specific industries, for all materials and for specific products, natural resources and residuals.

Physical Input-Output Tables

While the two dimensional rectangular (product × industry) supply and use tables show separately the origin and destination of the flows, symmetric physical input-output tables (PIOTs) merge this information into one single square matrix (with either the dimensions product × product or industry × industry). Additional assumptions and techniques are required to convert physical supply–use tables into physical input-output tables. These assumptions are in fact the same as those underlying monetary input-output tables (cf. Commission of the European Communities 1993: Chapter XV; United Nations 1999). This conversion leads to an information loss since either the industry or product dimension disappears. However, it also adds information since an input-output table directly connects supply to use. This interconnected quantification of production chains presented in input-output tables serves various analytical purposes.

Table 30.5 shows an example of an industry-by-industry physical input-output table. A cell in the table shows the amount of material flowing from an activity/category, identified in the row headings of the matrix, to an activity/category identified by the column headings. For example, it shows that 121 million tons of products are transferred from agriculture, fishing and mining to manufacturing, electricity and construction.

Table 30.5 Physical Input-Output Table, Million Tons (SEEA-2003: Table 3.25)

			Industries				*Capital*	*Households*	*Row exports*	*Residuals*	*Accumulation*	*Total*
			I1	I2	I3	I Total	CF	C	X	R		
Industries	I1	Agriculture, fishing and mining	26	121	11	158	46	14	32	35	0	285
	I2	Manufact., electricity and construction	26	146	10	183	67	13	36	187	0	486
	I3	Services	0	1	0	1	0	0	0	58	0	60
	I	Total industries	53	268	21	342	112	28	69	280	0	831
	CF	Capital								73	72	145
	C	Households								48	17	65
	M	ROW imports	21	69	10	100	7	11	32	6	−52	104
	N	Natural resources	196	65	0	261	0	2	1			525
	E	Ecosystem inputs	15	81	25	121	0	24	2			268
		Absorption of residuals	0	3	4	7	26				0	40
		Total	285	486	60	831	145	65	104	406	37	

The figures are fictitious and do not relate to any specific country.

Physical input-output tables are equally established on the basis of material balance identities which means that total input (a column total) is by definition equal to total output (the corresponding row total). This input-output identity holds for each industry, household category, capital category or the rest of the world. For example, Table 30.5 shows that input of agriculture, fishing and mining equals 285 million tons. Subsequently, this industry delivers 158 million tons of products to (other) industries, and 46, 14 and 32 million tons to capital formation, households and exports correspondingly. Furthermore, this industry generates 35 million tons of residuals. In total, this amounts to 285 million tons of outputs which correspond to the total sum of inputs.

Complete physical input-output tables for national economies have, for example, been constructed by Stahmer et al. (1998) and Gravgård (1999).

PIOTs provide an interconnected picture of inter-industry flows. The physical input-output tables enable – based entirely on a physical representation – modeling and analysis of the physical flows and the economic activities lying behind these. Based on empirical results, Weisz et al. (2004: 53) concludes that monetary input-output tables cannot adequately approximate the physical interrelations of an economy and that PIOTs are to be preferred, for example, for the calculation of raw material equivalents of imports and exports. Furthermore, as shown by Gravgård (2004), physical input-output tables can be used to construct industry specific waste accounts based on the material balance principle. Experiences with the analytical use of physical input-output tables are still very limited. Alternatively, so-called hybrid input-output tables are often used. Examples of such applications are given below.

Comparison of SEEA-2003 and Economy-Wide MFA

Economy-wide material flow accounting (MFA) as defined in Commission of the European Communities (2001) and compiled by e.g. Steurer (1992), Adriaanse et al. (1997), Matthews et al. (2000) and Bringezu and Schütz (2001), are examples of accounting frameworks that are totally restricted to (1) the material exchanges across the boundary between the environment and the economy and (2) to the material inputs and outputs connected to international trade. In the latter system, the economic system itself remains basically a black box. Contrary to this, the physical supply–use tables and input-output tables of SEEA-2003 are used to address the physical flows *within the economy* (products) as well as the material flows *exchanges* of the economy with the environment. However, the SEEA physical accounts can be aggregated into an economy-wide MFA type of account for direct flows. This is illustrated in Table 30.6.

The SEEA-2003-based economy-wide MFA account is established on the basis of the following accounting identity:

$$\begin{gathered}\textbf{Natural resource extraction} + \textbf{imports}\\ \equiv \textbf{residual output} + \textbf{exports} + \textbf{net addition to stock (NAS)}\end{gathered}$$

Table 30.6 Economy Wide Material Flow Account[a] Based on SEEA-2003 (Table 3.24)

	Inputs	Outputs
	Million tons	
Economic sphere		
Imports of products	150	
Exports of products		101
Environmental sphere		
Subsoil deposits	238	
Non-cultivated biological assets	16	
Water	12	
Air (O_2, N_2)	142	
Residuals		
To air		211
To water	0.1	1
Solid waste	33	188
Material accumulation in the economic sphere/net application to stock (NAS)		89
Total Inputs /outputs	**591**	**591**

[a]This account differs from traditional Economy Wide MFA by including water end ecosystem inputs.

This accounting identity corresponds to the one underlying the economy-wide MFA system as published by Eurostat (Commission of the European Communities 2001: 60)

SEEA-2003 is totally restricted to the recording of *direct* physical flows, i.e. flows that are observable at the borderline of the economy and for which statistical observation is feasible. These accounts can, in principle, be constructed on the basis of resource extraction statistics, foreign trade statistics, production statistics, waste statistics and emissions inventories. Economy-wide MFA goes one step further, and includes *indirect* flows e.g. flows taking place outside the system in focus and the borders of the national economy. For example, the MFA indicator TMR (Total Material Requirement) does not only address physical inputs connected to imports and resource extraction but also certain physical flows in other countries that are the consequence of import flows. For example, indirect flows related to imports of minerals include the amount of resources, which are excavated but end up as wastes during mining and processing abroad. Those flows can only be estimated on the basis of data from other countries. In the SEEA-2003, those indirect flows are not part of the accounting framework itself, but are instead regarded as an analytical extension of the accounts. This is in fact completely in line with similar kind of recommendations made in the Eurostat MFA handbook to calculate indirect flows associated with imports and exports, using input-output techniques in the same way as embedded energy or pollution is usually being calculated (Commission of the European Communities: 2001 para. 3.54). In SEEA-2003, the notion of indirect flows is not necessarily restricted to the natural resource input side (as in MFA), but may also refer to pollution or any other use of the environment. Below, it is described how input-output tables extended with physical flow accounts can facilitate these kinds of analyses and also how input-output analyses can be combined with a SEEA-2003 breakdown of the MFA indicators.

Differences Between SEEA Physical Accounting and Conventional Environmental Statistics

Since SEEA-2003 is a satellite accounting system, it is based on national accounts definitions. For example, the national economy is defined in terms of economic activities under the control of resident units. These units may include persons, legal and social entities. A resident unit belongs to the national economy, in which it has a center of economic interest, that is, when it engages for a period of typically 1 year or more in economic activities on this territory (Commission of the European Communities et al. 1993: para. 14.12). Certain production and consumption activities carried out by resident units, including their environmental consequences, may however appear outside the national territory. This is, especially, the case for (international) transportation and tourism. Both activities may be performed on foreign territory, but are still part of the home economy.

Contrary to this, conventional environment statistics, especially emission inventories, often take a geographic view of the boundaries, irrespectively of the kind of economic activity which lies behind. Thus, pollution and solid waste data, as derived from conventional environmental statistics, must be adjusted to national accounts definitions and classifications before they enter the SEEA-2003 physical flow accounts.

The estimation of pollution according to the resident principle has at least two advantages. Firstly, all world-wide emissions are completely allocated to (the economies of) individual countries, taking fully into account emissions from international transport. Secondly, this total is consistent with macroeconomic indicators such as gross domestic product.

Whether the different accounting principles lead to very different numbers for the emissions depend on the country and type of emission in focus. For countries such as the Netherlands (cf. De Haan and Verduin 2000) and Denmark, these differences are big when it comes to international road transport, marine transport or aviation.

This is illustrated in Table 30.7, showing the Danish fuel consumption for water transport according to the SEEA-2003 principle as well as the IPPC[2] principle. Due to the inclusion of, especially, the emissions from fuel bunkered by Danish ships abroad the difference between the IPPC total for Danish water transport and the corresponding SEEA environmental accounting total is very large, not only when the difference is related to the activity itself, but also when seen in relation to the total Danish emissions. For SO_2 emissions, for example, the inclusion of this single item almost doubles the Danish SO_2 emissions.

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[2] International Panel of Climate Change.

Table 30.7 Danish Emissions from Water Transport[a] 2001 – Different Accounting Principles (Olsen and Jensen 2003)

	CO_2	SO_2	NO_3
	Million tons	1,000 t	
1. IPCC principle (fuel sold in Denmark for Danish port to Danish port transport)	**0.4**	**1.4**	**6.9**
2. Fuel sold in Denmark for Danish international sea transport	1.2	10.3	26.0
3. Fuel bunkered aboard by Danish ships	17.5	383.4	476.9
4. SEEA principle , Environmental accounting approach, $(=\mathbf{1}, +\mathbf{2}, +\mathbf{3}.)$[b]	**19.0**	**395.1**	**509.9**
4. as per cent of total Danish emissions (SEEA principle)	23%	93%	72%

[a]Including fishing.

[b]Bunkering in Denmark by non-residents for Danish port to Danish port transport should in fact be subtracted, but this amount is negligible.

Besides differences in measuring the total sum of environmental pressures of one country, another important difference relates to the classification of activities. Emission registers usually look at the technical characteristics of emission sources: e.g. stationary versus mobile; combustion versus other processes. In contrast, in the national accounts, production activities are classified by the (economic) characteristics of their main product or service output. For example, in traditional environmental statistics all transport is typically combined together, irrespective of which economic activity this transportation relates to. According to the SEEA approach, transport is carried out by households, by transport industries (as services) but also by various other industries (i.e. own account transport).

Aggregating Information: The Need for Consistency

One of the key strengths of accounting is that it provides information at various levels of detail in a coherent and coordinated way. Accounts may deliver detailed data sets to, e.g. researchers for analytical purposes as well as the so-called accounting aggregates used for policy evaluation.

Indicators may contribute to condensed and comprehensible information useful for target setting and score keeping. They allow for direct comparisons between different periods in time and between regions or countries. One advantage of defining and embedding indicators within accounting frameworks is the explicit exposure of definitions and concepts. A consistent representation of indicators *and* accounts undoubtedly improves the communication between different stakeholders: accounting aggregates or indicators provide the main messages while on a more detailed level the accounts deliver the statistical tools required for remedy evaluation.

The aggregation levels of data are presented together with their corresponding target groups by the so-called aggregation and information pyramid in Fig. 30.1. In

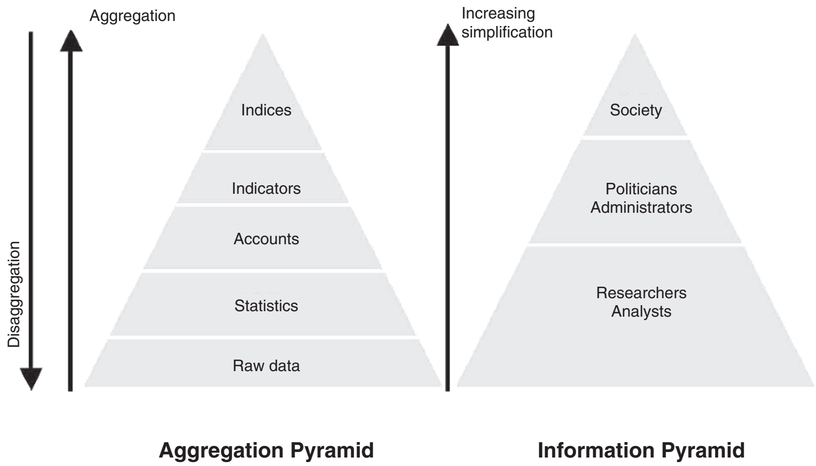

Fig. 30.1 Aggregation and Information Pyramids (Gravgård 2002)

the aggregation pyramid, information from raw data via statistics and various indicators are condensed to composite indicators or indices. The information pyramid shows that the provision of information at various levels serves different users with various backgrounds and interests.

Using an accounting structure is instrumental in ensuring *vertical consistency* (from the bottom to the top) because the strict definitions and identities of the accounts contribute to binding information at various levels together. The accounts provide users with the possibility of going deeper into the data structure underlying indicators targeting driving forces, pressures and responses. Also *horizontal consistency* is ensured by the accounting structure. This means, for example, that the monetary and physical indicators in the information system are consistent in such a way that it is meaningful to compare, e.g. indicators for the economy with indicators for the environment.

Environmental Pressure Indicators: Aggregation and Weighting

A comprehensive implementation of physical flow accounts may result in the recording of a wide range of materials and substances. As a consequence, communicating the results of physical flow accounts requires some degree of aggregation as indicated above by the pyramids. A fundamental question is how far information can reasonably be aggregated in a sensible way. Indicators such as pressure indices (Jesinghaus 1999), Ecological Footprint (Wackernagel and Rees 1996) and Total Material Requirement (Adriaanse et al. 1997) all attempt to aggregate the variety of material flows or environmental impacts of economic activities. It has been argued that the weighing and aggregation methods underlying these indicators are either rather arbitrary or less relevant from an environmental–economic perspective. There has been a lively debate about the soundness of such aggregate indicator approaches (cf. Van den Bergh and Verbruggen 1999; Kleijn 2001a).

In addition, this journal has published a range of articles discussing indicators that may show trends in de- or rematerialization (cf. Kleijn 2001b; Lifset 2000; Cleveland and Ruth 1999; Reijnders 1998). A repeated point of criticism found in these articles is that most indicators used for this purpose are rather imprecise with regard to the environmental threats that they are supposed to represent. This is, especially, problematic when using indicators addressing bulk material throughputs in the economic system. Cleveland and Ruth (1999: 41) refer to various authors who use material input measures as proxies for environmental impacts, assuming that "...a decrease in the amount of material – measured in tons – that is extracted, fabricated and consumed will decrease the amount of waste material released to the environment".

Obviously, a common unit of account (e.g. weights, energy contents) contributes to accounting consistency according to the material balance principle. However, introducing alternative accounting units may be instrumental in indicating some of the specific environmental characteristics of different kinds of material flows. Accounting units, other than mass or volume related units, may emphasize certain quality aspects of physical flows in relation to specific environmental problems. Potential environmental stress equivalents may indicate the average expected contribution of an individual pollutant to a particular environmental problem. These equivalents can be used for weighting and aggregating a wider range of substances into one environmental pressure indicator. As an example, Adriaanse (1993) developed for the Netherlands a comprehensive system of so-called "environmental theme indicators". These themes correspond to the key environmental problem fields identified in the Dutch national environmental policy plans. Examples of environmental stress conversion factors underlying these kinds of indicators are:

- The conversion of greenhouse gas pollutants into CO_2-equivalents
- The conversion of halogenated hydrocarbons contributing to ozone layer depletion into CFC-11 equivalents
- The conversion of sulfur, nitrogen oxides and ammonia into acidification equivalents, i.e. H^+ moles
- The conversion of nitrogen and phosphor pollution into nutrient equivalents, based on the ratio in which both nutrients appear under natural conditions
- The conversion of toxic pollutants on the basis of predicted no-effect concentrations and dispersion patterns in ecosystems or acceptable daily human intakes

Since Adriaanse, some additional work has, to some extent, been carried out to further develop this kind of aggregation methods, especially in the field of product based Life Cycle Assessment (cf. Udo de Haes et al. 1999; Goedkoop and Spriensma 2000; Guinée 2002). Udo de Haes et al. (1999) distinguish in this context two levels at which indicator aggregation can take place: midpoint indicators at the level of environmental problems (e.g. climate change, human toxicity) and end-point indicators at the level of specifically addressed damaged areas (e.g. human or ecosystem health).

Theme indicators are compiled on the basis of the expected damage of particular pollutants according to objective knowledge on cause-effect relationships. The range of resulting indicators explicitly underline the multidimensional character of environmental depletion and degradation, and the evaluation of these various concerns is explicitly acknowledged as a policy assignment. It must be emphasized that the theme indicators reflect the *potential* stress on the environment. Combinations of various stresses as well as spatial and timing conditions usually together determine the factual environmental consequences of pressures represented by the various theme-indicators.

Comparable Physical and Monetary Indicators

The combined physical and monetary accounts facilitate a composite use of physical and monetary indicators such as eco-efficiency indicators. These may be defined as output or value added generated per unit of energy or material used. Such ratio based indicators are quite similar to, for example, labor productivity measures. The numerators and denominators of such ratios should preferably be consistent and refer to the same population. However, this is often not the case. Examples may be domestic energy consumption as published in relation to most energy statistics. It measures the sales of fuels on the national territory, but this is – as illustrated by Table 30.7 above – not the same as the energy used by the resident companies and households, which together make up the entire economy as described in the national accounts. Therefore, there is an advantage of applying national accounts definitions and classifications to resource use and environmental pressure indicators as foreseen by SEEA-2003. A uniform application of accounting rules is an important precondition for achieving genuine comparability and horizontal consistency between monetary and physical indicators and concomitant indicator ratio's.

In general, combined monetary and physical flow accounts facilitate integrated environmental–economic performance monitoring. The accounts may help to show in what ways industries and households reduce or increase their environmental impacts in relation to their economic performance. The key policy question underlying this performance monitoring is, of course, the extent to which economic growth may coincide with reducing levels of environmental deterioration. The national accounts provide in this context the relevant economic growth measures, i.e.gross or net domestic product at national economy level, the value added at industry level and the consumption expenditure of households. The SEEA-2003 physical flow accounts supplement these mainstream economic measures with their corresponding physical counterparts

Especially on higher levels of aggregation with respect to activities or material flows, material throughput measures inevitably suffer from double counting. This is why national account aggregates such as total output (i.e. the total value of production in the domestic economy) and intermediate consumption (i.e. the sum value of all goods and services used in the course of production) are of limited economic significance. They do not serve as meaningful macroeconomic indicators. Intermediate consumption largely consists of unfinished products which may be transferred several times between different manufacturers. It is the *balance* between output and intermediate consumption that determines the value added or generated income of individual production activities. The sum of value added of all industries in an economy makes up gross domestic product, one of the most well-known indicators included in the system of national accounts.

Similarly, the difference between the total product outflow and product inflow in mass terms equals the balance of natural resource extractions and residual disposals. This analogy is illustrated in Fig. 30.1. This figure shows that the meaningful indicators, which physical flow accounts may put forward, should either address natural resource inputs directly withdrawn from the natural environment or the direct residual outputs. Both types of material exchanges, ultimately determine the state of the natural environment.

However, this does not in any way imply that the recording of material throughputs is irrelevant. Following a thermodynamic perspective, the natural resource inputs are connected to the residual outputs, and understanding the causalities between resource use and waste generation is an important precondition for cost-effective environmental management. The supply–use or input-output tables as represented in SEEA-2003 foresee in a systematic mapping of product flows, either in money or physical terms in such a way that the causalities can be analyzed.

Combining Physical and Monetary Flow Accounts in Environmental–Economic Analysis

In order to juxtapose the physical information in environmental accounts and the monetary information in the national accounts, so-called hybrid flow accounts can be used. The hybrid accounts are a pragmatic approach serving as a data framework for integrated economic–environmental analysis and modeling of the interactions between the economy and the environment. The hybrid approach combines consistently monetary information from the national accounts with selected parts of the physical supply–use tables for natural resources, products and residuals. The acronym NAMEA, National Accounting Matrix including Environmental Accounts, is often used for these types of tables. The NAMEA originates from the work developed by, for example, Leontief (1970), Victor (1972) and more recently, De Haan and Keuning (1996). This approach is now used in some form or another by many statistical offices for expanding the national accounts with information on the physical characteristics of production and consumption activities.

The physical flow accounts in the NAMEA primarily focus on the material transfers from and to the natural environment. Normally, the underlying physical flows of commodity transactions do not enter these accounts. Table 30.8 shows an example of a highly aggregated hybrid industry by industry input-output table. Monetary entries are shown in italics. In this case, the economic part comprises a monetary

Table 30.8 Hybrid Industry-by-Industry Input-Output Table – Currency Units (Italics) and Million Tons (SEEA-2003: Table 4.14)

		Industries				Capital formation	Final consumption	Row exports	Total use	Residuals
		I1	I2	I3	I Total	CF	C	X		R
						Currency units				Million tons
Industries	I1 Agriculture, fishing and mining	*19*	*97*	*14*	***130***	*31*	*3*	*66*	***229***	35
	I2 Manufact., electricity and construction	*28*	*206*	*30*	***264***	*204*	*63*	*159*	***690***	187
	I3 Services	*11*	*90*	*14*	***115***	*152*	*28*	*72*	***367***	58
	I Total Industries	***58***	***393***	***58***	***509***	***387***	***94***	***297***	***1,286***	280
	MROW Imports	*16*	*100*	*14*	***130***	*95*	*47*	*91*	*363*	6
	Taxes on products	*3*	*19*	*3*	***25***	*24*	*5*	*16*	*70*	
	Total final uses					*146*	*506*	*403*	*1,719*	
	Value added	*152*	*179*	*292*	***622***					
	Total production	***229***	***690***	***367***	***1,286***					
					Million tons					
	CF Capital formation									73
	CFinal consumption									48
	NNatural resources	196	65		261		2	1		
	EEcosystem inputs	15	81	25	121		24	2		
	Absorption of residuals	0.2	2.7	3.9	6.8	25.8				

input-output table including product deliveries between industries, product deliveries to final demand and furthermore taxes, value added and the value of total output. At the bottom of the table, *inputs* (in million tons) of natural resources and ecosystem inputs are shown, and at the right the total sum of residual *outputs* from the various industries and other economic entities are shown.

Hybrid accounts can be used as the data framework to derive eco-efficiency indicators and for analytical applications based on a hybrid input-output model. A number of applications are illustrated below.

Environmental Effects from Foreign Trade

Determining the total environmental consequences of consumption or international trade is one example of the way in which hybrid accounts can be used. Trade liberalization and the opening of domestic markets will generally increase shares of foreign supply in domestic commodity consumption as countries specialize according to their comparative advantages. As a result, the product composition of domestic output will increasingly differ from the product composition of domestic consumption, So-called ‘de-industrialization’ and transformation towards a services or knowledge-based economy has been considered a strategy to increase simultaneously social (employment) and environmental performance. However, sustainability on a worldwide scale is not improved when the specialization in services of some countries implies an increasing reliance on foreign supply of environmentally unfriendly products. For the global environment as a whole, this substitution may not be optimal, since pollution is principally ‘exported’ and not necessarily diminished. This implies that information about resource use and environmental impacts displaced via international trade, the so-called foreign indirect effects, is essential in appraising the environmental performance of an economy.

However, the direct mass flow coinciding with imports or exports is less relevant from an environmental impact perspective. What matters is the resulting environmental impacts. The so-called ‘environmental balance of trade’ determines for specific pollution types (or any other environmental requirement such as energy, a natural resource or the land disruptions resulting from mining operations) the balance of environmental requirements embodied in exports minus pollution embodied in imports.

An accurate input-output based modeling estimate of the environmental balance of trade requires knowledge about the production technology applied in countries from which imports originate. However, based on the assumption that the domestic production technology is representative of other countries as well, the domestic input-output model in the hybrid accounts can be used to obtain a first estimate of the indirect environmental impacts in foreign countries, displaced via imports to the country in question

Table 30.9 shows an example of such estimations for the Netherlands. The ‘environmental balance of trade’ (indicator II in Table 30.9 brings about a shift in focus from the producer oriented direct recording of environmental requirements

Table 30.9 Environmental Balance of Trade and Environmental Consumption, The Netherlands, 1997 (de Haan 2002)

	Co_2	No_x	So_2	NH_3	P	N
			1,000 t			
Emissions attributed to imparts	125,420	313	134	155	53	610
Emissions attributed to exports	155,850	521	239	181	73	854
II. The environmental balance of trade	**30,430**	**207**	**105**	**65**	**20**	**244**
I. Net emission by resident units	**201,020**	**701**	**236**	**188**	**78**	**917**
III. Environmental consumption (I–II)	**170,590**	**494**	**131**	**122**	**59**	**673**

(I) to the indirect recording or imputed environmental requirements to the final commodity consumption in an economy. The latter is labeled in Table 30.9 as 'environmental consumption' (III). This indicator also includes the direct environmental impacts from intra-household activities, such as own account transportation and house heating. Further, this indicator includes all pollution from foreign and domestic production processes that are attributable to domestic consumption. The significant amounts of pollution displaced by imports and exports reveal the highly open structure of the Dutch economy. These results underline the necessity to take into consideration import and export flows when analyzing the total environmental requirements of domestic consumption.

Indicator (I) in Table 30.9 principally results from direct statistical observation. The second indicator is determined by imputing pollution to the international trade (i.e. measuring the indirect effects). This imputation is accomplished by reallocating the environmental impacts from industries to their outputs and subsequently to imports and exports. The third indicator is calculated as the difference between the total emissions by residents and the environmental balance of trade. As such it represents a kind of environmental consumption of the residents, i.e. the emissions created globally as a result of the domestic final demand of the residents.

Material Use and CO_2 Emissions of Private Consumption

Hybrid input-output analyses can be used to rank and prioritize within environmental policy by assessing the whole upstream production chain and corresponding resource use and environmental pressures derived from the consumption of various products. To exemplify this, Table 30.10 shows an attribution of total material requirements, TMR[3] and CO_2 emissions to the Danish consumption of food. TMR is here used as an indicator for the resource inputs to show the link to MFA indicators. The approach can, of course, be used for specific types of resource inputs, for example, energy or metallic minerals.

[3] TMR is an economy-wide material flow indicator for the total amount of natural resources needed to feed the national economy with resources and imported products.

Table 30.10 TMR and CO_2 Emissions of Danish Private Food Consumption, 1997 (Gravgård 2002; Statistics Denmark (www.statbank.dk))

	Total material requirement, TMR		CO_2 emissions	
	Direct	Direct and indirect	Danish indirect emissions	Global indirect emissions
	1,000 t		Tons	
Private food consumption, total	3,800	22,709	2,598	4,670
Bread and cereals	186	1,989	385	657
Meat	2,365	8,941	670	1,084
Fish	44	315	98	221
Eggs	22	506	43	62
Milk, cream, yoghurt etc.	33	2,870	297	403
Cheese	182	1,256	139	220
Butter, oils and fats	202	1,098	104	170
Fruit and vegetables except potatoes	361	2,059	373	947
Potatoes etc.	116	464	56	94
Sugar	33	156	28	35
Ice cream, chocolate and confectionery	146	1,928	307	588
Food products n.e.c	111	1,127	97	189

Direct TMR of consumption is the TMR calculated for the specific products that are consumed. Direct and indirect TMR of a consumption group includes in addition all resource requirements related to the intermediate deliveries of supporting industries, for example, inputs such as energy and packing materials used during the processing and distribution stage. Production of these inputs requires further production in other industries, which again requires inputs and so on. For milk, cream, yoghurt, etc. and, to a lesser extent, also for eggs the input-output calculation shows a very large indirect TMR of the consumption. This result relies on the fact that a part of the large TMR of agriculture (biomass) is related to the domestic consumption of milk and eggs via the input-output calculations.[4]

This calculation approach does not affect the estimate of the national TMR, it only relates the TMR to the demand components and ensures that all relevant parts of TMR are attributed to the relevant products. Input-output modeling avoids double counting problems in the sense that no part of the total economy TMR is attributed to more than one type of consumption.

For CO_2 emissions related to consumption of food no direct emissions exist, only indirect emissions via the derived production in industries. Table 30.10 shows

[4] Probably, the calculations overestimate the direct and indirect TMR of dairy products and underestimate the direct and indirect TMR of, for example, meat consumption. This is due to the quite simplistic assumptions about constant scale – and proportionality between physical flows and monetary outputs – that are built into traditional monetary and hybrid input-output models.

both Danish and global indirect CO_2 emissions related to the Danish consumption of food. The Danish indirect emissions include all the emissions from Danish industries related to the entire upstream chain of production. The global indirect emissions include emissions generated by the upstream production activities abroad due to exports of food for direct consumption as well as all kinds of intermediate consumption by Danish industries related to the food consumption. The approach used here is the same as that used for the calculations of the environmental trade balance in the previous section.[5]

Similar examples of such analysis in a policy-oriented context are reported for example in Moll et al. (2004). It has also been suggested that input-output analysis can function as supplement to conventional life cycle assessment (LCA). Thus, Lenzen (2000) shows that conventional process based LCA might involve a truncation error of the order of 50%, since LCA is based on a bottom-up process analysis in which only a limited number of processes are included. Contrary to this, analysis based on input-output modeling can provide a rough, but a more complete estimate of the total resource use and environmental pressures created by the consumption.

Structural Decomposition Analysis

Another application of integrated sets of monetary and physical accounts is the so-called structural decomposition analysis based on input-output modeling systems. This method may help to quantify the underlying determinants of eco-efficiency or eco-productivity (the latter being defined as GDP per money unit of resource input or residual output) developments. Structural decomposition analysis quantifies several economic driving forces, which together determine the development of resource inputs or residual outputs over time. Figure 30.2 illustrates an example for the Netherlands derived from de Haan (2001). For the period 1987–1998, the bold line indicates the cumulated total annual percent change in CO_2 pollution from domestic production. The remaining three lines show how these annual changes are broken down according to the following three economic driving forces:

- Eco-efficiency effects (pollution per money unit of output)
- Structure effects (changes in the industry and household demand composition)
- Volume effects (volume growth of GDP)

Basically, two major forces have determined the development of CO_2 pollution over time. On the one hand, GDP growth strongly triggered CO_2 pollution. On the other hand, eco-efficiency improvements led to a downward movement. Structure effects such as shifts from manufacturing to services production were less strong.

[5] Since the global emissions are calculated on the assumptions that all production takes place with the same (average) technology as used in Denmark, the interpretation of the global emissions should rather be taken as what the emissions would have been in Denmark if all imports were produced in Demark with the given Danish technology.

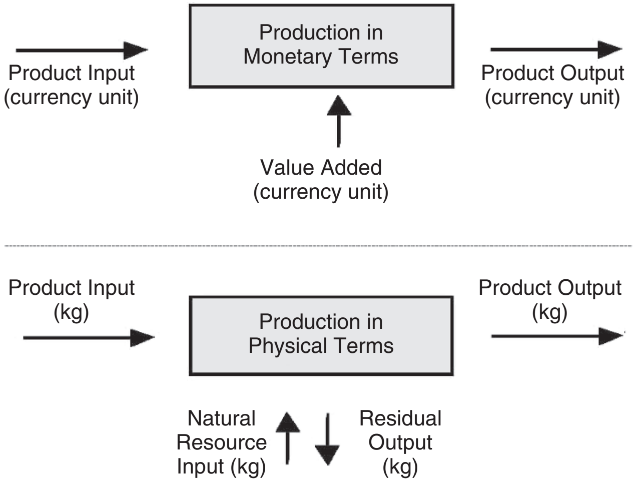

Fig. 30.2 Simultaneous Monetary and Physical Indicators (de Haan 2004: Figure 3.6)

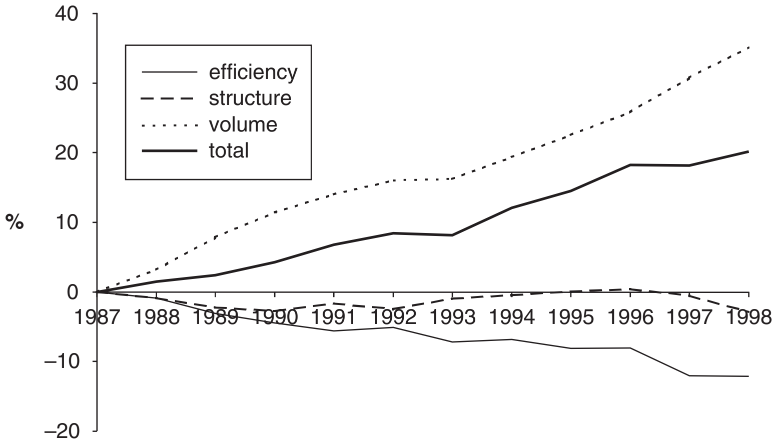

Fig. 30.3 Decomposition of Annual Changes in Production Related CO_2 Pollution in the Netherlands (de Haan 2001)

In general, structure related changes may have been somewhat underestimated due to the fairly condensed input-output tables used in the analysis. However, similar structural decomposition analysis (Olsen and Jensen 2003) for Danish air emissions based on a 130 industry by 130 industry input-output table also indicates that structure related changes in the period 1980–2001 were rather small (Fig. 30.3). Furthermore, the same conclusion is reached by Harris (2001). In spite of substantial efficiency gains of more than 12%, production related CO_2 emission increased between 1987 and 1998 by 20%. Without the eco-efficiency improvements and structure changes, pollution growth would have reached 35%.

Conclusions

Physical flow accounting is a fundamental step in understanding the interrelationships between the natural environment and the economic system. SEEA-2003 provides a comprehensive system for physical flow accounting based upon the definitions and concepts as laid down in the System of National Accounts. SEEA-2003 ensures a (horizontal) consistency in the description of the economic and monetary flows. This is in contrast to most other conventional systems for environmental information and emissions inventories. This article illustrated the benefits of physical flow accounting according to national accounts principles. Firstly, national accounts guidelines contribute to a sound attribution of pollution to individual economies. Secondly, this delineation contributes to a sound comparability of national accounts indicators and environmental pressure indicators and thus for the construction of eco-efficiency indicators and the analysis of the so-called decoupling of economic development and environmental pressures. The representation of physical flow accounts in a national accounts framework illustrates the economic relevance and dependencies on material exchanges. Furthermore, a consistent linkage of environmental and economic indicators guarantees a consistent comparison of environmental burdens to economic benefits, or environmental benefits to economic costs.

At the same time the use of an accounting structure ensures a (vertical) consistency in the sense that it is possible to move from one level in the information pyramid to another. When indicators derived from the accounts display certain interesting developments, it is possible to further analyze these developments in more detail based on the detailed information system provided by the accounts.

If a uniform physical unit (e.g. tons, PJ) is used when various physical flows are accounted for, aggregation of the flows is conducted without problems. The corresponding totals (total product weight imported, total SO_2 emitted and total energy used, for instance) are well-defined and easy to understand. Thus, using physical units avoid the problems of monetary valuation of natural resources and emissions, and difficulties with interpretations of indicators based on such valuations are also avoided.

However, controversies over the aggregation of physical flows also exist. Probably, the most controversial is the summing up of all physical flows in a few or only one number as found, e.g. in economy-wide MFA. The total flow of materials (total weight per year) is a meaningful and interpretable concept as such, but we doubt that this in itself indicates anything meaningful about the pressure on the environment, since for instance 1 kg of rather harmless sand is included in exactly the same way as 1 kg of hazardous chemical product. However, these aggregates seem to appeal to politicians and the public, and they have been useful in raising debates. We have shown that the SEEA-2003 physical supply and use tables provide most of the information for compiling MFA type of economy-wide measures. At the same time, it is emphasized in the paper that rigorous aggregation methods may ignore the fact that physical flows may bring about a wide variety of different environmental problems. Therefore, it is argued that alternative weighing schemes may in specific cases provide more meaningful indicators.

Finally, for reasons of transparency, consistency and analytical purposes, this article shows that such measures should preferably be derived from an accounting system. The national accounts provide a very good basis in this respect. A national accounts based physical flow accounting system allows for presenting and analyzing physical flows in connection to the underlying economic driving forces. This is illustrated by several examples in this article.

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Chapter 31
Environmental Input-Output Database Building in Japan

Keisuke Nansai

This chapter reviews the history and discusses the role of the primary environmental data that have become the foundation of environmental input–output analyses in Japan. It also describes two practical approaches to estimating unit environmental burden: an exogenous estimate approach and an endogenous estimate approach. As a case study, the endogenous estimate approach is used to estimate sectoral unit carbon dioxide (CO_2) emissions based on the Japanese Input–Output Tables for 2000. The technical problems that exist in determining CO_2 emission for each sector by that approach are explained. In addition, this chapter uses an input–output analysis to calculate the embodied CO_2 emission intensities of the approximately 400 sectors in the Japanese Input–Output Tables, and summarizes the quantitative characteristics of intensities for the major sectors. To examine the relationship between economic final demands and CO_2 emissions, the Japanese CO_2 emission structure in 2000 is illustrated using those intensities.

Introduction

About 70 years have passed since the Nobel Prize-winning economist W. W. Leontief released his input–output (IO) table for the US economy (Leontief 1936). IO analysis based on IO tables has not only proved itself highly capable of analyzing the structure of a single country's economy, but use of IO analysis has been broadened to include applied analyses focused on the relationships between economic activity and environmental problems (Leontief 1970). It can be argued that today's environmental analyses from the life-cycle perspective are built on the

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foundation of 1970s energy analyses triggered by the oil shocks (Chapman 1974; Wright 1974; Bullard and Herendeen 1975) and on theoretical research on economic metabolism (Ayres and Kneese 1969). The field of life-cycle assessment (LCA), in particular, makes extensive use of the framework of IO analysis. Methods such as IO–LCA (Hendrickson et al. 1998) and a hybrid approach combining IO–LCA with process-based LCA as a method of life-cycle inventory (LCI) analysis (Moriguchi et al. 1993a), have been proposed. The strengths of these methods lie in the definiteness of the system boundaries of LCI (Suh et al. 2004). This has been achieved by advances in the methodological theory of energy analysis (Wright 1974; Bullard and Herendeen 1975; Bullard et al. 1978). Currently, LCI that applies IO analysis has been incorporated into some commercial LCA software packages (Kobayashi et al. 2002; PRé Consultants (2005).

It was in 1955 that IO tables were first released in Japan. These tables were independently prepared and released by what are now the Cabinet Office and the Ministry of Economy, Trade and Industry (METI), who had both analyzed Japan's economy in 1951, 6 years after the war. The tables had different purposes. That by the Cabinet Office was a nine-sector table meant for use in Japan's national accounting system, whereas METI's table comprised 182 intermediate sectors. METI's 1957 report, "Input–Output Analysis of the Japanese Economy" (METI 1957), was a substantial document that included the 1951 IO table; it also included the results of analyses of that year's final demand and its relationships to employment and added value, and even quantity tables showing the supply–demand balance for 345 products in terms of physical values. Since that time, the government has produced Japanese IO tables for 1955, 1960, 1965, 1970, 1975, 1980, 1985, 1990, 1995, and 2000. The government also releases extended tables to cover the 4-year hiatus, and linked IO tables that adjusted to reflect fluctuations in currency values caused by 10-year inflation and deflation.

As in other countries, Japan has created IO tables and applied them not only to economic analyses, but also to environmental analyses. Needless to say, the use of IO tables in environmental analyses has made it essential to compile environmental data in a form enabling IO analysis, and various countries are presently tackling the development of environmental databases for IO analysis, as summarized by Suh (2005). For that reason, this chapter will first review the history of the primary environmental data that have become the foundation of Japan's environmental IO analysis, and discuss the role that these environmental data have played. Then, it will mention the characteristics of two practical approaches for determining sectoral environmental burdens for IO analysis. Additionally, as a case study, embodied CO_2 emission intensity will be calculated by using the most recent Japanese IO table (2000), and the relationship between CO_2 emission and economic final demand will be analyzed.

Historical Review of Japanese Environmental Input–Output Tables

For Use with the Leontief Pollution Abatement Model: The 1970s

In Japan, substantiative implementation of IO analysis in environmental analyses dates from the 1970s, when the compilation of environmental output data corresponding to IO tables also began. The “Input–Output Table for Environmental Pollution Analysis” created by METI in 1971 (METI 1976) was the first of its kind in Japan. This table, representing the 1968 IO system for the Kanto coastal region, was based on the Leontief pollution abatement model (Leontief 1970) and was used to analyze emissions of sulfur oxides (SO_x). Four years later, in 1975, when Japan was still in the midst of rapid economic growth, the government produced an “Input–Output Table for Environmental Pollution Analysis” for the entire country, based on the 1973 extended table (a table with extended estimates based on the 1970 table) (METI 1976). This table was released in 1976, and it contained Japan’s first environmental data for IO analysis that could be publicly used. More environmental outputs were included than in the 1971 table, with SO_x, chemical oxygen demand (COD), suspended solids (SS), and industrial waste being taken into account. This table comprised 25 intermediate sectors. The input structures for pollution-response measures pertaining to each intermediate sector and for the gross domestic fixed capital formation sector of the final demand sector are clearly noted independently of pure production activities. Using this table, the relationship between each final demand and the environmental outputs covered was quantitatively analyzed.

For Energy Analysis: The 1970s and 1980s

In the 1970s and 1980s, many energy analyses sparked by the oil shocks of the time were performed in Japan (Kaya 1980); they were based on not only process analysis but also on IO analysis. As seen in the research of Tezuka and Kaya (1984), energy analyses that used the Japanese IO table had detailed sector classification. In those years, regarding the publicly available energy data corresponding to the IO table, there was a book focusing on the life-cycle energies of clothing, food, and housing (Science and Technology Agency 1979). This book contained embodied energy intensities for 160 sectors; the intensities had been calculated by using the 1974 IO table estimated from the 1970 IO table. Embodied energy intensity is a coefficient showing the amount of energy consumed both directly and indirectly per unit of production activity in a sector defined in an IO table.

For Life-Cycle CO_2 Analysis: The First Half of the 1990s

In the early 1990s, increasing concern about global warming prompted the initiation of CO_2 analyses that utilized energy analysis methods. In Japan, this was the time when the autumn 1990 "Action Program to Arrest Global Warming" was developed, and preparations were under way for the June 1992 Earth Summit. Hence, it was important at that time, not only for the sake of research but also for policy, to calculate CO_2 emissions to more accurately reflect the actual situation. In response to this need, CO_2 and other environmental outputs of fuel-burning origin, which corresponded to sectors in IO tables, were elaborated.

Many energy analyses using IO analysis calculate the embodied energy intensity of a particular sector by taking the respective total production output (yen) of the energy production sectors induced by unit final demand to that sector and multiplying it by the energy costs (kcal/yen) of those sectors (Science and Technology Agency 1979; Oka 1986; Japan Resources Association 1994). However, in calculating emissions of CO_2 to the environment, it is necessary to consider not only emissions from the combustion of primary energy such as coal, oil, and natural gas, but also sources including CO_2 from limestone decomposition, and to deduct carbon fixed as petrochemical feedstock. Accordingly, unlike embodied energy intensities, embodied CO_2 intensities are not determined only on the basis of the activities of the energy production sectors. Rather, an environmental output calculation framework is adopted that sets net CO_2 emission for all sectors. Namely, "unit direct CO_2 emission" (CO_2 emission per unit production) is first calculated for each sector. Next, the embodied CO_2 emission intensity of a particular sector is determined by taking the total production output of that sector induced by unit final demand to the sector and multiplying it by the unit direct CO_2 emission corresponding to each sector.

An example of an attempt to elaborate CO_2 emissions and environmental outputs by sector is the research of Yoshioka et al. (1991) at Keio University, who used the 1985 IO table to estimate emissions of CO_2, nitrogen oxides (NO_x), and SO_x for each of the table's approximately 400 sectors. They made detailed estimates of each sector's fuel consumption by combining the quantity table (a supplement to the IO table) with various government statistics. They innovated with the emission coefficients of NO_x and SO_x, such as by using sector-specific values that reflected differences in each sector's emission mitigation technologies and by finding the actual amounts of pollutants emitted to the environment. In 1992, they released estimates of embodied CO_2 emission intensities for each of the approximately 400 sectors (Yoshioka et al. 1992).

Meanwhile, Moriguchi et al. (1993b) estimated CO_2 emissions according to Japan's so-called "energy balance table" (ANRE 2004), and compared the results with CO_2 emissions estimated by using fuel consumption in the IO table's quantity table. Despite some small differences, sectoral emissions calculated in both ways were in general agreement, thereby demonstrating that IO analysis can be positively applied in the quantitative analysis of CO_2 emissions. Currently, the CO_2 counting that Japan officially reports to the Framework Convention on Climate Change secretariat (FCCC) is calculated according to this energy balance table (GIO 2005). These challenging studies to determine actual environmental burdens have elevated the soundness and reliability of environmental analyses using IO analysis, and that in turn could be considered one reason why IO analysis was brought into Japan's LCA research so quickly, and is actively used.

LCA research gained momentum in the 1990s, and there were many LCI analyses of CO_2 emissions in particular. In 1994, an international conference on LCA, the International Conference on EcoBalance, was held in Tsukuba City. This decade was a time of extensive discussion in Japan on LCA methodology and case studies. As IO analysis and hybrid analysis came to be used as LCI methods in many case studies during this time (e.g., Ikaga and Ishifuku 1994; Dohnomae et al. 1994; Hondo and Uchiyama 1994; Suga et al. 1994; Tiwaree et al. 1994; Yagi 1994), there was a growing need in LCAs for embodied environmental burden intensity determined by IO analysis.

For Life-Cycle Inventory Analysis: The Second Half of the 1990s

In the second half of the 1990s, universities, research institutions, and academic societies began offering, in the form of databases usable by anyone, the environmental data for IO analysis that they had themselves produced and were using. Those who released their data included Yoshioka et al. at Keio University (KEO 1996), Ikaga et al. at the Architectural Institute of Japan (AIJ 1999), the Building Research Institute of the former Ministry of Construction (Inaba 1998), Hondo et al. at the Central Research Institute of Electric Power Industry (CRIEPI) (Hondo et al. 1996, 1997), Kondo and Moriguchi at the National Institute for Environmental Studies (NIES) (Kondo and Moriguchi 1997), and Harada et al. at the former National Research Institute for Metals (now the National Institute for Materials Science) (NIMS 1997). Additionally, in 1997 the private-sector company Toshiba Corporation offered, as commercial software, its own LCI data derived from IO analysis that it had been using in-house from 1995 (Suzuki 2000). The range of data offered, the media by which they were provided, the types of environmental burdens covered, the methods for estimating environmental burden, and the sector classifications differed according to institution. Moreover, although not for LCA, in 1999 METI compiled and released energy consumption data corresponding to the international IO table for Asia (METI 1999).

For Updating Data and Analyzing Multiple Environmental Burdens: The 2000s

In 2000, compilation of environmental burden data for the 1995 IO table was implemented in order to analyze environmental burdens based on that table, which had been released the previous year. Already in March 1999, Toshiba Corporation had begun selling environmental burden data based on the 1995 table, but other institutions started releasing data in 2000 and thereafter. In 2000, Moriguchi and Nansai jointly released direct burdens and embodied intensities for energy and CO_2 on their Kyoto University website, and Asakura et al. from Keio University released data in book form in 2001 (Asakura et al. 2001). This was followed in January 2002 by a report released by Hondo et al. (2002) at CRIEPI. It included embodied intensities for all greenhouse gases. Further, in March 2002 Nansai et al. published a data book (3EID) (Nansai et al. 2002, 2003) containing an improved version of the previously mentioned data released on the Kyoto University website. 3EID considered not only energy and CO_2 but also air pollutants (NO_x, SO_x, and particulate matter). This was done in consideration of the increasing interest shown at this time by researchers in the West – mainly Society of Environmental Toxicology and Chemistry (SETAC) Europe (e.g. Suh and Huppes 2002) – in LCA performed using IO analysis. Because 3EID was expected to be used in Japan and abroad, it included both English and Japanese explanations of estimation methods and how to use the book. In 2003, Ikaga et al. (AIJ 2003) reworked the data of Hondo et al. (2002) and released them through the Architectural Institute of Japan. Institute members found the data very convenient to use because, for example, the architecture-related sectors for building analysis had been subdivided and the additional environmental burden due to capital formation had been added.

Meanwhile in Japan, passage of the Fundamental Law for Establishing a Sound Material-Cycle Society in May 2000 turned resource cycling and waste issues into important research areas. Against this backdrop Nakamura and Kondo, who had long been performing waste analyses using IO analysis (Nakamura and Kondo 2002), made a Waste Input–Output Table (WIO) generally available in November 2002 (Nakamura 2005). The existence of such highly reliable environmental data for IO analysis, which has clearly specified ways to calculate environmental burdens and wastes and which can be used by anyone, has not only broadened the base of people who perform LCA in Japan, but also facilitated international comparisons in environmental analyses. Although the availability of data from multiple institutions has presented users with the problem of which set one should use, the ability to compare values has benefited LCA research in terms of accuracy and reliability improvement of IO–LCA, and this has helped improve methods of estimating sectoral environmental burdens. It seems to have played a major role in enhancing LCA research by, for example, quantitatively showing differences in LCI results that arise due to differences in methods of calculating the data for environmental burdens (e.g. allocation to each sector).

A recent event is the release in 2004 of the 2000 table (MIC 2004), which requires the corresponding environmental data for significant IO analyses. Researchers have begun compiling data based on findings to date for energy, greenhouse gases, air and water pollutants, wastes, and other categories (Box 31.1).

Box 31.1 Accounting Structure of Japanese IOT

In Japanese Input–Output (IO) tables, the most detailed transaction matrix comprises the commodity by commodity framework (MIC 2004). However, even if commodities are produced using an identical activity, in case they differ greatly in application or unit price, the transaction matrix describes them as distinct products by dividing the row sector corresponding to that activity. The recent matrix is therefore not a squared matrix, but is rather composed of about 500 row sectors and about 400 column sectors. For instance, petroleum refinery activity is defined as one column sector, but their produced commodities are defined as gasoline, kerosene, diesel, jet fuel and heavy oils, which are categorized as separate row sectors. As a result, the practical framework of the transaction matrix is probably approximately that of commodity (row) by activity (column) sectors. In terms of the description of scrap and byproducts yielded by each sector, Stone's method is used in the Japanese IO tables.

On the other hand, the Japanese IO tables also include a make-table that comprises data organized as industry (row) by commodity (column) sectors. The make-table is provided as a supplemental material to the IO tables: only about 100 sectors are given for rows and columns, respectively. Unfortunately, a use-table is not supplied in the IO tables. Other useful supplemental materials include: the quantity table, which expresses commodity transactions among sectors by physical values; the fixed capital table, which describes annual commodities input to fixed capital formations; the labor and occupation tables, which show how many people of what job type worked for annual production of each commodity; the scrap and byproduct table, which shows what scrap and byproducts are traded among sectors; and the domestic average unit-price table, which lists the average unit prices of approximately 4,000 domestic commodities.

Sector Classification

The number of sector classifications depends on the year of the IO table (Table 31.1). The table below summarizes the number of intermediate sectors for each year's table. As a concrete example of sector classifications, sector names for the 2000 tables are listed at the end of this chapter.

Table 31.1 Number of Intermediate Sectors for Each Year's Japanese Input–Output Tables

Year for the IO tables	1951	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000
Row sectors[a]	182	310	453	467	541	554	541	529	527	519	517
Column sectors[a]	182	278	339	339	405	405	406	408	411	403	405

[a] Number of intermediate sectors.

Key Reference

Ministry of Internal Affairs and Communications in Japan (MIC) (2004). *2000 input-output tables: Explanatory report* (pp. 30–31). Tokyo: The National Federation of Statistical Association (in Japanese).

(continued)

Box 31.1 (continued)

Where to Get Data
Printed publications of the IO tables are available from the National Federation of Statistical Association (NAFSA) of Japan (http://www.nafsa.or.jp/). Publications for each year often consist of three reports (explanatory report, data reports I and II). Electric data of the IO tables are sold at the Research Institute of Economy, Trade and Industry of Japan (http://www.chosakai.or.jp/).

Practical Determination of Sectoral Environmental Burdens

The embodied environmental burden intensity t_j of sector j according to the IO quantity model can generally be expressed by Equation (31.1).

$$\mathbf{t} = \mathbf{e}\,(\mathbf{I} - \mathbf{A})^{-1} \tag{31.1}$$

where row vector $\mathbf{t}$ $\{t_j\}$ is an embodied environmental burden intensity vector with t_j as an element; row vector $\mathbf{e}$ $\{e_j\}$ is a unit direct environmental burden vector with e_j, the direct environmental burden per unit production in sector j, as an element; matrix $\mathbf{A}$ $\{a_{ij}\}$ is the direct requirements matrix with a_{ij}, the direct input of sector i per unit of sector j's output, as an element; and $\mathbf{I}$ is the identity matrix.

In many instances, matrix $\mathbf{A}$ can be determined by Equation (31.2) by use of a transaction matrix $\mathbf{Z}$ $\{z_{ij}\}$ representing money flow z_{ij} among sectors and the total production vector $\mathbf{x}$ $\{X_j\}$ with domestic total output X_j as an element in the IO table.

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{31.2}$$

where symbol ˆ means a diagonal matrix. However, vector $\mathbf{e}$ must be calculated independently. It is not an overstatement to say that the setting of vector $\mathbf{e}$ influences the reliability of vector $\mathbf{t}$. The preparation of various kinds of environmental data in Japan as described above has required much time and effort for the accurate estimation of vector $\mathbf{e}$.

Practical methods of estimating vector $\mathbf{e}$ can be roughly classified into two approaches according to their methodological characteristics. Here they are called the "exogenous estimate approach" and "endogenous estimate approach". This section briefly describes the differences between the two approaches, and then Section "Case Study: Calculation of Direct and Indirect Sectoral CO_2 Emissions Based on the Japanese Input–Output Table" actually determines vector $\mathbf{e}$ for CO_2 emission with the endogenous estimate approach and calculates embodied CO_2 emission intensity t_j.

Exogenous Estimate Approach

In actuality, the unit direct environmental burden e_j is rarely estimated directly; instead, it is nearly always calculated from Equation (31.3) after determining the total environmental burden E_j corresponding to the total production X_j of sector j. It is therefore appropriate to consider the two approaches as different ways to estimate E_j and to understand how they are different.

$$e_j = \frac{E_j}{X_j} \tag{31.3}$$

The exogenous estimate approach uses available environmental data, as preliminarily determined by observations, investigations and estimations, for setting E_j. It then finds the correspondence between the emission source category j' of the data used in the observations, investigations and estimations and sector j defined with the IO table. It then directly quotes the data's total environmental burden, $E_{j'}$, and sets the total environmental burden of sector j as in Equation (31.4). Namely, this approach exogenously determines e_j independently of its IO structure defined in the IO table, as in Equation (31.5).

$$E_j = E_{j'} \tag{31.4}$$

$$e_j = \frac{E_{j'}}{X_j} \tag{31.5}$$

Environmental burden data available for this approach include the National Greenhouse Gas Inventory (GIO 2005), the Pollutant Release and Transfer Register (PRTR) (MOE 2005), and the Environmental Statistics (MOE 2004) in Japan. These data indicate the direct environmental burdens of source categories defined in the respective data, so one just needs to find the sectoral correspondence between the data's emission source categories and the IO table. Similarly, environmental information that shows actual environmental burdens is being compiled in Western countries. This information includes the National Emission Inventory (NEI) (USEPA 2005a), the Toxics Release Inventory (TRI) (USEPA 2005b), and the European Pollutant Emission Register (EPER) (EEA 2005). These environmental burden data are compiled by source (stationary or mobile) for the purpose of national environmental management. In terms of quantifying the amount of a sector's environmental burden, the exogenous estimate approach can be highly useful when the mechanism by which environmental burdens arise is complex, or when it is difficult to pin down emission substances and ascertain how they move. With this approach, the key to determining the soundness of the unit environmental burden is the appropriate accordance between the definition of the sector's activity in the IO table and that of the emission source categories of the environmental data provided. Therefore, when the scope of observation, investigation and estimation of environmental data and the definitions of categories do not strictly match the sectors defined in the IO table, the unit environmental burdens obtained will be values that contradict the input and output structures of that sector, leading to concerns that erroneous analysis results and interpretations will arise.

Endogenous Estimate Approach

On the other hand, the endogenous estimate approach focuses on the structure of the sector inputs. It follows the process by which analyzed environmental burdens arise in a sector from its inputs, and computes environmental burden in a bottom-up fashion, or endogenously. No matter which of these two approaches is adopted, exact computation of environmental burdens will ultimately lead to the same results. However, with environmental analyses using IO quantity models, it is usually desirable to organize the system to endogenously determine the relationship between production and environmental burdens, and hence the endogenous estimate approach can be recommended because it can comprehend how environmental burdens arise from sector inputs. However, it is in fact difficult to follow the mechanisms that cause environmental burdens; therefore, there are cases when the endogenous estimate approach cannot come up with realistic burden figures and cases when it is better to use the exogenous estimate approach. One must choose the approach most suited to the types of environmental burdens analyzed and to the purpose of the analysis.

Basically, the quality and quantity of environmental burden depend not only on inputs from the economic system (e.g. energy and materials) but also on inputs from the environmental system (e.g. air temperature, air pressure, and other environmental conditions). They are determined by the interaction of the inputs from the two systems. However, the endogenous estimate approach attempts to simplify the computation of environmental burdens by focusing on only specific inputs from among the many that govern the generation of the studied environmental burden. Such focused inputs are inputs that are "regarded as" the main causes of burdens. Inputs regarded as main causes are not limited to the substances and energy that are the components of the environmental burden, but are sometimes the substances and energy that trigger the generation of burden. For example, in the case of CO_2, the focus is on the carbon component of the fossil fuel inputs, whereas in the case of thermal NO_x generation, the focus is not on the nitrogen and oxygen components that compose NO_x but on the fossil fuels that create the high-temperature environment that triggers the formation of NO_x.

Below in this chapter, the inputs regarded as the main causes of environmental burdens are referred to as "burden causes". In short, this approach estimates sectoral environmental burdens on the basis of an understanding of the intra-sectoral flow of burden causes from their inputs until when they change to environmental burdens discharged into the environmental system. Theoretically, an IO table describes the input of burden cause h, which is an output of sector i to sector j, as an input coefficient, a_{hj}. When multiple burden causes need to be considered to calculate the direct environmental burden of sector j (for instance, in the case of considering three burden causes: h, h', h''), e_j with the endogenous estimate approach can be expressed as a function f of coefficients $(a_{hj}, a_{h'j}, a_{h''j})$ as Equation (31.6).

$$e_j = f\left(a_{hj}, a_{h'j}, a_{h''j}\right) \tag{31.6}$$

Case Study: Calculation of Direct and Indirect Sectoral CO_2 Emissions Based on the Japanese Input–Output Table

Estimation of CO_2 Emissions by the Endogenous Estimate Approach

To demonstrate a specific example of environmental data compilation that corresponds to an IO table, the CO_2 emissions for each sector in the latest Japanese IO table for 2000 are estimated here and concrete methods and procedures for the estimation are described. Also in this section, the embodied CO_2 emission intensity is calculated and the relationship between economic final demands and CO_2 emissions in 2000 is found.

The original transaction matrix in the 2000 IO table comprises 517 commodity sector rows and 405 commodity sector columns. So firstly, finding a square matrix of the transaction matrix necessitates integrating a number of sectors in the original sector classification. In the estimate performed here, a square matrix $\mathbf{Z}$ $\{z_{ij}\}$ composed of 401 intermediate sectors was compiled from the original matrix.

Secondly, the burden causes h of CO_2 emissions (CO_2 causes) that are considered here include materials that generate CO_2 by oxidization of the carbon they contain (*ho*) and materials that segregate contained CO_2 when they are used (*hs*). For materials of the former kind (*ho*), the annual inputs to sector j, $BC_{ho,j}$, were estimated for 20 types of fossil fuel, 2 types of waste, and 4 other types of fuel. For materials of the latter kind (*hs*), the annual input of limestone, $BC_{hs,j}$, was estimated.

Then, fuels and materials that were either consumed as feedstock, converted into secondary fuels, or used in applications where no release of CO_2 occurs were excluded from sources of CO_2 emission. To do this, net annual inputs causing CO_2 emissions ($NBC_{ho,j}$ and $NBC_{hs,j}$) were calculated by multiplying $BC_{ho,j}$ and $BC_{hs,j}$ by the net contribution rate, $CR_{ho,j}$ or $CR_{hs,j}$, respectively. The net contribution rate is defined as how the fuel or material consumption relates directly to CO_2 emission.

Next, in terms of fuels and wastes, direct CO_2 emission from CO_2 cause *ho* in sector j was determined by multiplying $NBC_{ho,j}$ by the corresponding calorific value CL_{ho} and CO_2 emission factor EF_{ho}. The CO_2 emission for limestone was obtained by multiplying $NBC_{hs,j}$ by only the CO_2 emission factor, EF_{hs}.

Finally, the total of the CO_2 emissions generated from CO_2 causes *ho* and *hs* was set as the annual total CO_2 emission of sector j, TC_j (t-CO_2/year), and unit direct CO_2 emission, e_j (t-CO_2/million yen) was calculated by dividing TC_j by domestic total output, X_j (million yen/year). The sequence of procedures for determining e_j can be summarized as Equation (31.7):

$$e_j = \frac{\sum_{ho} \left(BC_{ho,j} \times CR_{ho,j} \times CL_{ho} \times EF_{ho}\right) + BC_{hs,j} \times CR_{hs,j} \times EF_{hs}}{X_j} = \frac{\sum_{ho} \left(NBC_{ho,j} \times CL_{ho} \times EF_{ho}\right) + NBC_{hs,j} \times EF_{hs}}{X_j} = \frac{TC_j}{X_j} \tag{31.7}$$

Here, the basic approach to estimating $BC_{ho,j}$ and $BC_{hs,j}$ is mentioned. Consistency between a sector's environmental burden and its input structure is important; here the values in the 2000 IO table's quantity table are used to the greatest extent possible. The quantity table is a table supplementary to the IO table, and it contains physical quantities of commodities output by sector i and input to sector j. It is compiled on the basis of the transaction matrix of monetary units $\mathbf{Z}$ $\{z_{ij}\}$, which specifies input coefficients, and it therefore provides the input quantities of burden causes corresponding to the sector categories and definitions peculiar to the IO table. Hence, the quantity table is a highly useful numerical table for estimating environmental burdens that are consistent with each sector's input structure.

However, since most of the values in the quantity table are quantities calculated by dividing the transaction value, z_{ij} (yen), by the respective averaged domestic unit price of commodity i, p_i (yen/unit physical quantity), Japan's quantity tables are regarded as experimental, and as such have some quantities that, judging from other statistical information, diverge considerably from reality. Especially in cases where sector j is a big customer of commodity i or uses imported commodity i, a physical quantity converted by unit price, $z_{ij} \times p_i^{-1}$, tends to be greatly different from a realistic quantity obtained from statistics because of the discrepancy between p_i and sector j's actual unit purchase price p_{ij}. Improving the quantity table from an experimental table to a practical table necessitates conversion of z_{ij} into a physical quantity with a unit price p_{ij} that takes into consideration its difference among purchase sectors.

Accordingly, in this example, sectors are consolidated to compare the input amounts of burden causes in the quantity table with the values in other related statistics, and when the values in the quantity table are seen to be clearly different from reality, the values from other statistics are quoted to amend those in the quantity table. In particular, byproduct gases and other fuels are not appropriately stated in the quantity table, because they are often traded without a monetary transaction, making it difficult for the monetary-based transaction matrix in the IO table to adequately capture their inputs. To deal with such gases and fuels adequately, the input amounts in each sector were estimated with reference to various statistical data and to conditions in actual production processes that, in view of sector definitions, were determined to match. Here too, the connection between input structure and CO_2 emission quantity was taken into consideration, such as by performing estimates by using the monetary value of inputs in the transaction matrix that are relevant to the use of byproduct gases and fuels in a sector. Further, because fossil fuels are basically burden causes whose annual domestic consumptions can be obtained from statistics, quotation of the values from the statistics and amendment of the values in the quantity table have been carried out so that the sum total of sectoral inputs do not conflict with the consumption figures shown in the statistics. Additionally, this estimate checked the correctness of the quantity table values of the burden causes considered here, especially for sectors with large inputs, and amended input amounts as appropriate. Table 31.2 gives the burden causes spotlighted here. Asterisks indicate burden causes for which quantity table values were amended, or which were calculated during this case study.

Attribution of CO_2 Emitted in the "On-Site Power Generation" Sector

The following method was used to find the burden causes in the "on-site power generation" sector. First we need to consider the matter of how industries generate their own power. The steel industry produces power with coal-derived byproduct gases, whereas the petrochemical industry uses byproduct gases produced in oil refining. Although they both produce electricity, there is a big difference in the CO_2 emissions per unit power production. Japan's IO tables integrate on-site power generated with different technologies into a single "on-site power generation" sector. In view of consistency with this sector's input structure, the burden causes in this sector should be all fuels used for on-site power generation by these industries. However, if one assigns this consolidated fuel input amount to the "on-site power generation" sector, the CO_2 generated by that sector, which is proportional to the monetary value of any one sector's input from the "on-site power generation" sector, becomes part of that input sector's embodied intensity. Hence, some of the CO_2 from petroleum-derived byproduct gases ends up being assigned to the embodied intensity of steel-related sectors due to their input into the "on-site power generation" sector, whereas petrochemical-related sectors end up with some CO_2 from blast-furnace gases (BFG). Consequently, their embodied intensity values are far from realistic.

Ideally, it should be good enough to split up the "on-site power generation" sector, create multiple consolidated on-site power generation sectors based on similarity of emission causes, describe the input and output structures of each sector, and, having accomplished this, compute the input amounts of burden causes for each on-site power sector. However, it is not easy to accurately determine an IO structure composed of about 400 sectors. This case study used a simplified substitute procedure that, instead of assigning the fuel peculiar to the on-site power generation of a certain industry to the "on-site power generation" sector, directly assigns it to the sector that uses that industry's on-site power generation. For example, the Coke oven gas (COG), BFG, and Linz Donawitz gas (LDG) used for on-site power are allocated to steel-related sectors in accordance with the amount of on-site power input.

Table 31.2 Environmental Input-Output Database Building in Japan[a] Calorific Values and CO_2 Emission Factors of Fuels and Material

Method[a]	Fuels and materials (*ho, hs*)	Calorific value (CL_{ho})	Unit[b]	CO_2 emission factor (EF_{ho}, EF_{hs})	Unit
*	Coking coal	28.9	GJ/t	0.0915	t-CO_2/GJ
*	Steam coal, lignite, and anthracite	26.6	GJ/t	0.0889	t-CO_2/GJ
*	Coke	30.1	GJ/t	0.108	t-CO_2/GJ
*	Coke oven gas (COG)	21.1	GJ/k-Nm^3	0.0405	t-CO_2/GJ
*	Blast furnace gas (BFG)	3.41	GJ/k-Nm^3	0.108	t-CO_2/GJ
*	Linz Donawitz gas (LDG)	8.41	GJ/k-Nm^3	0.108	t-CO_2/GJ
*	Crude oil	38.2	GJ/kl	0.0693	t-CO_2/GJ
	Fuel oil A	39.1	GJ/kl	0.0709	t-CO_2/GJ
*	Fuel oils B and C	41.7	GJ/kl	0.0711	t-CO_2/GJ
*	Kerosene	36.7	GJ/kl	0.0682	t-CO_2/GJ
*	Diesel oil	38.2	GJ/kl	0.0692	t-CO_2/GJ
*	Gasoline	34.6	GJ/kl	0.0667	t-CO_2/GJ
*	Jet fuel	36.7	GJ/kl	0.0666	t-CO_2/GJ
	Naphtha	34.1	GJ/kl	0.0654	t-CO_2/GJ
*	Petroleum-derived hydrocarbon gas	44.9	GJ/k-Nm^3	0.0455	t-CO_2/GJ
*	Hydrocarbon oil	42.3	GJ/kl	0.0771	t-CO_2/GJ
*	Petroleum coke	35.6	GJ/t	0.0930	t-CO_2/GJ
*	Liquefied petroleum gas (LPG)	50.2	GJ/t	0.0603	t-CO_2/GJ
*	Natural gas and liquid natural gas (LNG)	54.5	GJ/t	0.0512	t-CO_2/GJ
	Mains gas	41.1	GJ/k-Nm^3	0.0523	t-CO_2/GJ
*	Black liquor[c]	12.6	GJ/t (dry)	0.0942	t-CO_2/GJ
*	Waste wood[c]	16.7	GJ/t (dry)	0.0770	t-CO_2/GJ
*	Waste tires	33.9	GJ/t	0.0800	t-CO_2/GJ
*	Municipal waste[d]	10.1	GJ/t	0.0308	t-CO_2/GJ
*	Industrial waste[d]	16.2	GJ/t	0.0494	t-CO_2/GJ
*	Recycled plastic of packages origin	48.7	GJ/t	0.0654	t-CO_2/GJ
*	Limestone		–	0.440	t-CO_2/t

[a]Inputs of fuels and resources marked with an asterisk (*) to sectors were estimated by modifying values in the quantity table of the 2000 Japanese IO table.
[b]k-Nm^3 represents 1,000 × Nm^3 (1,000 × 1 m × 1 m × 1 m).
[c]Not added to the total CO_2 emission.
[d]Excluding CO_2 of biomass origin.

This way of allocating those gases allows only outputs of steel-related sectors to generate CO_2 originating from coal-derived byproduct gases used for on-site power generation. It can thereby avoid unrealistic situations where demand for the "on-site power generation" sector by other sectors, for instance by petrochemical-related sectors, directly generates CO_2 from such coal-derived byproduct gases. In the case of petroleum-derived byproduct fuels for on-site power (petroleum-derived hydrocarbon gases, hydrocarbon oils, and petroleum coke), because the correspondence information between sector classifications in industrial statistics and those in the IO table is limited to mining- and manufacturing-related sectors, the values for these fuels obtained from the statistics are naturally assigned to petrochemical-related sectors, which are assumed to use petrochemical-derived on-site power. In other words, these fuels were not allocated to the "on-site power generation" sector. In addition, because black liquor and wood waste are on-site power generation fuels peculiar to the pulp and paper industry, the input amount was assigned to pulp- and paper-related sectors. On the other hand, because fuel oil and coal are generally fuels used in all industries, they are assigned as is to the "on-site power generation" sector.

Judging by the input structure of the "on-site power generation" sector, this method of assigning burden causes unit direct CO_2 emissions of that sector to be underestimated, which sacrifices the accuracy of the "on-site power generation" sector's embodied intensity. However, if the embodied CO_2 emission intensities calculated in this case study are used mainly for publicly available inventory data for life-cycle analyses, one assumes that users will most often use the intensity of the steel and petrochemical product manufacturing sectors, which use on-site power, more than the intensity of the "on-site power generation" sector. For that reason, here this calculation has considered it more important to reflect the actual fuel consumption pattern in the intensity of these sectors than in the "on-site power generation" sector.

Setting the Net Contribution Rates and CO_2 Emission Factors of Burden Causes

Net Contribution Rates

In order to deduct the amounts of burden causes not involved in generating CO_2 in sector j, the net contribution rate ($CR_{ho,j}$, $CR_{hs,j}$), which is the portion that contributes to generating CO_2, was created. Although usually a detailed calculation of the rates would be necessary, it is not easy to accurately determine the rates for about 400 sectors, so in this case study these rates were for simplicity set to either 1 (involved in generating CO_2) or 0 (not involved; used for raw material or energy conversion into other fuel). When the sector that converts fuel re-inputs the converted fuel, the rate of the fossil fuel that was converted is set to 0, and the converted fuel is considered to have been input once again into that sector.

On the other hand, coke used in blast furnaces is not directly released as CO_2 from the blast furnace, but is ultimately converted to BFG and LDG, which are carbon-rich gases despite their low calorific value. Hence, when allocating CO_2 from coke on the basis of the actual places that release CO_2 to the environment, most of the CO_2 from the coke used in blast furnaces is attributed not to the "pig iron" sector that uses the blast furnace, but to sectors further downstream that consume a lot of BFG and LDG, such as the "electric power for enterprise use" sector that merely utilizes a little part of all energy of the coke through those gases. However, considering the original necessity for coke in blast furnaces, as an agent for reducing iron oxide, most of the responsibility of CO_2 from the coke should be attributed to the "pig iron" sector. As mentioned before, the embodied intensities described in this chapter will be used mainly for life-cycle analyses; therefore, it is very important to clearly represent how an environmental burden is attributed to each sector in the IO table.

In this estimate the amount of CO_2 from coke used in blast furnaces that is ascribed to each sector is proportional to the amount of coke-derived energy consumed in each sector (Moriguchi et al. 1993b). Accordingly, to determine the amount of coke-derived energy consumed in blast furnaces, the net contribution rate was set to 0 in the "pig iron" sector for coke used for blast furnaces, and all its coke energy was assigned here. For BFG and LDG, these inputs were also estimated for each sector. Then to avoid double counting the energy of BFG and LDG, for descriptive purposes, this case study created fuel-type items "BFG-generated" and "LDG-generated", and assigned the BFG- and LDG-generated amounts (same as their total inputs to each sector) as negative values to the "pig iron" and "crude steel (converter)" sectors, respectively.

CO_2 *Emission Factors*

CO_2 emissions from fuel and waste combustion were calculated by using the CO_2 emission factors for each fuel type on a calorific value basis, as given in Table 31.2. The calorific value of each fuel was determined by using the unit calorific values in Table 31.2 as multipliers. For limestone, this case study counted as inputs only those from applications that emit CO_2, and multiplied these input amounts by the factors in Table 31.2 to calculate CO_2 released when used. However, for BFG and LDG, the CO_2 allocation method mentioned above required the use of the same emission factor as that of coke.

Results and Discussion

Direct CO_2 *Emissions and Embodied Intensities by Sector*

The total CO_2 emission (the total of TC_j) based on the 2000 IO table was estimated at 1,308 Mt-CO_2. The emission breakdown by burden cause was 28% from coal-based fuels, 53% from petroleum-based fuels, 13% from natural gas-based fuels, 4% from limestone, and 2% from wastes and others. By matching the system boundary counting CO_2 between the official Japanese estimation of CO_2 emissions as reported to the FCCC (GIO 2005) and the IO table, in terms of total CO_2 from fossil fuels, the result of this study was about 1.8% larger than the official estimate. This discrepancy can be explained by differences in the following criteria: the statistics used for quotation of fuel inputs; the values of the CO_2 emission factors utilized; the fiscal year (on which the official estimate is based) and the calendar year (IO table); and the number of days in the year (365 days in the 2000 fiscal year; 366 days in the 2000 bissextile year).

As shown in Fig. 31.1, when the approximately 400 sectors are consolidated into 18 sectors to examine the emission percentages by sector, "electric power, gas and heat supply" is the largest at 410 Mt-CO_2 accounting for 31%, followed by "transportation" at 211 Mt-CO_2 accounting for 16%. "Household expenditures (Direct)" emits 172 Mt-CO_2 accounting for 13%, followed by "iron and steel" at 164 Mt-CO_2 accounting for 13%. These four sectors account for 73% of the total. The arrangement by burden cause generally seems to reproduce the pattern of inputs for fuels and raw materials found in actual production processes. For example, limestone-derived CO_2 accounts for 55% of that from "ceramic, stone and clay products", and the breakdown of CO_2 origin in "electric power, gas and heat supply" (45% coal, 21% petroleum, 27% natural gas, and 6% other) includes consumption of fuels that are used in common with on-site power generation and reflects the electric power energy mix.

Figure 31.2 plots the embodied CO_2 emission intensity t_j of each sector as calculated with Equation (31.1). Sectors with especially large values include "cement", "pig iron", "crude steel (converters)", "on-site power generation", and "ferroalloys".

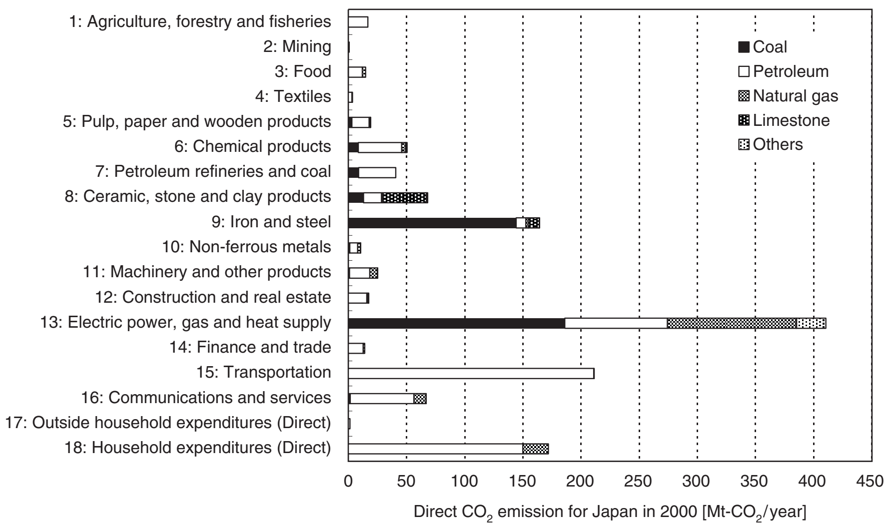

Fig. 31.1 Sectoral Direct CO_2 Emissions and Their Breakdowns by Origin (Coal, Petroleum, Natural Gas, Limestone, and Others) in Japan in 2000; Estimated CO_2 Emissions from 401 Sectors are Consolidated into 18 Sectors

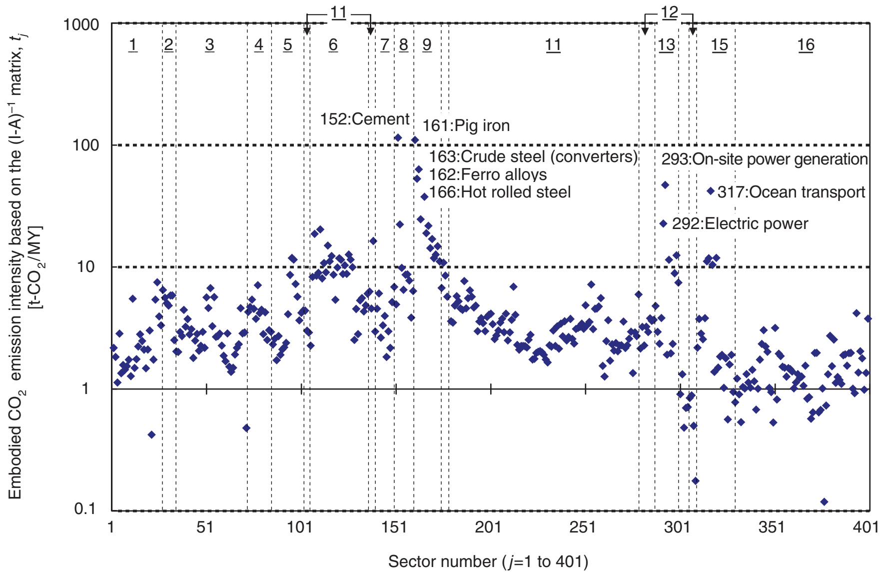

Fig. 31.2 Sectoral Embodied CO_2 Emission Intensities Based on the $(I-A)^{-1}$ Matrix; the Vertical Divisions Show Categories 1–16 of the 18 Consolidated Sector Categories of Fig. 31.1 and How They Cover the 401 Sector Classifications. Sector Names and Values of Embodied CO_2 Emission Intensities (tj) are Listed in the Appendix to This Chapter

The sectors "cement" and "pig iron" are especially large, exceeding 100 t-CO_2/MY. The "pig iron" sector includes CO_2 from coke used in blast furnaces. On the other hand, in categories that generally produce end products (including category 1, agricultural, forestry, and marine products; category 3, foods; category 4, clothing; category 11, machinery; and category 16, services), many sectors have intensities in the range of 1–10 t-CO_2/MY.

Sector names and the corresponding values of direct CO_2 emission (TC_j), unit direct CO_2 emission (e_j), and embodied CO_2 emission intensities (t_j) for each sector are included in the Appendix to this chapter.

Relationship Between CO_2 *Emission and Final Demand Sectors in 2000*

Here, the relationship between Japan's domestic CO_2 emissions and final demands in 2000 are quantitatively analyzed. This case study consolidated the final demand sectors of the IO table into nine categories (k = A,...,I): [A] "outside household expenditures", [B] "household expenditures", [C] "private nonprofit institutions serving households", [D] "central government expenditures", [E] "local government expenditures", [F] "public capital formation", [G] "private capital formation",

[H] "stock", and [I] "exports". Calculation of domestic CO_2 emission T_k^d induced by final demand k needs to exclude emissions related to import commodities. This can be determined by Equation (31.1). The summation of T_k^d for k plus direct emission from the final demand sectors ("outside household expenditures" and "household expenditures") equals the total emission of 1,308 Mt-CO_2.

$$T_k^d = \mathbf{t^d}(\mathbf{I} - \hat{\mathbf{m}})\mathbf{f}_k \tag{31.8}$$

where $\mathbf{f}_k$ $\{f_{ik}\}$ is a column vector of which element f_{ik} is the annual input from sector i to the final demand sector k and written in the IO table and $\hat{\mathbf{m}}$ is a diagonal matrix of a column vector $\mathbf{m}$ whose elements are the import rates m_i of a product output by sector i. Note that for "exports" the import rates are all 0. $\mathbf{t^d}$ denotes a row vector of which element t_j^d is sector j's embodied CO_2 emission intensity excluding that for import commodities; it can be calculated from Equation (31.2). The values of t_j^d are listed in Appendix in this chapter.

$$\mathbf{t^d} = \mathbf{e}\left(\mathbf{I} - (\mathbf{I} - \hat{\mathbf{m}})\,\mathbf{A}\right)^{-1} \tag{31.9}$$

The outer ring of Fig. 31.3 shows the portion of CO_2 generated by final demand, to which was added the directly generated CO_2 from the "outside household expenditures" and "household expenditures" sectors (A1, B1), whereas the inner ring

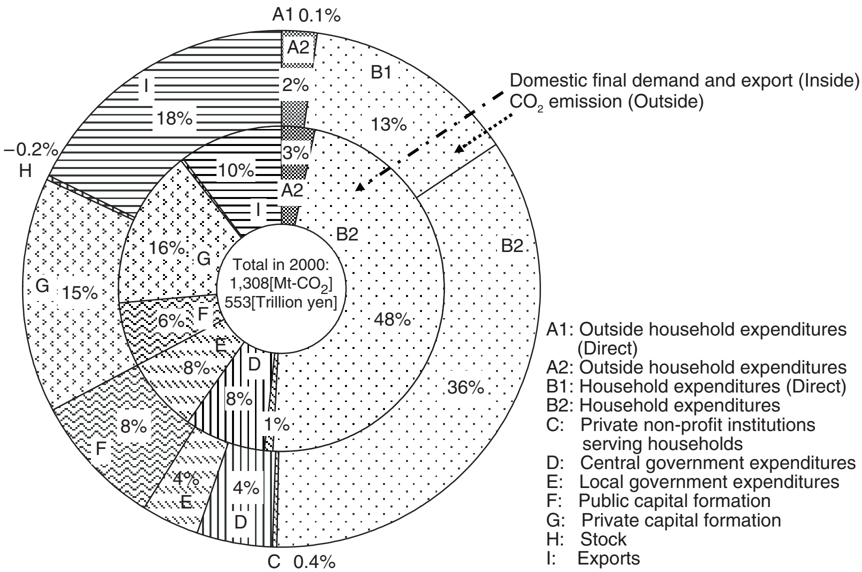

Fig. 31.3 Shares of Economic Domestic Final Demands and Their Directly and Indirectly Generated Domestic CO_2 Emission in Japan in 2000; These Values Exclude Final Demands and CO_2 Emission for Import Commodities

shows the proportion of final demand value excluding imported items. The direct and induced emissions from the "household expenditures" sector account for the biggest share at 49%, which is basically unchanged from the 1995 value (Nansai and Moriguchi 2006), and nearly equal to the 48% for final demand value. Of the 13% direct emissions, 7% is gasoline and diesel fuel consumption by automobiles, which allows confirmation of the large contribution. Of the 36% induced portion, 8% is due to demand from the "electric power for enterprise use" sector, and household automobiles and electric power accounted for 15% of the total.

"Central government expenditures" and "local government expenditures" each amount to 8% of final demand value, whereas they each account for only 4% of CO_2 emissions. "Public capital formation" and "private capital formation" account for 6% and 16% of final demand value, and 8% and 15% of CO_2. From this comparison it is evident that expenditures by the central and local governments in healthcare, nursing care, education, and other areas can be seen as low-burden fiscal expenditures from the perspective of CO_2 emissions. In "exports", largely due to ocean transport and air transport, emissions are 18%, which is nearly double the 10% share of final demand value and an increase of about 3% over its 1995 value (Nansai and Moriguchi 2006). As industry and power generation proceeds with the transition from heavy oils and coal to liquefied natural gas (LNG) with its smaller CO_2 emission factor (See Table 31.2), the large consumption of fuel oil C for ocean shipping is one factor behind the increased share of CO_2 emissions by "exports". If one takes into account the emissions from transport for international trade, exports are seen as economic demand with a high CO_2 emission.

This chapter will now examine in detail "household expenditures", which have a high share of CO_2 emissions: 36% of Japan's CO_2 emissions are induced by household expenditures. To obtain the big picture, Fig. 31.4 presents a skyline graph that comprehensibly describes the relationships between the amount of demand for a commodity, its embodied CO_2 emission intensity, and the quantities of CO_2 emission induced by the demand. The horizontal axis in this figure shows the cumulative value of annual demand $f_{i,B}$, or the cumulative expenditures including those to import goods by households in each sector in order of the 401 sectors, whereas the vertical axis indicates the magnitude of embodied CO_2 emission intensity. In the figure, the larger embodied CO_2 intensity of a particular sector is t_j calculated by Equation (31.1); the smaller embodied CO_2 intensity of that sector is $\bar{t}_j$ determined by Equation (31.10). The areas of the rectangles, whose bases represent amount of expenditure and whose heights represent embodied intensity, show the CO_2 emissions induced by expenditures.

$$\bar{\mathbf{t}}^{\mathbf{d}} = \mathbf{t}^{\mathbf{d}}(\mathbf{I} - \hat{\mathbf{m}}) \tag{31.10}$$

It is well known that emissions from electric power generation are large; however, even if service-related sectors have small embodied intensity values, because expenditures are large one can see that they cannot be ignored as consumption that increases emissions of CO_2. As typified by the "wholesale" and "retail" sectors, the CO_2 emissions of the supermarkets, department stores, and other businesses that

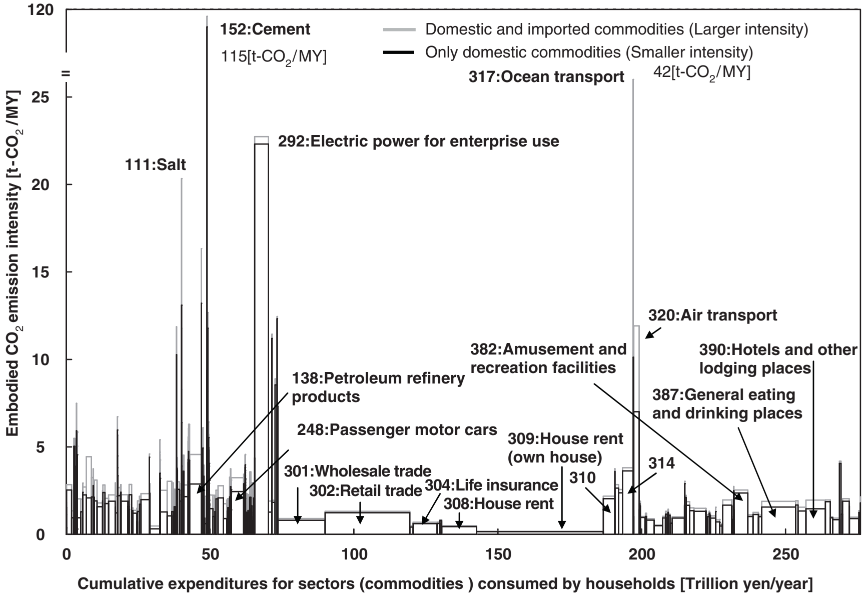

Fig. 31.4 Skyline Graph Describing the Relationship Between the Amount of Demand for a Commodity Consumed by Japanese Households in 2000, Its Embodied CO_2 Emission Intensities, and the Quantities of CO_2 Emission Induced by the Demand. The Horizontal Axis Shows the Cumulative Expenditure, Including that to Import Goods by Households, in Every Sector in Order of the 401 Sectors, Whereas the Vertical Axis Indicates the Magnitude of Embodied CO_2 Emission Intensity

households ordinarily use are not small. This graph also has the following implications about the future orientation of household consumption and technological development. Sectors whose bars in the figure are high are those considered to need improvements in production technology to achieve further CO_2 emission reductions. Sectors whose bars are both high and wide also need improved production technology, but consumers should prioritize efforts to reduce their expenditures in those sectors. These sectors include “electric power for enterprise use”, “air transport”, “petroleum refinery products”, and “passenger motor cars”. Sectors whose bars are not very high, but are wide, such as “amusement and recreation facilities”, “general eating and drinking establishments (excluding coffee shops)”, and “hotels and other lodging places” are sectors where consumers can make a contribution to reducing CO_2 emissions by considerably adjusting the amount of their expenditures. And then there are sectors whose bars are low but wide. If the quality of life improves because of increased expenditure in these sectors, then these can be considered sectors appropriate for allocating surplus money economized elsewhere. In other words, these sectors are perhaps recommended as commodities that can better suppress the rebound effect by which new consumption using surplus money generates new CO_2 emission.

Summary

This chapter has discussed the history of the compilation of environmental burden data that can be applied to IO analysis in Japan. Environmental data began to be assembled in 1971, starting with the preparation of the "Input–Output Table for Environmental Pollution Analysis" based on the Leontief pollution abatement model (Leontief 1970), in response to the changing environmental concerns of the day. In the 1990s, as IO analysis found greater use in LCA research, institutions started making their environmental data generally available; through the comparison of methodologies and data this brought major contributions to improving and raising the reliability of values and methods used to estimate environmental burdens. Some recent Japanese case studies applying IO analysis have been analyses of water pollutants (Nansai et al. 2005a), metals (Murakami et al. 2004), and hazardous chemicals (Nansai et al. 2005b). When the usefulness and problems of IO analyses of such substances are verified, and when the reliability of the data is assured, the data will probably be made generally available, as has been the case for other data. Analyzing a wide range of environmental burdens will not only broaden the possibilities of IO analysis in environmental analysis, but it also promises to contribute greatly to solving Japan's environmental problems.

Two practical approaches were described for estimating the direct environmental burden for each sector in an IO table. These approaches were characterized by whether the sectoral environmental burden was obtained exogenously (the exogenous estimate approach) or determined endogenously on the basis of the input structure of burden causes expressed in the IO tables (the endogenous estimate approach).

This chapter also described a case study for amassing environmental data corresponding to the IO tables. The endogenous estimate approach was used to find the embodied CO_2 emission intensities of individual sectors on the basis of the approximately 400-sector classification of Japan's 2000 IO table. Values of the embodied intensities are included in the Appendix to this chapter. This was followed by an analysis of the CO_2 emission structure as seen from final economic demand in 2000, which found that direct and indirect emissions by the "household expenditures" sector amount to 49% of Japan's CO_2 emissions. The skyline graph plotting indirect CO_2 emissions due to household expenditures suggested that there are sectors in which it is desirable to reduce CO_2 emissions by improving production technology, and other sectors in which consumers should help reduce emissions by adjusting their expenditures.

Electronic data (*version* 00) on the embodied intensities showed in this chapter are available on the 3EID website (Nansai and Moriguchi 2006).

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Appendix

Table 31.3 List of TC_j: Annual Total CO_2 Emission, e_j: Unit Direct CO_2 Emission, t_j: Embodied Emission Intensity Based on the $(\mathbf{I}-\mathbf{A})^{-1}$ Matrix, and t_j^d: Embodied Emission Intensity Based on the $(\mathbf{I}-(\mathbf{I}-\hat{\mathbf{m}})\mathbf{A})^{-1}$ Matrix. These Values Are for 2000 and the Unit MY Expresses a Million Yen. The Diagonal Matrix $\hat{\mathbf{m}}$ is Written as **M**.

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the (I-A)$^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the (I-(I-M)A)$^{-1}$ [t-CO_2/MY]
1	Rice	592240	0.243	1.694	1.487
2	Wheat, barley and the like	22679	0.161	2.172	1.833
3	Potatoes and sweet potatoes	40467	0.163	1.833	1.545
4	Pulses	9317	0.090	1.130	0.929
5	Vegetables	3680145	1.458	2.844	2.634
6	Fruits	110308	0.118	1.350	1.171
7	Sugar crops	9861	0.113	1.569	1.318
8	Crops for beverages	2273	0.018	1.442	1.166
9	Other edible crops	4941	0.250	1.541	1.077
10	Crops for feed and forage	27366	0.153	1.735	1.453
11	Seeds and seedlings	12768	0.120	1.276	1.049
12	Flowers and plants	2112482	3.859	5.490	5.258
13	Other inedible crops	46170	0.354	1.488	1.319
14	Daily cattle farming	38724	0.043	1.756	1.409
15	Hen eggs	23946	0.052	2.230	1.735
16	Fowls and broilers	20285	0.074	2.807	2.250
17	Hogs	13868	0.031	2.470	1.952
18	Beef cattle	12089	0.019	2.101	1.609
19	Other livestock	7307	0.064	1.479	1.170
20	Veterinary service	108083	0.892	2.106	1.904
21	Agricultural services (except veterinary service)	337554	0.715	3.015	2.760
22	Silviculture	57500	0.068	0.422	0.376
23	Logs	147429	0.434	1.740	1.632
24	Special forest products (inc. hunting)	679376	2.913	5.402	5.034
25	Marine fisheries	7648163	6.194	7.486	7.192
26	Marine culture	990094	1.755	3.937	3.365
27	Inland water fisheries and culture	128197	1.000	3.327	2.961
28	Metallic ores	10483	0.709	6.490	6.206
29	Materials for ceramics	284304	1.668	5.597	5.275
30	Gravel and quarrying	153662	0.358	5.047	4.747
31	Crushed stones	258312	0.409	4.820	4.520
32	Other non-metallic ores	10914	1.360	5.828	5.501

(continued)

Table 31.3 (continued)

33	Coal mining	16961	0.465	5.862	5.592
34	Crude petroleum and natural gas	5346	0.061	2.518	2.385
35	Slaughtering and meat processing	2014	0.001	2.028	1.621
36	Processed meat products	220162	0.260	2.014	1.461
37	Bottled or canned meat products	40721	0.474	2.932	2.475
38	Daily farm products	1285917	0.634	2.712	2.399
39	Frozen fish and shellfish	204666	0.127	4.448	3.625
40	Salted, dried or smoked seafood	234891	0.361	3.243	2.370
41	Bottled or canned seafood	112472	0.776	3.747	3.024
42	Fish paste	205366	0.448	2.796	2.129
43	Other processed seafood	217543	0.208	3.104	2.425
44	Grain milling	98499	0.035	1.801	1.594
45	Flour and other grain milled products	452772	0.654	2.490	1.930
46	Noodles	756537	0.693	2.827	2.454
47	Bread	443672	0.329	2.062	1.759
48	Confectionary	995455	0.391	2.261	1.968
49	Bottled or canned vegetables and fruits	84992	0.550	2.942	2.556
50	Preserved agricultural foodstuffs (other than bottled or canned)	175357	0.308	2.178	1.926
51	Sugar	805633	2.826	5.640	5.292
52	Starch	362094	2.462	4.618	4.050
53	Dextrose, syrup and isomerized sugar	334177	2.406	6.725	6.202
54	Vegetable oils and meal	458878	0.836	3.272	2.635
55	Animal oils and fats	58372	2.215	5.666	4.929
56	Condiments and seasonings	603270	0.403	2.674	2.270
57	Prepared frozen foods	372280	0.635	2.714	2.296
58	Retort foods	141299	0.716	2.849	2.412
59	Dishes, sushi and lunch boxes	1016732	0.388	2.269	1.901
60	School lunch (public)	360081	0.421	1.874	1.607
61	School lunch (private)	1121	0.359	1.693	1.431
62	Other foods	1428527	1.000	2.853	2.547
63	Refined sake	164098	0.238	1.519	1.364
64	Beer	790026	0.287	1.380	1.220
65	Whiskey and brandy	66044	0.324	1.495	1.320
66	Other liquors	315690	0.480	1.916	1.683
67	Tea and roasted coffee	183267	0.198	2.171	1.806
68	Soft drinks	1140500	0.332	2.329	2.008
69	Manufactured ice	1129	0.019	4.601	4.417
70	Feeds	524698	0.522	2.853	2.115
71	Organic fertilizers, n.e.c.	85622	0.530	2.906	2.370
72	Tobacco	103897	0.034	0.478	0.374
73	Fiber yarns	163671	0.561	4.289	3.633
74	Cotton and staple fiber fabrics (inc. fabrics of synthetic spun fibers)	154446	0.533	4.707	3.928
75	Silk and artificial silk fabrics (inc. fabrics of synthetic filament fibers)	100509	0.369	5.406	4.504
76	Woolen fabrics, hemp fabrics and other fabrics	62113	0.276	4.544	3.710
77	Knitting fabrics	19896	0.139	3.766	2.968
78	Yarn and fabric dyeing and finishing (processing on commission only)	2198864	3.334	7.086	6.216
79	Ropes and nets	16259	0.191	4.181	3.407
80	Carpets and floor mats	56900	0.286	4.469	3.616

(continued)

Table 31.3 (continued)

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the $(I\text{-}A)^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the $(I\text{-}(I\text{-}M)A)^{-1}$ [t-CO_2/MY]
81	Fabricated textiles for medical use	23895	0.273	2.818	2.387
82	Other fabricated textile products	338421	0.561	4.248	3.669
83	Woven fabric apparel	81098	0.035	2.521	1.938
84	Knitted apparel	110688	0.135	3.035	2.400
85	Other wearing apparel and clothing accessories	126455	0.366	2.944	2.431
86	Bedding	23468	0.094	2.319	1.725
87	Other ready-made textile products	73833	0.139	2.582	2.002
88	Timber	125448	0.122	1.722	1.314
89	Plywood	186111	0.235	2.714	2.183
90	Wooden chips	8724	0.094	1.900	1.414
91	Other wooden products	282968	0.226	2.112	1.746
92	Wooden furniture and fixtures	168827	0.113	2.196	1.787
93	Wooden fixtures	113516	0.179	2.389	1.951
94	Metallic furniture and fixture	167983	0.198	4.096	3.542
95	Pulp	1476102	2.150	8.618	7.757
96	Paper	11579950	4.933	11.865	10.790
97	Paperboard	3150245	4.400	11.517	10.565
98	Corrugated cardboard	129145	0.201	7.267	6.616
99	Coated paper and building (construction) paper	570838	0.952	5.718	5.013
100	Corrugated card board boxes	224650	0.169	3.657	3.331
101	Other paper containers	257163	0.294	4.210	3.681
102	paper textile for medical use	368660	0.747	4.394	3.866
103	Other pulp, paper and processed paper products	415837	0.403	4.382	3.895
104	Newspapers	157474	0.062	3.004	2.576
105	Printing, plate making and book binding	1447382	0.203	2.907	2.550
106	Publishing	164334	0.070	2.269	1.959
107	Chemical fertilizer	1137710	3.040	8.282	7.420
108	Industrial soda chemicals	2843477	5.138	18.743	18.001
109	Inorganic pigment	791156	2.682	8.473	7.529
110	Compressed gas and liquefied gas	198484	0.679	8.960	8.660

(continued)

Table 31.3 (continued)

111	Salt	877222	16.266	20.339	19.533
112	Other industrial inorganic chemicals	2207343	2.785	8.065	7.110
113	Petrochemical basic products	4884896	3.974	10.753	9.459
114	Petrochemical aromatic products (except synthetic resin)	1915774	3.201	9.052	7.977
115	Aliphatic intermediates	8344322	4.545	14.999	13.622
116	Cyclic intermediates	4219810	3.399	11.134	9.633
117	Synthetic rubber	2548219	4.282	12.335	11.479
118	Methane derivatives	361505	2.559	8.652	7.498
119	Oil and fat industrial chemicals	213418	2.488	5.388	4.764
120	Plasticizers	315218	3.062	9.905	8.271
121	Synthetic dyes	447293	6.212	11.786	10.129
122	Other industrial organic chemicals	3807381	4.277	11.450	10.410
123	Thermo-setting resins	903042	1.635	8.757	6.747
124	Thermoplastics resins	3470308	2.478	10.314	8.869
125	High function resins	841243	1.655	8.775	6.554
126	Other resins	1916656	4.780	12.651	10.697
127	Rayon and acetate	534845	5.630	11.510	10.420
128	Synthetic fibers	1486629	2.763	9.968	8.423
129	Medicaments	1282812	0.198	2.522	2.153
130	Soap, synthetic detergents and surface active agents	703656	0.923	4.531	3.803
131	Cosmetics, toilet preparations and dentifrices	168148	0.105	2.821	2.394
132	Paint and varnishes	210759	0.215	5.326	4.219
133	Printing ink	72021	0.212	5.573	4.396
134	Photographic sensitive materials	667999	0.836	4.322	3.657
135	Agricultural chemicals	321654	0.794	4.850	4.105
136	Gelatin and adhesives	257502	0.975	6.053	4.997
137	Other final chemical products	2585321	1.410	6.302	5.170
138	Petroleum refinery products (inc. greases)	32288275	2.729	4.573	3.335
139	Coal products	8404850	11.639	16.334	13.676
140	Paving materials	32087	0.075	2.958	2.351
141	Plastic products	3251983	0.317	4.564	3.726
142	Tires and inner tubes	804009	0.866	6.089	5.371
143	Rubber footwear	31607	0.579	2.637	2.092
144	Plastic footwear	56309	0.532	3.326	2.783
145	Other rubber products	821097	0.431	3.966	3.450
146	Leather footwear	37047	0.126	1.832	1.331
147	Leather and fur skins	73129	0.825	2.968	2.379
148	Miscellaneous leather products	26649	0.094	2.173	1.708
149	Sheet glass and safety glass	1134233	2.146	5.156	4.754
150	Glass fiber and glass fiber products, n.e.c.	839142	3.435	6.870	6.369
151	Other glass products	1918060	2.045	4.941	4.600
152	Cement	53619370	106.985	115.081	114.371
153	Ready mixed concrete	342997	0.188	22.344	21.777
154	Cement products	1080753	0.654	9.860	9.431
155	Pottery, china and earthenware	3449279	4.104	6.508	6.098
156	Clay refractories	614402	2.440	8.654	7.950
157	Other structural clay products	1375499	5.295	8.696	8.269
158	Carbon and graphite products	699891	3.150	7.732	7.046
159	Abrasive	206895	1.016	3.843	3.322
160	Miscellaneous ceramic, stone and clay products	2878713	3.203	6.350	5.850

(continued)

Table 31.3 (continued)

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the $(I\text{-}A)^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the $(I\text{-}(I\text{-}M)A)^{-1}$ [t-CO_2/MY]
161	Pig iron	128809502	102.538	109.972	107.456
162	Ferro alloys	4920343	43.638	52.817	50.965
163	Crude steel (converters)	−2382699	−1.117	63.232	60.130
164	Crude steel (electric furnaces)	7712412	7.621	24.572	19.627
165	Steel scrap	0	0.000	0.000	0.000
166	Hot rolled steel	10174864	2.242	37.663	35.115
167	Steel pipes and tubes	1263591	1.536	18.956	17.196
168	Cold-finished steel	4812247	1.869	21.784	19.816
169	Coated steel	2092687	1.593	14.262	12.862
170	Cast and forged steel	1746336	5.906	16.987	15.570
171	Cast iron pipes and tubes	726393	4.880	11.837	11.348
172	Cast and forged materials (iron)	4172801	3.186	12.669	11.900
173	Iron and steel shearing and slitting	162695	0.114	14.774	13.208
174	Other iron or steel products	163518	0.784	11.134	10.183
175	Copper	471283	1.509	6.732	3.344
176	Lead and zinc (inc. regenerated lead)	576776	3.141	10.863	9.282
177	Aluminum (inc. regenerated aluminum)	1008482	2.369	8.499	6.293
178	Other non-ferrous metals	393474	0.799	5.719	3.065
179	Non-ferrous metal scrap	0	0.000	0.000	0.000
180	Electric wires and cables	258556	0.251	3.591	2.447
181	Optical fiber cables	52601	0.188	3.499	2.898
182	Rolled and drawn copper and copper alloys	423272	0.782	4.834	3.461
183	Rolled and drawn aluminum	619144	0.543	5.767	2.981
184	Non-ferrous metal castings and forgings	1141067	1.197	5.228	3.223
185	Nuclear fuels	63703	0.316	4.592	1.767
186	Other non-ferrous metal products	479621	0.829	4.448	2.599
187	Metal products for construction	587850	0.221	7.684	6.857
188	Metal products for architecture	775958	0.291	4.591	3.763

(continued)

Table 31.3 (continued)

189	Gas and oil appliances and heating and cooking apparatus	213637	0.223	5.557	4.830
190	Bolts, nuts, rivets and springs	547211	0.431	6.429	5.745
191	Metal containers, fabricated plate and sheet metal	666811	0.395	5.719	5.043
192	Plumber’s supplies, powder metallurgy products and tools	443716	0.512	4.647	3.972
193	Other metal products	1863109	0.558	4.815	4.259
194	Boilers	91702	0.208	2.972	2.601
195	Turbines	116485	0.255	3.567	2.968
196	Engines	198477	0.178	3.811	3.299
197	Conveyors	96245	0.081	3.462	2.980
198	Refrigerators and air conditioning apparatus	169967	0.138	2.978	2.505
199	Pumps and compressors	221821	0.118	3.901	3.357
200	Machinists’ precision tools	114926	0.149	4.063	3.394
201	Other general industrial machinery and equipment	434107	0.200	4.151	3.662
202	Machinery and equipment for construction and mining	332553	0.173	3.399	2.978
203	Chemical machinery	67013	0.065	2.570	2.212
204	Industrial robots	53579	0.069	2.750	2.282
205	Metal machine tools	203869	0.122	3.020	2.626
206	Metal processing machinery	99608	0.138	3.502	3.105
207	Machinery for agricultural use	152039	0.231	3.775	3.300
208	Textile machinery	62877	0.133	2.926	2.467
209	Food processing machinery	37285	0.116	4.149	3.522
210	Semiconductor making equipment	139466	0.070	2.500	1.936
211	Other special machinery for industrial use	222295	0.109	2.913	2.439
212	Metal molds	225785	0.133	3.684	3.267
213	Bearings	284682	0.295	6.893	6.177
214	Other general machines and parts	237659	0.218	4.050	3.461
215	Copy machine	100083	0.073	2.299	1.775
216	Other office machines	87682	0.084	2.094	1.646
217	Machinery for service industry	110012	0.071	2.248	1.833
218	Electric audio equipment	84921	0.045	2.255	1.748
219	Radio and television sets	19650	0.030	2.240	1.734
220	Video recording and playback equipment	15076	0.010	2.192	1.634
221	Household air-conditioners	70880	0.062	2.531	2.063
222	Household electric appliances (except airconditioners)	110310	0.046	2.777	2.265
223	Personal Computers	162300	0.066	1.748	1.227
224	Electronic computing equipment (except personal computers)	57054	0.066	1.768	1.143
225	Electronic computing equipment (accessory equipment)	142479	0.034	1.970	1.377
226	Wired communication equipment	130673	0.070	2.020	1.571
227	Cellular phones	107606	0.068	2.042	1.546
228	Radio communication equipment (except cellular phones)	124165	0.076	1.999	1.532
229	Other communication equipment	50212	0.118	1.902	1.545
230	Applied electronic equipment	94081	0.043	1.745	1.317
231	Electric measuring instruments	38649	0.026	1.654	1.213
232	Semiconductor devices	454246	0.375	2.286	1.943

(continued)

Table 31.3 (continued)

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the (I-A)$^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the (I-(I-M)A)$^{-1}$ [t-CO_2/MY]
233	Integrated circuits	1096574	0.217	2.226	1.863
234	Electron tubes	204734	0.407	3.020	2.607
235	Liquid crystal element	172431	0.116	2.257	1.752
236	Magnetic tapes and discs	158810	0.329	3.262	2.760
237	Other electronic components	740210	0.081	2.138	1.707
238	Rotating electrical equipment	195712	0.156	3.434	2.900
239	Relay switches and switchboards	174528	0.065	2.698	2.209
240	Transformers and reactors	7062	0.026	3.593	2.960
241	Other industrial heavy electrical equipment	65060	0.082	2.498	1.995
242	Electric lighting fixtures and apparatus	132112	0.161	2.668	2.240
243	Batteries	182172	0.178	3.748	2.937
244	Electric bulbs	209894	0.401	2.573	2.189
245	Wiring devices and supplies	70900	0.124	2.356	1.893
246	Electrical equipment for internal combustion engines	183148	0.110	3.106	2.591
247	Other electrical devices and parts	636741	0.348	3.162	2.335
248	Passenger motor cars	666048	0.055	3.234	2.740
249	Trucks, buses and other cars	246330	0.104	3.440	2.921
250	Two-wheel motor vehicles	55685	0.088	3.117	2.641
251	Motor vehicle bodies	292046	0.164	4.865	4.231
252	Internal combustion engines for motor vehicles and parts	1045597	0.219	3.356	2.873
253	Motor vehicle parts and accessories	3396563	0.218	3.548	3.023
254	Steel ships	124729	0.091	7.188	6.388
255	Ships (except steel ships)	4621	0.084	3.099	2.642
256	Internal combustion engines for vessels	142997	0.282	4.539	4.030
257	Repair of ships	10363	0.045	4.571	4.013
258	Rolling stock	53250	0.134	4.747	4.101
259	Repair of rolling stock	608159	1.455	5.570	5.055
260	Aircrafts	101662	0.104	1.549	1.176
261	Repair of aircrafts	18329	0.037	1.266	0.704
262	Bicycles	35262	0.157	2.465	1.692

(continued)

Table 31.3 (continued)

263	Other transport equipment	84167	0.116	3.663	3.202
264	Camera	38961	0.086	1.706	1.266
265	Other photographic and optical instruments	98332	0.143	2.320	1.984
266	Watches and clocks	40756	0.117	2.067	1.519
267	Professional and scientific instruments	18203	0.175	2.379	2.071
268	Analytical instruments, testing machine, measuring instruments	120972	0.087	2.043	1.640
269	Medical instruments	215875	0.224	2.271	1.832
270	Toys and games	33037	0.047	2.281	1.742
271	Sporting and athletic goods	114143	0.222	3.572	3.005
272	Musical instruments	21807	0.072	2.165	1.757
273	Audio and video records, other information recording media	23550	0.092	2.284	1.916
274	Stationary	49978	0.142	2.582	2.194
275	Jewelry and adornments	63688	0.139	2.953	1.954
276	"Tatami" (straw matting) and straw products	5289	0.037	1.350	1.114
277	Ordnance	94815	0.245	2.910	2.336
278	Miscellaneous manufacturing products	333250	0.165	2.719	2.242
279	Reuse and recycling	413407	0.264	5.966	4.842
280	Residential construction (wooden)	614540	0.052	2.148	1.842
281	Residential construction (non-wooden)	1230044	0.118	3.234	2.886
282	Non-residential construction (wooden)	40564	0.055	2.277	1.987
283	Non-residential construction (non-wooden)	1917131	0.149	3.239	2.901
284	Repair of construction	1488565	0.166	2.933	2.591
285	Public construction of roads	3449387	0.358	3.798	3.513
286	Public construction of rivers, drainages and others	2511094	0.255	3.612	3.355
287	Agricultural public construction	1247311	0.469	3.692	3.413
288	Railway construction	212315	0.149	4.791	4.391
289	Electric power facilities construction	148692	0.119	2.936	2.586
290	Telecommunication facilities construction	135214	0.094	2.352	2.027
291	Other civil engineering and construction	1315500	0.214	3.825	3.515
292	Electric power for enterprise use	323111804	20.799	22.726	22.304
293	On-site power generation	53694272	44.660	47.156	46.298
294	Gas supply	657661	0.274	1.907	1.270
295	Steam and hot water supply	1101217	7.459	11.440	11.194
296	Water supply	155423	0.051	1.959	1.841
297	Industrial water supply	19510	0.138	2.343	2.256
298	Sewage disposal	4461107	3.921	8.893	8.540
299	Waste management services (public)	13944853	10.936	12.455	12.324
300	Waste management services (private)	13222529	6.271	7.446	7.315
301	Wholesale trade	5413566	0.089	0.907	0.817
302	Retail trade	7527214	0.207	1.320	1.235
303	Financial service	617599	0.023	0.481	0.425
304	Life insurance	349636	0.043	0.699	0.621
305	Non-life insurance	120798	0.038	0.710	0.631
306	Real estate agencies and managers	297584	0.084	0.844	0.787
307	Real estate rental service	1447238	0.237	0.886	0.846
308	House rent	1493460	0.123	0.498	0.454
309	House rent (imputed house rent)	0	0.000	0.176	0.156
310	Railway transport (passengers)	751211	0.119	2.185	2.079
311	Railway transport (freight)	90296	0.594	3.756	3.592
312	Bus transport service	3615453	2.133	2.844	2.699

(continued)

Table 31.3 (continued)

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the $(I-A)^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the $(I-(I-M)A)^{-1}$ [t-CO_2/MY]
313	Hired car and taxi transport	4548526	1.922	2.564	2.426
314	Road freight transport	35521314	2.886	3.810	3.633
315	Self-transport by private cars (passengers)	52568283	8.685	11.134	10.486
316	Self-transport by private cars (freight)	34853466	9.418	11.775	11.175
317	Ocean transport	40452889	21.677	42.040	22.401
318	Coastal and inland water transport	8678326	9.126	10.435	10.148
319	Harbor transport service	1091854	0.784	1.380	1.302
320	Air transport	28082982	10.653	11.912	11.608
321	Freight forwarding	306372	0.769	1.498	1.395
322	Storage facility service	76002	0.056	1.841	1.750
323	Packing service	74899	0.061	1.901	1.629
324	Facility service for road transport	263272	0.076	1.023	0.963
325	Port and water traffic control	95402	0.797	1.782	1.662
326	Services relating to water transport	13204	0.146	0.563	0.523
327	Airport and air traffic control (public)	17659	0.112	1.591	1.466
328	Airport and air traffic control (industrial)	39783	0.326	1.903	1.788
329	Services relating to air transport	45049	0.098	0.943	0.865
330	Travel agency and other services relating to transport	78297	0.072	0.779	0.693
331	Postal service	371354	0.175	1.216	1.030
332	Fixed telecommunication	390623	0.051	0.903	0.824
333	Mobile telecommunication	313647	0.054	0.536	0.495
334	Other telecommunication	83516	0.026	1.038	0.943
335	Other services relating to communication	6106	0.096	1.012	0.941
336	Public broadcasting	45308	0.067	1.324	1.157
337	Private broadcasting	364832	0.161	1.130	0.966
338	Cable broadcasting	44632	0.132	1.025	0.919
339	Public administration (central)	3476615	0.304	1.439	1.254

(continued)

Table 31.3 (continued)

340	Public administration (local)	7292357	0.294	1.155	1.091
341	School education (public)	2049176	0.131	0.677	0.636
342	School education (private)	1394227	0.259	1.003	0.924
343	Social education (public)	246674	0.221	1.742	1.645
344	Social education (private, non-profit)	58185	0.257	2.342	2.182
345	Other educational and training institutions (public)	922602	1.735	3.036	2.904
346	Other educational and training institutions (profitmaking)	1191987	1.356	2.232	2.109
347	Research institutes for natural science (public)	534703	0.443	2.016	1.919
348	Research institutes for cultural and social science	23643	0.436	1.021	0.943
349	Research institutes for natural sciences (private, nonprofit)	2071	0.255	0.942	0.872
350	Research institutes for cultural and social science (private, non-profit)	1191	0.122	0.530	0.485
351	Research institutes for natural sciences (profitmaking)	727894	1.177	3.165	3.007
352	Research institutes for cultural and social science (profit-making)	1471	0.031	0.820	0.716
353	Research and development (intra-enterprise)	4069509	0.383	1.945	1.793
354	Medical service (public)	2780994	0.470	1.864	1.665
355	Medical service (non-profit foundations, etc.)	2324458	0.325	1.521	1.359
356	Medical service (medical corporations, etc.)	5606687	0.273	1.494	1.324
357	Health and hygiene (public)	242439	0.392	1.264	1.144
358	Health and hygiene (profit-making)	68497	0.215	1.486	1.345
359	Social insurance (public)	86878	0.099	1.455	1.363
360	Social insurance (private, non-profit)	66530	0.134	1.392	1.310
361	Social welfare (public)	331763	0.215	1.012	0.908
362	Social welfare (private, non-profit)	511977	0.200	1.129	1.011
363	Nursing care (In-home)	388040	0.295	1.324	1.218
364	Nursing care (In-facility)	732998	0.272	1.231	1.103
365	Private non-profit institutions serving enterprises	426201	0.409	1.265	1.107
366	Private non-profit institutions serving households, n.e.c.	768525	0.241	1.061	0.932
367	Advertising services	937014	0.103	1.554	1.362
368	Information services	773501	0.055	0.833	0.735
369	News syndicates and private detective agencies	26555	0.030	0.856	0.716
370	Goods rental and leasing (except car rental)	330642	0.030	0.570	0.484
371	Car rental and leasing	311720	0.192	0.641	0.585
372	Repair of motor vehicles	318480	0.048	1.970	1.676
373	Repair of machine	264503	0.043	1.981	1.625
374	Building maintenance services	429712	0.102	0.642	0.560
375	Judicial, financial and accounting services	436833	0.163	0.672	0.606
376	Civil engineering and construction services	1243336	0.302	1.010	0.905
377	Worker dispatching services	27151	0.017	0.119	0.106
378	Other business services	1161906	0.083	0.732	0.643
379	Motion picture and video production, and distribution	162402	0.108	1.322	1.131

(continued)

Table 31.3 (continued)

Sector number	Sector name	TC_j: Annual total CO_2 emission [t-CO_2/year]	e_j: Unit direct CO_2 emission [t-CO_2/MY]	t_j: Embodied CO_2 emission intensity based on the $(I\text{-}A)^{-1}$ [t-CO_2/MY]	$t^d{}_j$: Embodied CO_2 emission intensity based on the $(I\text{-}(I\text{-}M)A)^{-1}$ [t-CO_2/MY]
380	Movie theaters	80002	0.468	2.735	2.546
381	Theater and entertainment facilities	24980	0.197	1.540	1.428
382	Amusement and recreation facilities	2545990	0.507	2.540	2.395
383	Stadiums and promoters of bicycle, horse, motorcar and motorboat races	399508	0.222	1.122	1.033
384	Sport facility service, public gardens and amusement parks	720004	0.275	1.254	1.155
385	Theatrical companies	19694	0.033	1.188	1.014
386	Other amusement and recreation services	181697	0.164	1.099	1.025
387	General eating and drinking places (except coffee shops)	4545201	0.308	1.890	1.628
388	Coffee shops	634303	0.479	1.925	1.714
389	Eating and drinking places for pleasures	2387024	0.347	1.552	1.371
390	Hotels and other lodging places	2735193	0.329	1.966	1.780
391	Cleaning, laundry and dyeing services	2147521	0.714	1.974	1.871
392	Barber shops	447449	0.503	1.004	0.944
393	Beauty shops	714806	0.303	0.925	0.841
394	Public baths	1310158	2.491	4.186	4.051
395	Photographic studios	122042	0.113	1.366	1.161
396	Ceremonial occasions	1245607	0.544	2.038	1.898
397	Miscellaneous repairs, n.e.c.	52849	0.306	1.783	1.608
398	Places for private lessons	387357	0.114	0.988	0.908
399	Other personal services	129760	0.253	1.356	1.245
400	Office supplies	0	0.000	3.771	3.107
401	Activities not elsewhere classified	1727904	0.410	2.144	1.910
	Total of intermediate sectors	1134966970			
A1	Outside household expenditures (Direct)	1417272			
B1	Household expenditures (Direct)	171901557			
	Total	1308285799			

Chapter 32
Developing the Sectoral Environmental Database for Input-Output Analysis: Comprehensive Environmental Data Archive of the U.S.

Sangwon Suh

This paper elucidates the data sources and data preparation procedures used in developing the sectoral environmental data of the U.S. The database described in this paper interlinks (1) Input-Output Table (IOT), (2) environmental emission and resources use statistics, and (3) characterization factors from Life Cycle Impact Assessment (LCIA) that quantify environmental impacts. Each of these three modules was designed to describe (1) the economic process generates environmental interventions, (2) the quantity of the environmental intervention generated, and (3) the process that these environmental interventions realize environmental impacts, respectively. The resulting database encompasses 1,344 different types of environmental interventions generated by 480 commodities of the U.S. input-output table, linked to 86 commonly used LCIA models. This paper aims to share the experiences of and to elucidate the procedures and the data sources used for developing the sectoral environmental database in the U.S.

Introduction

Dealing with environmental issues associated with economic activities requires addressing at least three main question areas: (1) the mechanism in the economic system that generates the environmental interventions, (2) the amount of environmental interventions generated by the economic system, and (3) the mechanism in the environment, with which these environmental interventions finally realize adverse environmental impacts.[1] The first question area requires a detailed insight into

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[1] Given the mutual interconnectedness between the two systems, it is not only that the economy influences the environment but also that the aggravated environment adversely affects the economy.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

how an economic system is structured with respect to the technological relations between its components. The second question area demands extensive effort in environmental data mining. The third question area requires insights into how the biotic and abiotic systems of the Earth are configured by means of physicochemical and biological relationships. Therefore, environmental economic analyses demand knowledge not only from economics but also from diverse fields including environmental statistics, environmental sciences, toxicology, biology, chemistry, physics, and geosciences.

In this paper, the development of sectoral environmental data for use in environmental economic analysis is presented, which connects the three question areas by interlinking (1) Input-Output Table (IOT), (2) environmental emission and resources use statistics, and (3) characterization factors from Life Cycle Impact Assessment (LCIA) that quantify environmental impacts. This paper aims to share the experiences of and to elucidate the procedures and the data sources used for developing the sectoral environmental database in the U.S.

In the next section, the content of the developed database is briefly introduced. Sections "Input-Output Data", "Compilation of Sectoral Environmental Data", and "Characterization Factors of LCIA" describe the sources and the procedures used to compile the database: Section "Input-Output Data" describes the IO data sources; Section "Compilation of Sectoral Environmental Data", which is the main part of the paper, deals with the environmental data; Section "Characterization Factors of LCIA" introduces how characterization factors are derived in LCIA field. Section "Discussion and Future Outlook" concludes the paper.

Comprehensive Environmental Data Archive 3.0

What is generally referred to as an 'environmental problem' is often a combination of diverse issues which may include natural resources use, land coverage and transformation, radiation, noise, and various emission-related issues from toxic impacts to climate change. Basically they are all kinds of disturbances that anthropogenic activities adversely affect the delicate physicochemical and biological balances of the biotic and the abiotic systems of the Earth. Each of these impact areas is associated with various stressors, or environmental interventions, that become effective through a variety of complex mechanisms, which are partly known but are still largely unknown. For instance, the number of chemical substances known to humans exceeds 26 million,[2] but only a small fraction of them has so far revealed their amount of production, fate and the exposure mechanisms, and potential environmental implications.

The latter is sometimes considered as a part of an environmental problem as is in the case of resources depletion.

[2] The number of chemicals listed in the Chemical Abstract Service (CAS) Registry database, which is considered as the largest chemical database in the World.

Traditionally, however, analyses from the economics side tend to represent environmental impacts in an overly simple manner using a limited set of well-known pollutants, mainly CO_2, SO_2 and NO_X (see e.g., Dasgupta et al., 2002; Cole 2000; Suri and Chapman 1998; Grossman and Krueger 1995). While these substances are certainly important ones, focusing only on these substances may lose the insight on the possible problem shifting between different areas of environmental concerns, or safeguard subjects, especially from well-known ones to diffuse, but persistent, ones. The recent efforts in National Accounting Matrices including Environmental Accounts (NAMEA) accomplished a more comprehensive coverage of environmental interventions (de Haan and Keuning 1996; EC 2001), but depending on the types of application, they may still fall short in addressing the diverse environmental issues.

When the number of environmental interventions in an economic model falls in the order of several hundreds, then another problem arises: how to communicate the result? Many studies choose to simply add up hundreds of toxic substances into the total mass (see e.g., Hettige et al., 1992; Mani and Wheeler 1997; Wheeler 2001), while the meaningfulness of the resulting figures is questionable given the enormous differences in the fate and exposure characteristics and the toxicity of different substances.

In the domain of Life Cycle Assessment (LCA), the information of a more comprehensive set of environmental interventions is collected generally at a detailed process level (see e.g., Frischknecht et al., 1996; Frischknecht 2005). This information is then connected to LCIA models, where their behaviors in the environment and the corresponding impacts are analyzed using up-to-date knowledge from various natural sciences. Recently, increasingly more IOTs are connected to LCA studies forming a new branch of LCA approach, called Input-Output (IO) LCA. Now, national IOTs of Australia, Denmark, Germany, Japan, the Netherlands, Sweden and the U.S. are being used in connection to LCA studies (Lave et al., 1995; Nansai et al., 2002, 2003; Nijdam and Wilting 2003; GDI 2004; Weidema et al., 2005; see Suh et al., 2004 for a survey of existing databases).

The sectoral environmental database of the U.S., named ‘Comprehensive Environmental Data Archive (CEDA)’ 3.0, follows the tradition of IO-LCA but with more ambitious objectives: CEDA 3.0 covers a total of 1,344 environmental interventions that are related to the 480 commodities distinguished in the U.S. and that are linked to 86 widely used environmental models. The environmental interventions covered range from 1-(3-Chloroallyl)-3,5,7-Triaza-1-Azoniaadamantane Chloride to Ziram with the base-year of 1998.[3] The database is derived from various environmental databases, including the Toxics Releases Inventory (TRI), National Toxics Inventory (NTI), National Emissions Trend (NET) databases, greenhouse gas emissions and sinks data, agricultural chemical and fertilizer use data, mineral and fossil fuel resource use database, energy consumption data, and land use data. The interventions covered include resource use (6 items), land use (1 item), and environmental emissions to air (551 items), to freshwater (331 items), to industrial

[3] In 1998 U.S. EPA extended the sector coverage for their TRI report, dramatically increasing the completeness of the database.

soil (236 items), and to agricultural soil (219 items) and relate to over 480 commodities produced in the U.S. With the 1,344 environmental interventions, CEDA 3.0 covers the key driving causes of major environmental impacts such as global warming, ozone layer depletion, various toxic impacts to humans and ecosystems, acidification, eutrophication, land use and resource depletion.

The data on environmental interventions that are compiled and related to the U.S. input-output sectors are then connected to characterization factors of LCIA, allowing users to aggregate environmental interventions into environmental impact scores. The selected impact assessment methods include Global Warming Potentials (GWPs), Ozone Depleting Potentials (ODPs), CML2002 methods, Strategies in Product Development (EPS) method, Swiss Eco-Point method and Eco-Indicator 99 methods, which cover diverse environmental issues such as natural resources depletion and various toxic impacts to humans and ecosystems. A description of environmental LCIA models, including those selected for inclusion in CEDA 3.0, can be found in Guinée et al. (2002).

The resulting database is applicable to various environmental economic analyses including policy modeling, Material Flow Analysis (MFA), Substance Flow Analysis (SFA), LCA, analyses of consumption and its environmental impacts, and alternative material selection in environmental design.

Input-Output Data

CEDA 3.0 uses the U.S. 1998 annual input-output tables (BEA 2002, Annual input-output table – make and use matrices for 1998, unpublished) and a calculation procedure to derive commodity × commodity table that follows the standard U.S. make and use framework provided in BEA (1995a, b). The 1998 annual input-output table, which distinguishes around 500 sectors, is appended with capital flows information. The most recent capital flow matrix available then was for the year 1992 (BEA 1995c, Benchmark survey for 1992 – capital flow matrix, unpublished). The amount of capital goods used by each sector has been inflated or deflated depending on price change information and gross output differences between 1992 and 1998 for the sector in question. In the 1992 benchmark survey by BEA, uses of 163 capital goods by 64 industries were compiled on the basis of SIC code. These have been reassigned to the relevant IO categories for inclusion in the use matrix (see e.g., Lenzen 2001).[4]

The resulting make and use matrices are then used to construct commodity × commodity technology coefficient matrices following the standard industry-technology models.

[4] In CEDA 3.0, any data involving SIC code are first assigned to the most detailed set of SIC codes, which distinguish 1,037 different industries, and then reclassified under a BEA code to preserve as far as possible the detail of the primary data.

Compilation of Sectoral Environmental Data

Compilation of environmental data is not a straightforward process of simply collecting data, but involves various assumptions and modeling efforts to harmonize and assemble fragment, and often incompatible, information. In this section, the data sources and the data preparation procedures used in developing CEDA 3.0 database are described.

Greenhouse Gas Emission

Total U.S. greenhouse gas (GHG) emissions, including carbon dioxide (CO_2) emissions, are fairly well established. Apart from the CO_2 emission data for the electric utility sector compiled by Energy Information Administration (EIA) and Environmental Protection Agency (EPA), however, data at the level of individual sectors are not readily found. Consequently, the rest of the estimation procedure for combustion-oriented CO_2 emissions focuses on sectors other than electric utility sector.

With regard to transportation, there are two categories of CO_2 emissions to be distinguished: those of household transportation and industrial transportation. In CEDA it is assumed that the use of all trucks, buses, aircraft, boats and vessels and locomotives are part of industrial activities. CO_2 emissions from international bunker fuel combustion, construction equipment and agricultural vehicles are also assigned to industrial use. CO_2 emissions from all other activities, mainly driving passenger cars, are assumed to be household activities.[5]

CO_2 emissions reported under the headings 'industry' and 'commercial' have been assigned to individual IO industries based on the transaction records for the fuel types in question and the data on combustion-oriented CO_2 emissions by fuel type compiled by EPA (EPA 2002a). Non-combustion-oriented CO_2 emissions have been assigned based on the source process cited by EPA (2002a). The remaining emission sources could be allocated directly to the appropriate IO industrial sectors (Table 32.1).

Methane

In 1998, emissions of methane (CH_4) accounted for 9.3% of total industrial and households GHG emissions of the U.S. (627.1 Tg CO_2-equivalents). Besides enteric fermentation (particularly by ruminants), industrial processes such as landfills,

[5] In reality some of the passenger cars are used as a part of industrial activities by e.g., insurance careers, likewise, some of the heavy-duty trucks and buses are used for private purposes. These overlaps were, however, not considered to be significant and were assumed to be canceled out.

Table 32.1 Direct U.S. Industrial Carbon Dioxide Emissions, by Sector[a]

	Aggregated sector	Sources	Emission (Tg CO_2)	Share (%)
	Electric utility	Electric utility	2160.3	46
Combustion-oriented	Industry (based on fuel consumption)	Coal	137.8	21
		Natural gas	484.1	
		Petroleum	194.2	
		Lubricant oil	12.7	
		Other petroleum	171.3	
	Transportation	Light duty trucks	356.4	24
		Other trucks	257.9	
		Buses	12.4	
		Aircraft	183.0	
		Boats and vessels	47.8	
		Locomotives	33.8	
		Construction and agricultural equipment	93.0	
		International bunker fuel	112.9	
	Commercial (based on fuel consumption)	Coal	8.7	
		Natural gas	163.5	5
		Petroleum	47.2	
Non-combustion-oriented	Industrial processes	Iron and steel	67.4	4
		Cement manufacturing	39.2	
		Waste combustion	20.3	
		Ammonia manufacturing	20.1	
		Limestone and dolomite	21.9	
		Natural gas flaring	6.3	
		Soda ash manufacturing	5.8	
		Titanium dioxide	4.3	
		Ferroalloys	1.8	
		CO_2 consumption	1.4	
	Total		4665.5	100

[a] An international platform where these activities are lively discussed, developed and disseminated is the Life Cycle Initiative by the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (see e.g., Jolliet et al. 2003b).

natural gas systems and coal mining are the predominant sources, and these ‘area sources’ can be readily assigned to a relevant IO classification.

Given the CH_4 emission factors for residential and commercial coal combustion (300 and 10, respectively) and respective consumption of the two sectors in

Table 32.2 U.S. Industrial Methane Emissions, Based on Direct Emission[a]

Source		Emission (Gg CH_4)	Share (%)
Landfills		9,571	39.91
Natural gas systems		5,820	24.27
Coal mining		3,235	13.49
	Dairy cattle	624	2.60
	Swine	864	3.60
	Beef cattle	161	0.67
Manure management			
	Sheep	2	0.01
	Goats	1	0.00
	Poultry	130	0.54
	Horses	29	0.12
Wastewater treatment		1,326	5.53
Petroleum systems		1,114	4.64
Stationary sources		334	1.39
Rice cultivation		376	1.57
Mobile sources		123	0.51
Petrochemical production		78	0.33
Agricultural residue burning		37	0.15
Others		153	0.66
Total		23,984	100

[a] See e.g. the European Pollutant Emission Register (EPER) <http://eper.cec.eu.int/>. For a list of national emission registers, see <http://eper.cec.eu.int/eper/National_links.asp?i=>, also for Japan see <http://www.prtr.nite.go.jp/english/prtr-e.html>, and for the USA <http://www.epa.gov/ttn/chief/net/index.html>.ions.

1998 (13 and 92 Tbtu), based on coal consumption, only 19% of CH_4 emissions from 'stationary' sources have been assigned to intermediate industries (EPA 2002a; EIA 2002). According to EPA (2002a) 42% of CH_4 emissions from mobile sources were due to passenger cars. Assuming other means of transportation can be assigned to intermediate industries, 58% of 'mobile' CH_4 emissions can then be assigned on the basis of transportation service transaction records, and this has been done in CEDA (Table 32.2).

Nitrous Oxide Emissions

Because of their very minor contribution to overall GHG emissions, only two N_2O sources have been deemed significant: 'agricultural soil management' and 'mobile sources', contributing 1.0 and 0.2 Tg of CO_2-equivalent GHG emissions (963 and 191 Gg as N_2O), respectively. Following the same line of reasoning as for CH_4, 46% of N_2O emissions from mobile sources have been assigned to intermediate industries on the basis of transportation service utilization.

Other Greenhouse Gas Emissions

CEDA 3.0 also covers the following greenhouse gases: Trichloromethane, Sulfur Hexafluoride, Tetrachloromethane, Perfluorobutane, Perfluorocyclobutane, Perfluoroethane, Perfluorohexane, Perfluoromethane, Perfluoropentane, Perfluoropropane, Methylbromide, Methyl Cyclohexane, Halon-1211, Halon-1301, 7 different HCFCs, 13 different HFCs, 6 different CFCs, and Dichloromethane. However, their contribution is generally insignificant for most industries.

Criteria Pollutants

The term ‘criteria pollutants’ in the U.S. refers to six air pollutants: carbon monoxide (CO), nitrogen oxides (NO_X), sulfur dioxide (SO_2), particulate matter (PM),[6] ozone (O_3) and lead (Pb). Four of these, CO, NO_X, SO_2 and PM, have been compiled and maintained by the U.S. National Emissions Trend (NET) database, which is now being absorbed into the National Emissions Inventory (NEI) database together with the National Toxics Inventory (NTI) database for Hazardous Air Pollutants (HAPs) (EPA 2002, National toxics inventory (NTI) 96 database, unpublished, 2002c). The NET database covers both point sources and non-point sources, including area sources and mobile sources. The point source emissions compiled in the NET database provide detailed information on emission sources at the facility level and also indicates the SIC code of the facility. The point source section of the database can therefore be readily assigned to the appropriate industry on the basis of SIC codes. In CEDA 3.0, the most detailed SIC code set has been used to assign SIC-based information without losing resolution. The NET database for point source criteria pollutant emissions covers a total of 1,037 SIC industries, and these emissions have been converted into 500 BEA industry codes, based primarily on the standard comparison between SIC and BEA codes prepared by BEA. In cases where an SIC code can be subsumed under more than one BEA heading, additional data sources such as main source facility type or total amount of industry output have been employed to split the emission figure over multiple BEA sectors.

Non-point sources have no SIC code, but as these are described in detail they can readily be tied to an IO industry classification code. For non-point sources, including both mobile and area sources, NET provides a more aggregated classification of emission sources (less than 200 source-types). Therefore, emissions from non-point sources have been converted to the BEA industry classification based on several assumptions. For instance, CO emissions from “agricultural fires” have been assigned to 16 agricultural industries in the BEA classification based on their share of total output, and NO_X emissions from “on-road vehicles” have been assigned to 500 BEA industries based on the rate of on-road vehicle utilization by each industry,

[6] Based on EPA (2002a), EIA (2002) and own calculations.

assuming that use of truck and bus services represents industrial use of on-road vehicles. Non-anthropogenic sources such as forest wildfires have not been assigned to intermediate industries.

Volatile Organic Compounds (VOC) and Ammonia

These two pollutants are also covered by the NET database and the procedure and data sources employed in CEDA to compile these pollutants are similar to those used for the criteria pollutants.

Toxic Pollutants

The toxic pollutants part of the database is the most challenging, even in the U.S., which probably has the most advanced monitoring and reporting system for toxic chemicals in the world. In the U.S., toxic emissions are dealt with under a number of different initiatives, including the Toxics Releases Inventory (TRI), National Toxics Inventory (NTI) and National Center for Food and Agricultural Policy (NCFAP) database (EPA 2002, National toxics inventory (NTI) 96 database, unpublished, 2002b, c–; NCFAP 2000). These databases comprise extensive arrays of toxic chemicals: 535 in TRI98, 188 in NTI and 235 in NCFAP. Nonetheless, certain important chemicals could be missing, although the list is based on up-to-date knowledge of toxic chemicals. However, identification and quantification of other toxic chemical releases than those covered by these databases was not considered a priority in CEDA 3.0, and, thus, only those chemicals listed in the cited databases have been included.[7]

Table 32.3 summarizes the scope of the three databases in terms of emission source types, industries, environmental media and emissions from facilities below the threshold limit.

A glance at Table 32.3 indicates that none of the databases cover emissions to water and land (other than pesticides) by mobile and area sources, NTI covering only Hazardous Air Pollutants (HAPs) and TRI mainly point sources only. While toxic pollutant emissions to environmental media other than air by mobile sources are not considered to be significant, those from area sources, such as leachate emissions from landfills, could be considerable. These gaps have meanwhile been fairly well filled, however, following a recent extension of the TRI databases, especially for Mining (SIC 1021–SIC 1474), Logistic services (SIC 4212–SIC 4581), Sewerage and refuse systems (SIC 4952 and SIC 4953) and Solid waste management (SIC 9511). In addition to these sectors, since 1998 most major chemical-handling sectors have also been included in the TRI database, and industry coverage by this database

[7] Based on EPA (2002a).

Table 32.3 Coverage of Toxic Emission Databases

Scope of database		TRI	NTI	NCFAP
Source type	Area	–	Good	Good
	Mobile	–	Good	–
	Point	Good	Good	–
Industry	Agricultural and mining	Moderate[a]	Poor	Good
	Manufacturing	Good	Good	–
	Services	Moderate[a]	Good	–
Substances	Air	Good	Moderate	–
	Water	Good	–	–
	Soil	Good	–	Moderate[b]
Coverage within industries	Reports from larger facilities only	Moderate	Good	–
	Estimation for facilities below thresholds	–	Good	–

[a]Since 1998 some of these activities have been covered by TRI.
[b]Whether the pesticide applied is an emission to air, water or soil depends very much on the properties of the applied chemical, climate conditions, etc. However, here the arguments are postponed to the stage of impact assessment method specification, and the emission itself is regarded as an emission to soil.

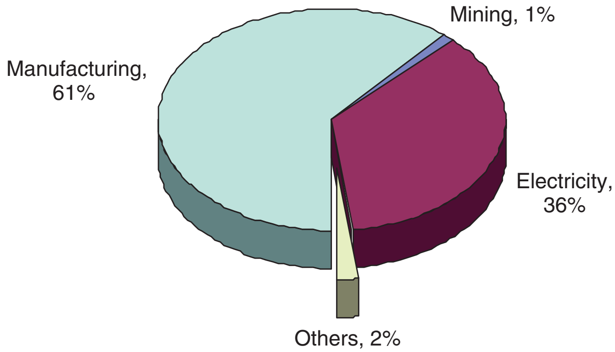

Fig. 32.1 Contribution by Industries to NTI Database by Mass

therefore seems reasonably complete, although obviously not 100%. This has indeed been confirmed, for air emissions at least (Fig. 32.1). According to the NTI database, a total of 3,669,196 t of HAPs was emitted in the U.S. in 1996, with Manufacturing industries (SIC 20–SIC 39) and Electricity, sewerage and refuse systems (SIC 49) contributing around 97%, emitting 2,202,304 and 1,338,170 t, respectively. Thus, the major industries generating all but 2% of HAP emissions are within the scope of the extended TRI database.

However, emission reports for the TRI 98 database are collected only from those facilities employing ten or more full-time equivalent employees or manufacturing or processing over 25,000 pounds or otherwise using over 10,000 pounds of any listed chemical during the reporting year. Although the emission from each individual facility not meeting these conditions may well be small, together they may be quite substantial. Therefore, it is important to quantify the possible magnitude of truncation in TRI database due to the threshold conditions.

The completeness of the TRI database has been examined using the NTI database and establishment size distribution data compiled by the Bureau of Census (2001). The NTI database estimates HAP emissions using reports as well as emission factors and activity rates, regardless of the size of facilities. A comparison between TRI and NTI for overlapping chemicals can therefore provide an indication of the truncation of TRI of facilities below the threshold. Unfortunately, however, NTI database for 1998 was not compiled and the most recent NTI data available then was the one for 1996, and, therefore, the comparison could have been carried out only between TRI 98 and NTI for 1996 (see Fig. 32.2). The data points in Fig. 32.2 show the amount of releases of overlapping chemicals reported in TRI 98 and the NTI for 1996 whose yearly releases are more than 1 t. The thin, main diagonal line indicates the case where TRI and NTI report the same value. The thick line above is the regression result based on the data from TRI and NTI. Even if the 2 years of temporal difference are taken into account, this comparison suggests that there might be significant systematic truncations in TRI showing only 17.2% of HAP emissions, on average, as compared to NTI. This strongly suggests that using only TRI may significantly underestimate the potential impacts of toxic releases.[8]

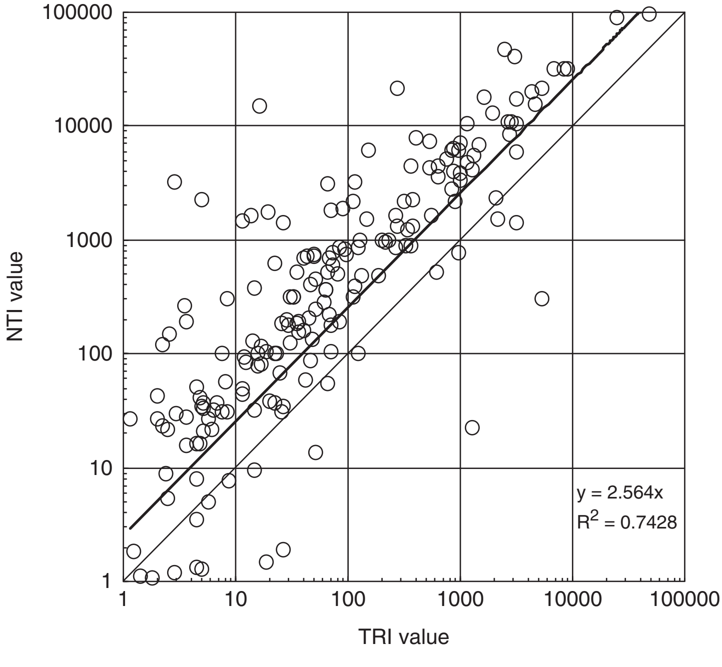

Fig. 32.2 The Relationship Between Reported Emissions by Mass in TRI and NTI

[8] PM10 and PM2.5 have been distinguished.

One explanation for such large differences between the two database might lie in the size distribution of establishments. Given the wide range of processes involved, each industry has different establishment size distribution characteristics. For instance, North American Industry Classification System (NAICS) 323, Printing and related support activities is dominated by establishments with less than ten employees, which account for 66% of the total of 42,863 establishments, while the share of these smaller establishments in the Paper manufacturing sector (NAICS 322) is only 20% of the total of 5,868 (U.S. Census Bureau 2001). The larger the number of smaller establishments in an industry, the less complete the TRI data for that sector will probably be. Besides following from the nature of the threshold, this is also due to emission standards generally being less strict for small-sized establishments and again, although such establishments may generate smaller volumes of toxic emissions individually, their sum total may be substantial.[9]

The regression study was further extended to the level of individual industries in order to reflect the differences in establishment size distribution. The TRI values for each sector represent, on average, 4.4–29.4% of the HAPs reported by NTI, depending on the sector involved.[10] These results do not support the argument that TRI can still indicate the relative magnitude of toxic impacts even though their absolute values are misleading due to homogeneous truncation. Due to the difference in the base years between the TRI and the NTI databases used for the comparison, the regression results are considered to be highly uncertain and, therefore, CEDA 3.0 contains not only the datasets with the estimation procedure but also the original data in these reports.

In compiling CEDA 3.0, the relatively complete data sources such as NTI for HAPs have been utilized as far as available. Otherwise, sectoral toxic emissions have been estimated based on TRI and the relationships between TRI and NTI values derived for each individual sector. In cases where no such sectoral relationships could not be established, owing either to sample size or to poor regression results, more general relationships between TRI and NTI have been used instead.

For mobile and area sources, direct use has been made of the NTI database, with no further adjustments as it is considered to cover most major emissions. Besides point source emissions, the NTI database also includes emissions from natural processes and post-production stages, including wildfire, household product usage, etc., and these emissions have been excluded from subsequent assignment to individual industries.

For pesticide emissions, direct use has been made of the NCFAP and other databases (Aspelin and Grube 1999; NCFAP 2000). This database compiles and maintains volume records of 235 pesticides applied to 88 types of crop. On the assumption that the amount of pesticide applied equals emission, pesticide emission data have been assigned directly to a BEA industry code based on crop type.

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[9] Some of the chemicals that are compiled in NET but are not included in these databases are identified and added to CEDA.

[10] These results also support, to some extent, the study by Ayres and Ayres (1998).

In CEDA 3.0, users can choose between the two sets of environmental data: one based on the data without using the estimation procedure that was employed to cover the missing emissions and the other with such procedure.

Land Use

In this part of the CEDA database, only uses of land by major land-covering activities are accounted for (in square meters).[11] In addition, mere occupation of land is all that is considered, with differences in neither land-use intensity nor land transformation being accounted for. Figure 32.3 shows the major forms of land use in the U.S. The Special uses cited in Fig. 32.3 include parks, wilderness, wildlife and related uses, transportation and national defense areas, while Others covers deserts, wetlands and barren land. Land uses that can be related to industrial production are croplands, grassland, part of Special uses (recreation, transportation and defense) and part of urban use (for industrial installations).

Urban use here includes industrial complexes and service areas other than agricultural uses, as well as urban residential areas. Most U.S. industrial activities take place in urban areas, accounting for around 3% of land use in this category. The average land coverage of each individual BEA sector is thus less than 0.006% at most, and these figures have therefore not been included in the CEDA database.[12] Among

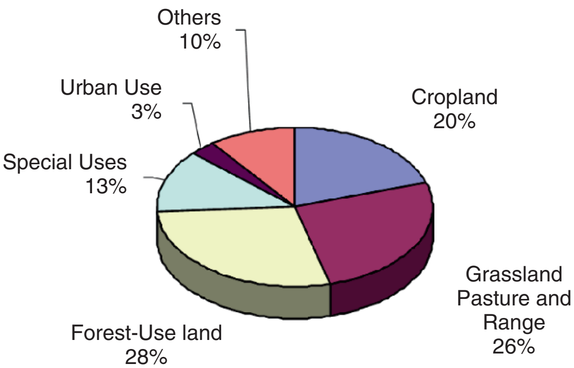

Fig. 32.3 Major Uses of Land in the U.S. (USDA 2002)

[11] Using the Bureau of Census (2001) data, the relationship between the completeness of TRI and the proportion of small-to-medium sized establishments in each industry was examined. The results show that the two are negatively correlated.

[12] The coefficients of regression lie between 2.1–7.1, depending on the sector. Several significant differences between TRI 98 (i.e., for 1998) and NTI for 1996 are observed for SIC 49, Utilities, although there was relatively little change in technology or regulation between the two periods. Formaldehyde and chlorine emissions, for instance, are reported to be 57.7 and 23.0 t, respectively, by TRI98, while NTI for 1996 reports, for the same chemicals, 15,965.5 and 1,514.0 t, respectively.

Special uses, natural parks are the largest category; however, these are not considered to be an environmental intervention and have therefore not been included in the CEDA database either. Several land use activities need to be allocated to appropriate industries. As both industrial and household activities contribute to land use for transportation, the share of the former was estimated based on the CO_2 emissions of passenger cars and other road vehicles such as trucks and buses. According to EPA (2002a) passenger cars are responsible for 36% of total CO_2 emissions by road vehicles. Thus, only 64% of total land use for transportation has been allocated to the transportation sector, based on respective total production values.[13] Grassland pasture and range has been allocated to livestock industries, again based on total production value. The remaining industrial uses of land have all been allocated directly to BEA codes (Table 32.4).

Nutrification

Nutrification is due principally to emissions of nitrogenous and phosphorus compounds to air, freshwater and soil. The main emission sources include combustion gases (for NOx to air) and application of fertilizer and manure (for emissions of nitrogenous and phosphorus compounds to freshwater). NO_X and NH_3 emissions from these sources are fully accounted for in the NET database. Although some nitrogenous emissions from manure application may subsequently undergo a series of biological processes known as nitrification and denitrification, forming nitrite (NO_2^-), nitrate (NO_3^-) and nitrogen gas (N_2), most are in the form of NH_3 or NH_4^+, depending on the ambient pH (or in the form of organic nitrogen), at the time of initial manure application to agricultural soils. For nitrogenous emissions, direct use has therefore been made of the NH_3 inventory of the NET database

Emissions of phosphorus (P) compounds are not readily available in any of the major statistical archives and these have therefore been estimated in terms of phosphorus equivalents, using several databases. The CEDA inventory covers phosphorus emissions due to manure application and phosphorus run-off from phosphate fertilizer application (Table 32.5).

NRCS (2000) provides data on the average mass excreted daily by each type of livestock, its P content and the average run-off ratio. These data have been employed together with the NASS (2003) statistics on U.S. 1998 livestock numbers to estimate annual P emissions to freshwater due to manure application (Table 32.6).

Over half the phosphate fertilizer applied in the U.S. is in the form of ammonium phosphate (NH_4HPO_4), containing 88–90% of active ingredient. The phosphorus content of ammonium phosphate fertilizer is thus around 22% by mass.

[13] Land use data for the year 1998 were not available in the data sources considered, and 1997 data were used instead (USDA, 2002). According to trend analyses by USDA (2002), however, the pattern of land use for different activities has remained fairly stable and no readjustments were therefore made to estimate values for 1998.

Table 32.4 Industrial Uses of Land in the U.S.

	Detailed use	Area (million square meter)	Share of total industrial use (%)
Cropland	Soybeans	408,777	10.68
	Corn for grain	397,729	10.39
	All wheat	303,821	7.94
	Cotton	75,495	1.97
	Sorghum for grain	47,875	1.25
	Other crops	40,509	1.06
	Corn silage	34,985	0.91
	Barley	27,620	0.72
	Rice	20,255	0.53
	Sunflower	20,255	0.53
	Oats	14,731	0.38
	Dry edible beans	11,048	0.29
	Noncitrus fruits	11,048	0.29
	Fresh market vegetables	11,048	0.29
	Sugarbeets	9,207	0.24
	Processing vegetables	9,207	0.24
	Peanuts for nuts	7,365	0.19
	Potatoes	7,365	0.19
	Canola	5,524	0.14
	Sugarcane	5,524	0.14
	Citrus fruits	5,524	0.14
	Tobacco	3,683	0.10
	Millet	3,683	0.10
	Tree nuts	3,683	0.10
	Rye	1,841	0.05
	Sorghum silage	1,841	0.05
Grassland pasture and range	Grassland pasture and range	2,339,108	61.09
Special uses	Transportation	101,173	2.64
	National defense	60,704	1.59

Total area of land in use: 2.3 billion acres (1997).

Table 32.5 Major Phosphorus Emissions from Livestock[a]

	Number (thousand)	g of P excreted/year per head	Estimated loss (%)	Annual emission (kg/year)
Beef cattle	33,885	18.23	15	92,648.88
Dairy cattle	9,199	9.9426	15	13,719.3
Chicken	425,045	53.0272	15	33,808.42
Swine	62,206	26.5136	15	247,395.8
Turkey	5,549	46.3988	15	38,618.66
		Total		3,773,225

[a]Own calculation based on Natural Resources Conservation Service (NRCS 2000) and National Agricultural Statistics Service (NASS 2003).

Table 32.6 Phosphorus Emissions Due to Fertilizer Application[a]

	Phosphate fertilizer applied (million pounds)	P content (kg)	P run-off (kg)	Share of total (%)
Corn	3,236.50	3.23E+08	4.85E+07	51.07
Wheat	1,326.40	1.32E+08	1.99E+07	20.93
Soybean	763.60	7.63E+07	1.14E+07	12.05
Cotton	378.20	3.78E+07	5.67E+06	5.97
Grapes	306.04	3.06E+07	4.59E+06	4.83
Sorghum	54.50	5.44E+06	8.17E+05	0.86
Oranges	35.94	3.59E+06	5.38E+05	0.57
Lettuce	35.41	3.54E+06	5.31E+05	0.56
Tomatoes	35.25	3.52E+06	5.28E+05	0.56
Melons	25.72	2.57E+06	3.85E+05	0.41
Onions	14.91	1.49E+06	2.23E+05	0.24
Corn	13.06	1.30E+06	1.96E+05	0.21
Carrots	12.38	1.24E+06	1.85E+05	0.20
Almonds	11.77	1.18E+06	1.76E+05	0.19
Beans, Samp, Proc.	8.93	8.92E+05	1.34E+05	0.14
Cabbage	8.91	8.90E+05	1.33E+05	0.14
Peas	8.84	8.82E+05	1.32E+05	0.14
Broccoli	8.13	8.12E+05	1.22E+05	0.13
Beans, Samp, Fresh	6.91	6.90E+05	1.03E+05	0.11
Celery	4.71	4.71E+05	7.06E+04	0.07
Peppers	4.65	4.65E+05	6.97E+04	0.07
Grapefruit	4.57	4.56E+05	6.85E+04	0.07
Apples	3.88	3.88E+05	5.82E+04	0.06
Cucumbers	3.17	3.17E+05	4.75E+04	0.05
Spinach	3.00	3.00E+05	4.50E+04	0.05
Strawberries	3.00	2.99E+05	4.49E+04	0.05

[a]Own calculation based on NASS (1998, 1999, 2000, 2003) and NRCS (2000).

NASS (1998, 1999, 2000, 2003) provides data on the amount of phosphate fertilizer applied to each type of crop (including fruits, vegetables and nuts). By applying the average phosphorus run-off rate to soil estimated by NRCS (2000), the level of phosphorus loss to soil was then estimated for use in CEDA 3.0.

Resource Depletion

The only resource types considered in CEDA are fossil fuels, iron ore, copper ore, and sand and gravel. Given the homogeneity assumption and the level of aggregation of the current IO table, there was felt to be little point to compile data on other mineral resources. For instance, any purchase from the ‘inorganic chemicals’ sector will be regarded in an IO framework as a blend of all kinds of mineral resources from gold to silicon, regardless of the specific material actually purchased. Compared with other industries using natural resources, however, the energy sector and the iron and steel industry are reasonably homogeneous.

Figures for natural gas extraction have been taken from EIA (2003a), data on crude oil consumption from EIA (2000) and data on coal from EIA (2003b). Statistics for iron ore, copper ore and sand and gravel extraction are from USGS (2000).

Derivation of Environmental Matrix

Since a commodity × commodity matrix is utilized for the input-output part, the dimension of environmental intervention matrix should likewise be intervention × commodity. For instance, the equation

$$\mathbf{m}^* = \mathbf{B}^I(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} \tag{32.1}$$

where $\mathbf{B}^I$ is an environmental intervention × industry matrix representing the environmental interventions caused by the production of \$1 worth of industry output, $\mathbf{A}$ a commodity × commodity input-output technology coefficient matrix, $\mathbf{y}$ a final demand vector, and $\mathbf{m}^*$ the total economy-wide environmental intervention calculated by this equation, is, although encountered in some of the literature, not congruent. In CEDA, the standards make and use framework is used to derive the intervention × commodity matrix.

Information on environmental interventions is compiled mainly on an industry rather than commodity basis. Environmental intervention matrix must therefore be derived from $\mathbf{B}^I$, by assigning the aggregate environmental intervention of each industry to its secondary products and scrap as well as its primary product. Assuming that the sum total of environmental interventions by a given industry is assigned proportionally to its primary and secondary products based on their economic value, the average environmental intervention due to a dollar's worth of commodity can then be calculated on the basis of market share as

$$\mathbf{B} = \mathbf{B}^I\mathbf{D} \tag{32.2}$$

where $\mathbf{B}$ is an environmental intervention × commodity matrix and $\mathbf{D}$ a market share matrix derived from make and use matrices. This method, which corresponds to the industry-technology assumption, was used for deriving the environmental intervention matrix in CEDA 3.0.

Alternatively, one can assume that each commodity generates its own characteristic environmental interventions, irrespective of the industry producing it. Under this assumption, commonly called commodity-technology assumption, the total environmental intervention of a primary product of a given industry is calculated by subtracting the total environmental intervention due to secondary products, indexed to industries producing these secondary products as primary products. In

LCA this method is referred to as the 'avoided impact' allocation method or 'system expansion' method and corresponds to the commodity-technology assumption in the make and use framework (for details, see e.g., Kagawa and Suh 2009). The resulting environmental intervention matrix generally contains numerous small negative values, which requires careful interpretation. In the public version of CEDA 3.0, only the environmental matrix derived from industry-technology assumption is included, while the one from commodity-technology assumption can be supplied upon request.

Characterization Factors of LCIA

Once the amount of total environmental interventions directly and indirectly generated is calculated using the input-output table and the environmental intervention data delineated in the two previous sections, quantification of environmental impacts follows. It is notable that LCIA is not the only approach to quantify environmental impacts, but there are a number of widely used approaches including Environmental Impact Assessment (EIA), Risk Analysis (RA) in addition to LCIA. Each of the approaches has different objectives and scope: EIA is a highly institutionalized procedure that is used to measure possible environmental implications of certain decision prior to the decision is actually enforced. An example is an EIA for a new, residential area development of a certain location, where the possible hazards of such development to its soundings are addressed. EIA is used more as a 'pass-fail' criteria, its main focus being on a local environment. The target problem of RA is more specific than EIA, and it generally deals with the fate, transportation and exposure of a specific, and generally toxic, substance in and around a contaminated site (EPA 1991). In contrast to EIA, a RA study generally, though not necessarily, takes place after certain contamination is noticed. As compared to these approaches, the scope of an LCA is much broader covering the major environmental concerns of the modern society. As a modeling framework, LCA is more time- and space- generic, meaning that it generally integrates the environmental impacts that take place over time and space in quantifying the potential environmental impacts of a product life-cycle.[14] Many characterization factors are derived at a national or at a continental scale rather than at the level of a specific contaminated site or of an emission source. The derived characterization factors are, therefore, more suitable for the analyses at a national or at a continental level, which is more in line with the geographical scale of IOA.

The rest of this section intends to provide a general introduction to how characterization factors in LCIA are derived. Detailed discussion on LCIA models, including these included in CEDA 3.0, can be found in Guinée et al. (2002).

[14] Furthermore, no statistics on land use were found that could be allocated to the detailed six-digit BEA industry level. As land use intensity in urban areas is considered relatively high, however, it is desirable to extend data coverage on urban use further, especially as impact assessment methods that can properly account for land use intensity become available.

LCA consists of four major steps: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 1998). In the goal and scope definition phase, the objective of the study, its intended application, the required data quality, system boundary and so on are set. In the Life Cycle Inventory (LCI) analysis phase, data on environmental interventions are collected or calculated, on-site from an appropriate industry or using LCA databases, respectively. In the impact assessment phase, the environmental impacts of the product or service are assessed by multiplying LCI results by relevant characterization factors quantifying the relative contribution of each environmental intervention to a particular environmental impact category such as global warming or ozone layer depletion (Guinée et al. 2002). To arrive at more aggregate indicators, this ‘characterization’ step may be followed by a number of additional steps, including normalization, grouping and weighting. These post-characterization steps are not incorporated in CEDA 3.0 but may be pursued by individual users.

The characterization step is briefly described below. The concept of characterization, as is currently used in LCA, has been developed independently in several scientific communities. In LCA, Global Warming Potentials (GWPs) and Ozone Depleting Potentials (ODPs) are among the most familiar characterization indicators currently employed. Once generated, any environmental intervention goes through a series of physical and chemical processes before eventually culminating an environmental problem. For instance, SO_2 emissions combine with water to form H_2SO_4, which may be ionized to $2H^+$ and $SO_4{}^{2-}$. As precipitation transfers these hydrogen ions to the soil system and lowers soil pH, the resultant acidification process may impact on vegetation and forestry. Together, these successive processes are referred to as an environmental mechanism (Fig. 32.4). Some environmental mechanisms are

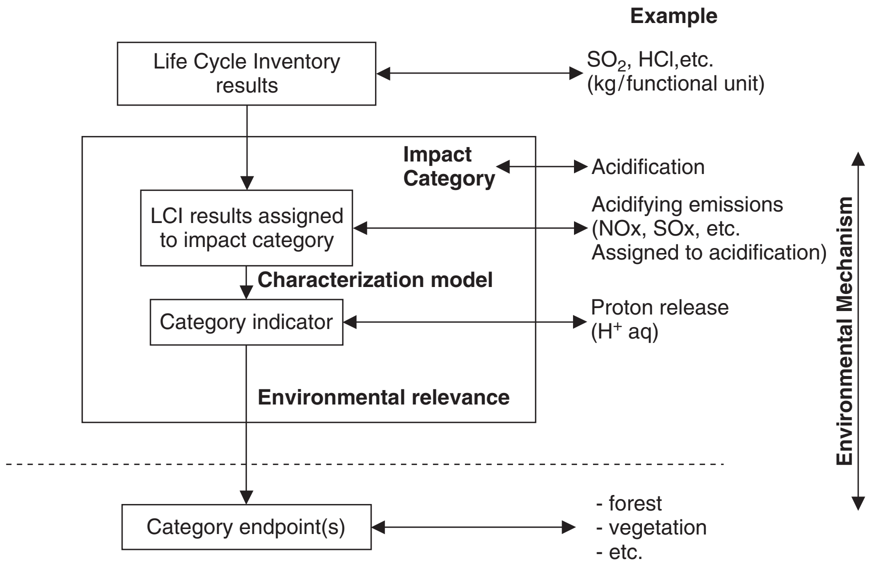

Fig. 32.4 Concept of Category Indicators (ISO 1999)

fairly simple, but most are complex and involve a multitude of physical and chemical transformations and fate and exposure routes. In an LCIA, a category indicator is chosen along with the environmental mechanism in such a way that the indicator reflects an important causal and quantitative relationship with the category endpoint. For instance, the total number of hydrogen ions generated in the process of acidification may provide a good category indicator. Using selected category indicators, each environmental intervention can be represented in terms of its equivalence to a reference intervention in the impact category in question. In the case of global warming, for instance, the radiative force of each greenhouse gas is chosen as category indicator (termed Global Warming Potential) and CO_2 as reference intervention for 1 GWP.

Characterization factors are simply a set of factors for converting environmental intervention results into the equivalent terms of a reference intervention. Depending on the characterization model used, the time horizon considered and the physical location of the category indicator, however, a number of different approaches are available to this end. Notably, the models used in LCIA can be categorized by the location where the category indicator is extracted along with the environmental mechanism. Early developments in LCIA generally preferred to choose the category indicator at an early stage of environmental mechanisms, such as the increased radiative force in global warming mechanism and proton release in acidification mechanism (see Heijungs et al. 1992a, b). Recently, LCIA models started to incorporate the category indicators near the category endpoints (Hofstetter 1998; Itsubo et al. 2004). Progresses are being made in these two schools of LCIA, namely mid-point and end-point modeling, and, to a certain extent, a combination of these two models are being implemented (see e.g., Heijungs et al. 2003; Jolliet et al. 2003a).[15]

The 86 methods included in CEDA 3.0 cover and embrace the characterization factor sets that are most widely referenced including those derived from the mid-point and the end-point models (Goedkoop and Spriensma 1999; Guinée et al. 2002). These factors are linked internally to all other interventions to avoid errors in linking interventions with appropriate factors. Nevertheless, individual users can choose other LCIA models than those used in the database by exporting the inventory results and linking them to the preferred characterization factors. For the list of LCIA models used in the database, see Suh (2004).

Discussion and Future Outlook

This paper describes the development of sectoral environmental data in the U.S. Compilation of sectoral environmental databases involves various modeling efforts to harmonize and to assemble fragment, and often incompatible, information. For

[15] There are several "within-industry" uses of transportation that are not visible in the input-output table. However, it has been assumed that utilization of transportation industry services reflects the relative magnitude of the transportation activities of each industry.

instance, in developing CEDA 3.0, a comparison between TRI and NTI databases indicated that the missing emissions due to the threshold condition in TRI may be significant, for which a regression analysis is carried out to estimate the missing portion. In this paper, the data sources and the data preparation procedures used in developing CEDA 3.0 database are described in detail.

Data works generally require significant amount of time and labor, while the result of this kind can never be complete. Nevertheless, a reliable and up-to-date primary data is, needless to say, a requirement for sound modeling practices. In this regard, there are yet many obstacles to be overcome to enable a more reliable sectoral environmental database.

First, economic statistics and environmental statistics need coordination. As the generation of environmental interventions are not separable from the embedding economic activities, the two need to share at least a common sector classification. Even in the U.S., where environmental statistics are well-established, the two use different sector classifications, demanding a laborious transformation procedure. As both economic and environmental statistics are based on rather institutionalized procedures, once established, they tend to be locked-in by the rigidity of the procedure and by the cost of nation-wide reform. This draws attention to the need of coordination between economic and environmental statistics in advance, especially for the countries planning to reform or to establish their environmental statistics. The Systems of Environmental and Economic Accounts (SEEA) and NAMEA frameworks (de Haan and Keuning 1996; EC 2001; UN 2003) certainly provide a starting point, while the efforts to fill-in such frameworks will need to be followed in individual countries.

Second, environmental information needs to be improved in most countries. The CEDA 3.0 database is based on U.S. environmental statistics, which covers an extensive list of environmental interventions. Such a database is, unfortunately, unavailable in most countries. There are a number of international initiatives that are underway to improve environmental statistics including Pollutant Release and Transfer Registers (PRTR).[16] These initiatives are expected to contribute to improving the coverage and reliability of environmental statistics, while its success is again dependant upon the efforts to be exerted by the individual countries in implementing these frameworks.

The database presented in this paper has been incorporated in commercial and non-commercial LCA software packages and has been successfully utilized in Integrated Product Policy (IPP) studies notably by the European Commission (EC) and the Danish Environmental Protection Agency (Goedkoop 2004; Weidema et al. 2005; Tukker et al. 2006). Nevertheless, the database is subject to further updates. First, quantitative uncertainty information needs to be attached to the database. Deriving and assigning quantitative uncertainty information to individual data cells has been a challenge, as the database contains half of a million data entries. If the background data used to derive them are included, there are over one million

[16] However, it is notable that major progresses have been made in LCIA to better take the spatial aspects into account (see e.g., Potting 2000; Wegener 2002).

cells that need to be assigned uncertainty figures. Second, environmental impacts associated with imports, which are currently assumed to be the same as those of domestically produced products, need to be better identified. Although the amount of imports in the U.S. is relatively marginal in monetary terms, their environmental implication may not be marginal as their monetary values suggest. Third, a number of key sectors that contribute a significant part of the overall environmental impacts need further disaggregation as well. The database is planed to be regularly updated using up-to-date data sources as well as LCIA models.

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Part IX
Advances in Modelling and Theory

Chapter 33
Ecological Input-Output Analysis of Material Flows in Industrial Systems

Reid Bailey

Ecologists have used input-output analysis since the early 1970s to study flows of materials and energy in complex networks. These ecological networks are very similar to material and energy flows in industrial systems, yet the input-output approach developed by ecologists has not been applied to industrial systems. In this paper, an overview of early work to adapt ecological input-output analysis to industrial systems is presented.

Introduction

The core development of input-output analysis is rooted in modeling economic flows in society. Connections to physical flows, such as material or energy, are typically made through conversion factors at the end of the analysis (e.g., \$ of steel production is converted to tons of steel through a factor with the units "t/\$"). In industrial ecology, the physical flows and their paths are a primary concern; their importance warrants more detailed analyses than allowed by economic-centric models. In this chapter, input-output tools used by systems ecologists are presented as a means through which material flows in industry can be modeled in greater depth.

Brief Review of Ecological IO Literature

Basics of Ecological IO: Network Analysis

In the early 1970s, several systems ecologists identified input-output analysis as a key way to trace nutrient flows in natural ecosystems. Ecosystems are defined in numerous ways, but ultimately reduce to a set of material and energy flows between

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organisms. To understand the behavior of ecosystems, the complex paths of materials and energy need to be well understood. From this need arose the use of input-output analysis to model nutrient and energy flows in ecosystems – termed *network analysis* in its most general form by ecologists (Fath et al. 2000).

First used to model ecosystems by Hannon (1973), network analysis' main advantage over other approaches to modeling physical flows in ecosystems is its ability to quantitatively model both direct and indirect effects, where an indirect effect is one that proceeds from one process to another through at least one intermediary process. In economic input-output models, an example of an indirect effect is the production of office supplies necessary to build a bridge. Office supplies are not directly used to build the bridge, but they are used by the contractors and the manufacturers of steel and concrete which are directly used to build a bridge. In an ecosystem, a plant will draw nitrogen from the soil while an animal (which has no direct connections to soil) will use that nitrogen by eating the plant. The nitrogen in the soil has an indirect effect on the animal.

Ecologists such as Patten and Fath have developed a theoretical foundation through which network analysis is connected to causal relationships in ecosystems (Fath et al. 2000, Patten et al. 1976). This foundation is not discussed in this chapter, but a key concept resulting from it is. *Causal closure* is a property of a system where all objects are "mutually causally related" (Patten et al. 1976). Ecosystems are causally closed systems. "Any cause introduced at the interface between an ecosystem and its environment propagates around the influence network define by component interactions and ramifies throughout the system to return eventually in dissipated strength to the point of original introduction" (Patten et al. 1979). Because ecosystems are causally closed, tracing the flow of nutrients and materials is not a simple mass balance problem and indirect effects can have a large influence on system behavior.

The purpose of this chapter is not to re-derive the mathematics used in ecological input-output mathematics. It is the same as that which is used in economic input-output analysis, with the main twist being that ecologists construct transposed matrices when compared to economists. That is, whereas the rows represent monetary flows flowing to the columns in economic input-output tables, the columns represent physical flows flowing to the rows in ecological input-output tables. The matrices in this paper are presented in the form used by ecologists. A comparison of the mathematics used by economists to that used by ecologists is presented by Suh (2005). In addition to comparing the two approaches, Suh generalizes the mathematics to highlight similarities.

The purpose of this chapter is, on the other hand, to demonstrate a few key ways ecologists use input-output analysis and how these approaches can be useful with industrial systems. To that end, there are two basic types of analysis for which ecologists use input-output techniques: structural and functional. Structural analysis is concerned with the presence and absence of connections between organisms and processes. Within functional analysis, there are three main areas: flow analysis, storage analysis, and utility analysis (Fath et al. 1999). In this paper, the focus is on structural analysis and flow analysis, two areas in which ecologists have performed significant work.

Structural Analysis

System structure refers to the presence or absence of processes and the presence or absence of connections between these processes. System structure is most easily seen visually, as shown in Fig. 33.1 with a directed graph (or digraph). To change the structure of the system in Fig. 33.2, a connection between the boxes in Fig. 9.1 must be added or deleted or a box itself must be added or deleted.

Structural analysis is used to identify and trace direct and indirect relationships within a network as show in Fig. 33.1. To do so, the digraph is represented in an adjacency matrix, **A**, in which an element (i, j) has a 1 in it if there is a flow from process j to process i. The adjacency matrix for the system in Fig. 33.1 is shown in Equation (33.1).

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{33.1}$$

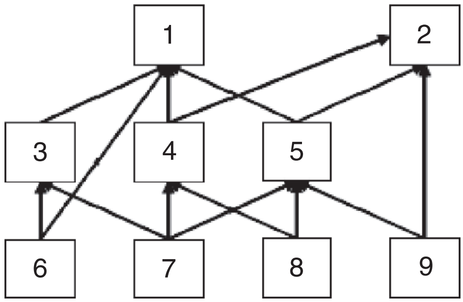


Fig. 33.1 A System with Nine Processes (Hardy et al. 2002)

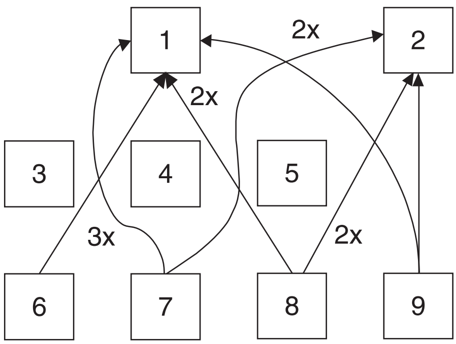


Fig. 33.2 Paths of Length=2

Matrix **A** represents all of the direct connections (i.e., connections with length = 1) between the nine processes in Fig. 33.1. When **A** is raised to the power n, the resulting matrix represents all connections within the network of length = n. Connections with lengths of two or greater are called *indirect* flows. Furthermore, when all connections of all lengths are accounted for, the resulting integral matrix represents all direct and indirect flows (as shown in Equation (33.2)). This ability to account for all direct and indirect flows is the feature that distinguishes ecological input-output analysis from other materials flow analysis (MFA) approaches.

$$B = I + A + A^2 + A^3 + A^4 + \ldots \tag{33.2}$$

B: integral
I: initial input
A: direct
A^n (for $n \geq 2$): indirect

For the example shown in Fig. 33.1, $\mathbf{A^2}$ is shown in Equation (33.3).

$$\mathbf{A}^2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 3 & 2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{33.3}$$

Non-zero elements of $\mathbf{A^2}$ represent the number of paths of length = 2 from process j to process i. For example, there is one path of length = 2 from process 6 to process 1 (from process 6 to 3 to 1). There are three paths of length = 2 from process 7 to process 1. Graphically, all paths of length = 2 are shown in Fig. 33.2.

There are not any paths of length = 3; therefore the integral matrix **B**, which represents all direct and indirect connections, is as shown in Equation (33.4).

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 & 2 & 3 & 2 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 2 & 2 & 2 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{33.4}$$

If any loops (i.e., a path that eventually returns to where it started) had been present in the network, then there would be paths of infinite length. Without any flows returning to a previous process, however, the maximum path length is finite. Indirect flows have a larger role when loops are present; accordingly, ecological input-output analysis is most useful when there are loops.

Flow Analysis

Flow analysis resembles economic input-output analysis more closely than does structural analysis. In economic analysis, the monetary output flow from a first industrial sector to a second industrial sector is normalized by the total monetary flow to the second sector. In flow analysis, the mass flow from a first organism or process to a second organism or process is normalized by the total mass to the second organism.[1] Or, stated more simply, monetary flows are replaced with physical flows.

Represented symbolically, each flow from process j to process i, f_{ij}, is normalized by the total flow to process i, T_i.

$$q_{ij} = \frac{f_{ij}}{T_i} \tag{33.5}$$

where q_{ij} is called the direct interaction or fractional inflow matrix. Analogous to the power series for structural analysis, the following power series is used to model all direct and indirect flows in flow analysis.

$$N = I + Q + Q^2 + Q^3 + Q^4 + \ldots \tag{33.6}$$

B: integral
I: initial input
Q: direct
Q^n (for $n \geq 2$): indirect

The expression in Equation (33.6) converges to the following.

$$N = (I - Q)^{-1} \tag{33.7}$$

There are two primary tools within the mathematics of flow analysis: flow metrics and environ analysis (Bailey et al. 2004a, 2004b). Flow metrics are used to characterize attributes of a network of flows. Environ analysis is used to trace the flows either from their origin or to their final outflow.

[1] Or, by the total mass flow *from* the first organism or process.

Metrics

Numerous metrics relevant to material flow systems can be derived with input-output analysis. The majority of these are based on **N** from Equation (33.7) and the total throughflow, T, of a process. Throughflow is the sum of all inflows into a process (which equals the sum of all outflows to a process[2]). Several key flow analysis metrics are summarized in Table 33.1.

The general goals of industrial ecology are to promote the efficient use of materials and energy at the system level through many means including recycling, reuse, remanufacturing, and the use of industrial by-products. Natural ecosystems are frequently used as models of efficient system level use of resources. It would appear

Table 33.1 Flow Analysis Metrics[a]

Metric	Mathematical expression	Meaning
Path length (PL)	$\frac{\sum_{k=1}^{n} T_k}{\sum IN}$ Where T_k is the sum of all inflows to a process k. and Σ IN is the sum of all flows into the system	The number of processes an average unit of flow travels through. If PL = 3, then the average unit of flow passes through three processes before exiting the system (Finn 1976)
Return cycling efficiency (REk)	$\frac{n_{kk}-1}{n_{kk}}$	The percent of flows at a process that are cycled. Bailey et al., use to measure percent cycled flows through consumptive and through production processes (Bailey et al. 2004a, 2004b)
Cycling index (CI)	$\frac{\sum_{k=1}^{n} RE_k T_k}{\sum_{k=1}^{n} T_k}$	The percent of flows in a system that are cycled (i.e., they pass through a process more than once) (Finn 1976). CI = 1 is indicative of a system completely sustained without any inflows or outflows
Dominance of indirect effects (DOI)	$\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}(n_{ij}-i_{ij}-q_{ij})}{\sum_{i=1}^{n}\sum_{j=1}^{n} q_{ij}}$	The numerator is all indirect flows and the denominator all direct flows. As dominance of indirect effects increases, the role of indirect flows in the system increases (Fath et al. 1999)
Amplification	$n_{ij} > 1,\ i \neq j$	If $n_{ij} > 1$, there is significant cycling of flows in the system leading to a process in the system having more material flow through it over time than is input into the system (Fath et al. 1999)

[a]Other metrics from flow analysis that are not introduced here include homogeneity, synergy (Fath & Patten 1999) and ascendancy (Ulanowicz & Baird 1999).

[2] More precisely, throughflow is the sum of all inflows and reductions from a stock (which equals the sum of all outflows and increases in stock size). In flow analysis, increases and decreases in stocks (i.e., storages) are treated as outflows and inflows, respectively.

that increasing path length, return cycling efficiencies, and cycling index would all align with the goal of industrial ecology. As materials and energy are used more efficiently, a linear flow of resources is shifted to a cyclical one. Furthermore, as this move from linear to cycling occurs, indirect effects within the system would begin to dominate and amplification would be seen in many processes in the system. Hence, the flow metrics in Table 33.1 are good candidates for measuring progress towards the development of industrial ecosystems.

Path length, return cycling efficiency, and cycling index have been explored in the context of industrial systems (Bailey et al. 2004a, 2004b). The relevance of dominance of indirect of effects (DOI) and amplification to industrial systems has not been studied. While it does seem that increasing the cycling index or path length would align with the objectives of industrial ecology, it has been shown that return cycling efficiency and its variants, consumption and production return cycling efficiencies, are more effective at modeling objectives of industrial ecology (Bailey et al. 2004a, 2004b). The basic problems with path length and cycling index is that there are major exceptions where an increase in path length or an increase in cycling index actually leads to less efficient material use.

Examples of each of these metrics is shown in a the Industrial Examples section of this chapter.

Environ Analysis

While metrics allow for quick snapshots of key system characteristics, environ analysis provides a means to study the paths of flows in depth. The path taken by material entering at a each inflow can be traced forward through the system to each outflow and vice versa. As an example, consider a "Type 3" ecosystem as shown in Fig. 33.3 (Jelinski et al. 1992).

For a unit of inflow z_{10}, environ analysis is used to determine the total flows through each process and the amount of outflow at y_{01}, y_{02}, and y_{03}. Similarly, for a

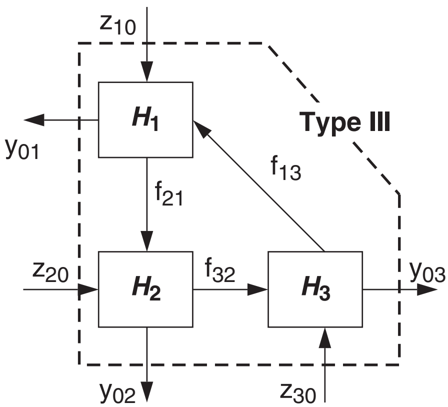


Fig. 33.3 Type 3 Ecosystem

unit of outflow y_{01}, environ analysis is used to determine the total flows through each process and the amount of inflow at z_{10}, z_{20}, and z_{30} needed to generate that unit of outflow. Details for how to perform environ analysis are described by Bailey (2000).

Relevant Similarities Between Ecosystems and Industrial Ecosystems

The connections between ecological and industrial systems that make applying ecological input-output analysis to industrial systems useful are straightforward. First, both ecosystems and industrial systems are networks of material and energy flows. Second, one reason ecological input-output analysis is powerful is its ability to model the indirect flows associated with cycles of flows. Cycles are extremely prevalent in nature at the ecosystem level. They are also prevalent in industry and will become even more so as concepts such as industrial ecology grow (Graedel et al. 1995). Finally, ecology treats biological systems holistically from a systems view. Industrial ecology is similar in its holistic view of industrial systems. In summary, the shared systems view of networks of material and energy flows, which frequently include cycling, are the relevant similarities between ecosystems and industrial ecosystems. These similarities provide the bridge with which ecological input-output analysis is applied to industrial systems.

Industrial Examples

An industrial example involving tufted carpet produced by Interface, Inc., is presented to highlight the capabilities of network analysis. Two models were originally constructed and studied: one for tufted carpet without any recycling of materials and one in which materials are recycled (Bailey et al. 2004a, 2004b). Some of the descriptions that follow are from (Bailey et al. 2004a, 2004b).

The original purpose of this study was to understand the advantages and disadvantages of recycling tufted carpet on a purely material basis and to seek approaches for improving the efficiency of materials use in the recycling model. The first step was to construct a material flow model and obtain the necessary data.[3] The carpet studied is composed of five materials: by mass, 16% of the carpet is nylon 6,6, 2% is fiberglass, 2.5% is polyester, 17.5% is latex and 62% is a polyvinyl chloride (PVC) compound (Parpart 1996). In the linear model, shown in Fig. 33.4, the carpet materials are modeled as proceeding directly from production to consumption and then to

[3] All data used in the case was measured at Interface's facilities in 1996. Certain information, such as the specific plant being modeled and the exact values of flows are not included in this paper because it is proprietary. Enough information, however, is included to demonstrate the usefulness of network analysis.

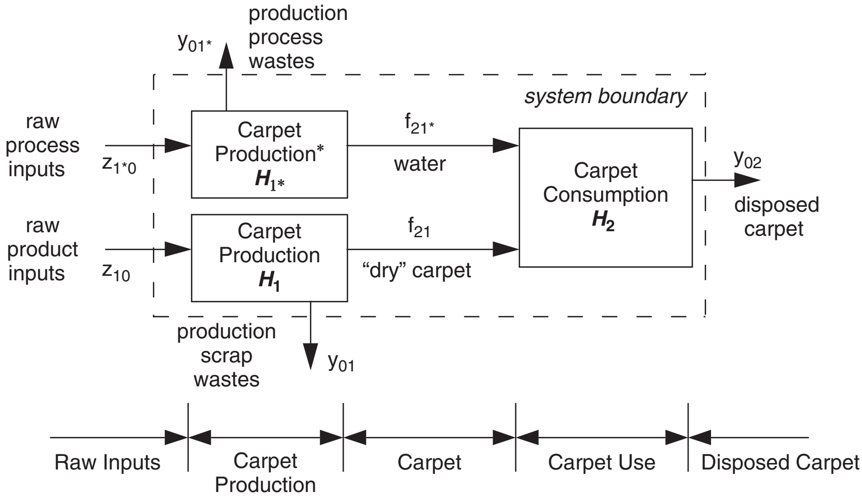


Fig. 33.4 Linear Interface Model

ultimate disposal. While the linear model is not explored significantly in this chapter, understanding it will help in understanding the more complex recycling model with is studied in greater depth.

Raw material enters carpet production as either process material (e.g., water, natural gas, air) or product material (e.g., nylon, PVC, fiberglass). Raw material scrap y_{01} exits the product-portion of carpet production while process scrap exits the process-portion as waste. Combined, flows of process water f_{21*} and "dry" carpet f_{21} (i.e., carpet minus the water from processing) represent the carpet that is sent to consumers. At consumption H_2, carpet is used and then disposed in a landfill.

Flows must be split into process and product flows at carpet production because these two types of flows travel through this process differently. Specifically, the ratio of outputs to inputs for process flows is different than that for product flows. Flow analysis is based on such ratios and, hence, the two material flow streams must be split. For example, almost all of the water in carpet production is disposed of without reaching consumption (just above 0% of water used is in the final carpet product), whereas nearly all of the nylon inputs to production (almost 100%) end up in carpet that is used by consumers. Hence, water and nylon flows (or more generally, process and product flows) need to be split for carpet production. An asterisk is used to denote model elements related to process flows.

Combined with additional data on the efficiency with which materials can be recycled and a few assumptions (noted by Bailey et al. [2004a, 2004b]), the data used to construct the linear model is extended to a recycling model. The recycling model is based on the linear model with the only differences lying in the addition of two processes – material separation and nylon reclamation. As shown in Fig. 33.5, material separation requires the recovery of waste raw material from production and consumption.

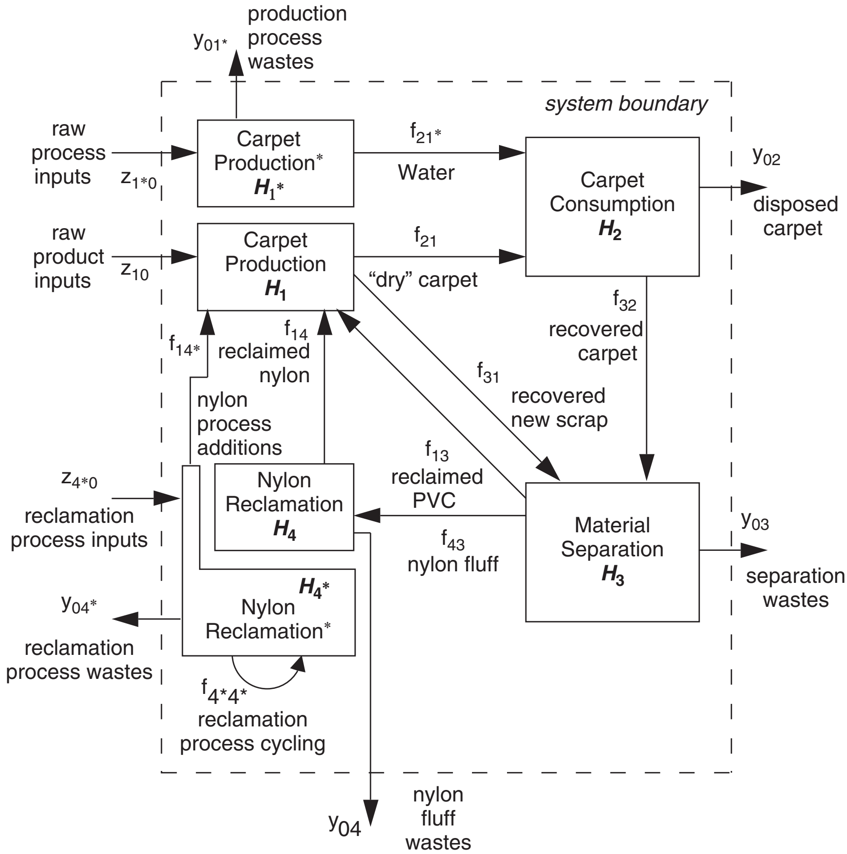


Fig. 33.5 Recycling Interface Model

Scrap materials from production (such as quality rejects and trimmings) are recovered and sent to material separation, where they are joined by carpet that is recovered after consumption. At material separation H_3, these materials are separated into nylon fluff (sheared from the top of the carpet), PVC, and all other materials. The nylon fluff flows to nylon reclamation H_4 as flow f_{43}, the PVC flows straight back to carpet production as f_{13}, and the remaining material leaves the system as waste y_{03}.

The nylon fluff must be processed further to prepare it to return to carpet production. This further processing is called nylon reclamation H_4 in the model. Due to the large amount of process materials needed for nylon reclamation (including air, water, natural gas, solvent, and nitrogen), H_4 is split into product flows and process flows similarly to how carpet production H_1 is split.

Nylon fluff f_{43} enters nylon reclamation H_4 and then is split into nylon that can be reclaimed (f_{14}) and nylon that cannot be reclaimed (y_{04}). To accomplish this reclamation, process materials flows through H_{4*}. A small percentage of process material flows to production with the reclaimed nylon. The modeling of nylon reclamation completes the Interface recycling model.

In the following section, a structural analysis of the recycling model is presented.

Structural Analysis

Structural analysis is useful to see causal connections within a system. By representing connections as either existent or not, relative magnitudes of flows do not affect the analysis (that is, a very small flow is treated the same as a large one). An example of material flows associated with an Interface, Inc., carpet plant is helpful in seeing the applicability of structural analysis to industrial systems.

The adjacency matrix, **A**, and the integral matrix, **B**, for the Interface recycling model are shown in Tables 33.2 and 33.3. Cells without any connections are indicated as blank cells. Completely blank columns and rows in the matrix are not shown.

The adjacency matrix follows directly from the graphical depiction of the Interface recycling model in Fig. 33.5. For instance, because there is a flow from H_1 to H_2, the cell in the H_1 column and H_2 row equals 1. Similarly, the leftmost and topmost cell is 1 because there is a flow from the environment to H_1.

The integral matrix **B** shows that the total number of paths between most processes is infinite. For example, between H_1 and H_2, there is one direct flow, one flow of length $= 3$, two flows each of lengths $= 4$ and $= 5$, four flows of length $=$ 6, and seven flows of length $= 7$. When all lengths are considered, there is an infinite number of paths between H_1 and H_2. Most of the cells in the rows relating to the process materials (those indicated with an asterisk) are blank because materials do not cycle back into these processes from the product.

Table 33.2 Adjacency Matrix for Interface Recycling Model

		From								
	A	z_{10}	z_{1*0}	z_{4*0}	H_1	H_{1*}	H_2	H_3	H_4	H_{4*}
To	H_1	1						1	1	1
	H_{1*}		1							
	H_2				1	1				
	H_3				1		1			
	H_4							1		
	H_{4*}			1						1
	y_{01*}					1				
	y_{02}						1			
	y_{03}							1		
	y_{04}								1	
	y_{04*}									1

Table 33.3 Integral Matrix for Interface Recycling Model

		From								
	B	z_{10}	z_{1*0}	z_{4*0}	H_1	H_{1*}	H_2	H_3	H_4	H_{4*}
To	H_1	∞	∞	∞	∞	∞	∞	∞	∞	∞
	H_{1*}		1			1				
	H_2	∞	∞	∞	∞	∞	∞	∞	∞	∞
	H_3	∞	∞	∞	∞	∞	∞	∞	∞	∞
	H_4	∞	∞	∞	∞	∞	∞	∞	∞	∞
	H_{4*}			∞						∞
	y_{01*}					1				
	y_{02}				∞	∞	∞	∞	∞	∞
	y_{03}				∞	∞	∞	∞	∞	∞
	y_{04}				∞	∞	∞	∞	∞	∞
	y_{04*}									∞

An infinite number of paths shown in **B** is indicative of a causally-closed system with loops resulting in material cycling. In such a system, indirect flows (i.e., any flow of length $=$ 2 or greater) have a significant influence. By only considering the direct connections, as is the case when input-output techniques are not used with materials flow analysis, the effects of making a change to the system will not be modeled completely. For example, if only direct flows are examined, a change in process H_2 (e.g., if more carpet is recovered from consumers) is only modeled as affecting process H_3 (the process that is directly dependent on H_2 as indicated in **A**). In fact, as is shown in **B**, a change in process H_2 will affect all processes except H_{1*} and H_{4*} and all outflows except y_{01*} and y_{04*}. Considering indirect effects is critical to understanding material flows in systems with significant cycling (such as industrial ecosystems). The degree of flow cycling or influence from one flow to another cannot be determined, however, without modeling the actual flow magnitudes. This is done in flow analysis.

Flow Analysis

The Interface case is studied in this section to explore the meaning of the flow metrics and environ analysis and show one way that they can be used with industrial systems. The flow metrics of the Interface case are shown in the following section.

Interface Flow Metrics

All but one of the metrics in Table 33.1 are derived from the integral matrix **N**. Hence, before introducing the metrics, **N** for the Interface recycling model is shown in Table 33.4.

Table 33.4 N for Interface Recycling Model

		From					
		H_1	H_{1*}	H_2	H_3	H_4	H_{4*}
To	H_1	1.245	0.004	0.195	0.248	0.029	3E − 04
	H_{1*}	0	1	0	0	0	0
	H_2	1.222	0.022	1.192	0.244	0.028	3E − 04
	H_3	1.227	0.018	0.978	1.245	0.028	3E − 04
	H_4	1.227	0.018	0.978	1.245	1.028	3E − 04
	H_{4*}	0	0	0	0	0	2.374

Table 33.5 Metric Values for Interface Recycling Model

Metric		Value
Path length	PL	2.12
Return cycling efficiencies	RE_1	0.197
	RE_{1*}	
	RE_2	0.161
	RE_3	0.197
	RE_4	0.028
	RE_{4*}	0.579
Cycling index	CI	0.211
Dominance of indirect effects	DOI	1.59

As an example of the meaning of the numbers in Table 33.4, rows 1 and 2 are explained. Row 1 represents the number of times a unit of flow that terminates in H_1 travels through each process. That is, a unit of flow that terminates in H_1 flows through H_1 an average of 1.245 times, through H_{1*} an average of 0.004 times, through H_2 an average of 0.195 times, etc. Row 2 has a similar meaning for a unit of flow that terminates in H_{1*}. It is clear from Row 2 that a unit of flow that terminates in H_{1*} flows through H_{1*} once and nowhere else.

A diagonal element equal to one means that flow goes through a process once and never loops back to it (a diagonal element is never less than one). Hence, return cycling efficiency, RE_k, and cycling index, CI, are based on these diagonal elements. A diagonal element in row and column k that equal to one results in $RE_k = 0$. An infinite value diagonal cell in row and column k results in an $RE_k = 1$.

The metrics for the Interface recycling model are shown in Table 33.5.

In addition to the metrics in Table 33.5, amplification occurs when any non-diagonal element is greater than one. As the number of cells in which amplification occurs increases, the amount of total flows throughout the system compared to the total inflows to the system increases. Four cells, three of which are flows from H_1, show amplification. This is likely because H_1 is involved in many material flow loops in the system (it has two outflows to other processes and three inflows from other processes in the system).

The path length of 2.12 indicates that the average unit of flow travels through 2.12 processes before exiting the system. For comparison, the path length for the linear model is 1.88. From this information, it is clear that materials stay within the economic system longer with the recycling model.

The return cycling efficiencies indicate the percent of material at a process that has cycled back to that process. For instance, 19.7% of all flows at H_1 are flows that have traveled through H_1 at least once before. The remaining 81.3% of flows only go through H_1 once. Of interest is that there are no cycled flows at H_{1*} and that over half of the flows at H_{4*} are cycled. The lack of cycled flows at H_{1*} is clear from investigating the model in Fig. 9.5. The large amount of cycling at H_{4*} is due to the large amount of process materials in nylon reclamation that are reclaimed and used again in nylon reclamation.

A cycling index of 0.211 indicates that 21.1% of all flows in the system are due to the cycling of flows through material flow loops. A DOI of 1.59 shows that indirect effects are more prevalent in the system than direct ones. This reinforces the point that materials flow analyses that do not consider indirect effects ignore a major part of materials flow systems with a large amount of cycling (e.g., industrial ecosystems).

In addition to using metrics to analyze a single system at one point in time, the flow metrics can be used to track performance over time of a system. Also, the metrics are useful in exploring different scenarios. More on these uses of metrics is demonstrated by Bailey (2000).

While flow metrics are excellent for producing single numbers that characterize the performance of a material flow system, a more in-depth analysis is provided by environ analysis.

Interface Environ Analysis

Environ analysis can take many forms depending on the nature of the system and the needs of the modeler. Here, to help demonstrate the capabilities of environ analysis, nine scenarios for the Interface recycling model are explored. These nine scenarios represent a baseline model plus eight possible changes to the system. Environs are shown in greater depth by Bailey et al., for models of single materials throughout the United States (2004a, 2004b).

All nine scenarios for the Interface model are for the same amount of carpet production. Scenarios 2 and 3 involved changes in flow magnitude; in this case, these scenarios involved reducing the necessary process materials in the model by 10% and by 20%, respectively. Scenarios 4 and 5 are based on increasing the recovery process efficiency. That is, the percent of the material in carpet consumption H_2 that stays in the system and flows to material separation H_3 increases in these two scenarios. Scenarios 6 and 7 involve increasing the percent of recovered material that is separable and sent either back to carpet production or on to nylon reclamation. A product that is easier to separate into its component materials would be represented by Scenarios 6 and 7. Finally, Scenarios 8 and 9 involve combining Scenarios 2, 4, and 6 or Scenarios 3, 5, and 7, respectively. The nine scenarios are summarized in Table 33.6.

Table 33.6 Nine Scenarios Explored with Environ Analysis

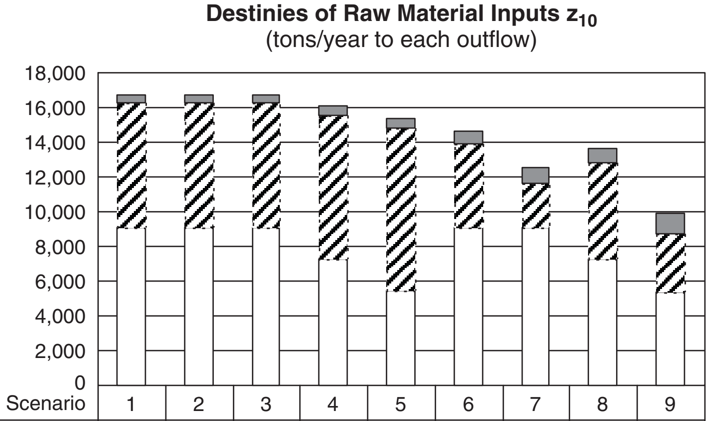
Scenario #	Description
1	Baseline scenario
2	Amount of process materials reduced by 10% from baseline
3	Amount of process materials reduced by 20% from baseline
4	Percent of carpet recovered from consumers increased from 50% (baseline) to 60%
5	Percent of carpet recovered from consumers increased from 50% (baseline) to 70%
6	Percent of recovered materials that can be separated from other materials increased from 50% (baseline) to 75%
7	Percent of recovered materials that can be separated from other materials increased from 50% (baseline) to 100%
8	Changes in Scenarios 2, 4, and 6 combined
9	Changes in Scenarios 3, 5, and 7 combined

Before exploring results from the scenarios, it is important to establish why each scenario is being explored. In all cases, the main purpose is to decide how to allocate future efforts.[4] If the greatest improvements are seen in Scenarios 2 and 3, then developing or redesigning the carpet production process and the nylon reclamation process to use process materials more efficiently would get the greatest returns. If Scenarios 4 and 5 generate the most desired system behavior, then efforts to increase the rate at which carpet is recovered from consumers is the preferred course of action. If Scenarios 6 and 7 show the greatest improvements over the baseline, then designing carpet that is easier to separate into its component materials or developing methods to more effectively separate materials from existing carpet is desirable. Scenarios 8 and 9 are shown as references to determine if the effects of each individual change are independent.

By examining path length and cycling index for the nine scenarios, it is shown elsewhere that both Scenarios 6 and 7 and Scenarios 4 and 5 increase the time that material stays within the system (Bailey et al. 2004a, 2004b). The question of how these scenarios increase the time that material stays within the system is of interest. Shown in Fig. 33.6 are output environs for inflow z_{10} (raw carpet product inputs) for each scenario.

The total height of each bar represents the total inflow z_{10} of product materials to carpet production needed for each scenario. The unshaded region of each bar is the actual amount of z_{10} that exits the system as carpet discarded by a consumer. The hatched section of each bar indicates the amount of z_{10} leaving the system

[4] The alternative scenarios must be constructed such that each represents goals that are obtainable with similar effort. In the example shown in this chapter, the effort to implement Scenarios 2, 4 and 6 is expected to be roughly the same. Similarly, the effort to implement Scenarios 3, 5, and 7 is expected be roughly the same. It must be considered when analyzing the results that Scenarios 8 and 9, in which the individual scenarios are combined, would require more effort to implement than the other scenarios.



Scenario	1	2	3	4	5	6	7	8	9
unreclaimed nylon fluff (y04)	469	469	469	542	615	702	932	810	1,215
separation wastes (y03)	7,109	7,109	7,109	8,214	9,316	4,815	2,532	5,559	3,300
disposed carpet (y02)	9,134	9,134	9,134	7,301	5,470	9,110	9,078	7,275	5,406

Fig. 33.6 Environs for Raw Materials Inputs z_{10}

because it cannot be separated adequately from other materials. The shaded section of each bar represents the amount of z_{10} that exits the system as waste from the nylon reclamation process. Recall that the amount of carpet produced for each scenario is the same; so, if the total height of a bar is smaller (as in Scenarios 4 through 9), then carpet is being made with less virgin material and more recycling material. In Scenarios 4 through 9, material is cycled through the system more effectively, which results in material staying within the system longer and less new material needed to flow into the system.

As expected, for Scenarios 4 and 5 where carpet recovery is increased, the unshaded part of the bar is smaller than the baseline and separation wastes actually increase (due to more material that is recovered and flowing into material separation H_3). Notice that the total heights (i.e., the total amount of product inputs needed) for Scenarios 6 and 7 are less than those for Scenarios 4 and 5. This is because of huge reductions in materials lost in material separation. In Scenario 7, the only materials exiting the system at material separation are those that cannot be recycled/reclaimed. Meanwhile, roughly the same amount of carpet is disposed of by consumers in Scenarios 6 and 7 as in the baseline case. In Scenarios 4 and 5 one outflow stream (disposed carpet y_{02}) is reduced while another (separation wastes y_{03}) is increased. In Scenarios 6 and 7, on the other hand, one outflow stream is reduced (separation wastes y_{03}) while all others are essentially held constant. The greatest improvement, as expected, is in combination Scenario 9 where the two main exits from the system (i.e., disposal by consumers and materials that cannot be separated) are each drastically reduced.

Environ analysis, as shown here, is an excellent tool to use in tandem with flow metrics in that reasons for changes in metric values are explained by tracing flows through a system. The reasons for increases in path length in cycling index in Scenarios 4 and 5 are very different than why these two metrics increase in Scenarios 6 and 7.

The industrial examples shown here are certainly not the only ways that network analysis can be used to model material flows in industrial systems. The exact way that network analysis is used with a given system will depend on the nature of the system and the questions of interest to the modeler. Some general considerations for when to use network analysis with industrial systems are outlined in the next section.

When to Use with Industry?

Network analysis is a very powerful application of input-output analysis to systems of material or energy flows. Its possible uses are very wide-ranging, limited as much by the user's creativity as by the approach itself. That said, a few guidelines for when one might want to use parts of network analysis are outlined in this section.

Structural analysis is a good place to start when using network analysis. The strengths of structural analysis include that it:

- Establishes the causal connections within a system. That is, if one changes flow X in the system, what other flows will be affected?
- Provides a snapshot of the connectivity of a system. If **B** is largely zeroes, then the system is not very tightly connected with cycles of flows. If **B** has few or no zeroes, then the system has significant cycling of flows.
- Does not require the large amount of data that flow analysis does and can provide results quickly. You need to know if a flow exists or not, not how big the flow is.

Flow analysis, while it does require more data and time than structural analysis, also provides more detailed and accurate picture of a system of material or energy flows. Whereas a minute flow is treated the same as an enormous one in structural analysis, differences in flow magnitude are modeled with flow analysis. Within flow analysis, the two primary tools are environ analysis and flow metrics.

Flow metrics characterize behavior of a flow system and can enable the quick tracking of system performance. One should consider using flow metrics when:

- Structural analysis indicates that a system is highly interconnected.
- Comparisons are being made between multiple systems or between a single system at different points in time. For instance, the cycling index for a system can be tracked over time in relation to goals for cycling index.
- One needs to know the effects of possible changes to a system.
- A link between model output and the goals of industrial ecology is needed (Bailey et al. 2004a, 2004b).

Environ analysis is helpful when a modeler seeks an in-depth analysis of a material flow network. One should consider using environ analysis when:

- Reasons behind changes in flow metrics values are sought.
- Information about the specific paths of material through a network of flows is required.
- Information about the sources of outflows and exits of inflows is needed. Specific questions depend on the nature of a system, but could include:

  (a) what percent of each raw material ends up in a domestic dump, being exported as a product, being exported as waste, etc.? or
  (b) what percent of production wastes are from raw materials versus what percent from reclaimed material?

Further Work

The work to date with network analysis and material flows in industrial systems is just the beginning. Three promising areas for further work are outlined in this section.

- **More real world applications are needed.**
  Applying network analysis to more real cases will better establish its strengths and weaknesses and further develop its capabilities. Several cases are explored by Bailey (2000). These cases effectively establish that network analysis has great potential for use with material flows in industrial systems, but more work is needed to fully investigate this potential.
- **There is more to be learned from the ecological analogy.**
  While the connections between ecosystems and industrial systems can undoubtedly be pushed to far, network analysis has been applied to ecosystems to explore concepts that could be relevant to industrial systems. For instance, the flow metrics have been used to study why ecosystems develop as they do over time (Fath et al. 2001). Additionally, there appears to be a link between the metrics and interactions between species in ecosystems such as predator-prey and mutualism (Fath et al. 1998).
- **The role of indirect effects in system behavior warrants further study.**
  It is clear from work presented here that indirect effects can play a large role in systems with material flow loops. An implicit goal of industrial ecology is to foster the development of material flow loops so that materials are used more efficiently. Hence, indirect flows play a large role in industrial ecosystems. Understanding exactly how these indirect effects affect system behavior and how they can be managed effectively, however, remains unclear.

Conclusion

Network analysis is an effective application of input-output analysis for studying systems of material or energy flows; materials have been the focus in this chapter. Because it models indirect effects, network analysis is particularly useful in systems where materials or energy flows through loops. For example, ecologists have used network analysis for over 30 years to study highly integrated systems of nutrient and energy flows. Three of the major ways that ecologists have used network analysis – structural analysis, flow metrics, and environ analysis – are presented in this chapter in the context of industrial ecology. The application of network analysis to industrial systems is new and more work is needed to fully investigate and further develop an industrial analog to this ecological modeling tool.

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Chapter 34
Modelling Sustainability of the Austrian Economy with Input-Output Analysis
Modelling Framework and Empirical Application

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On a scientific as well as a political level, there is wide consensus today that the concept of sustainable development requires integrated approaches to illustrate the interactions between economic, social and environmental concerns. Input-output analysis is regarded as an appropriate framework to provide a comprehensive picture of these linkages as it allows combining bio-physical and social data with economic (monetary) input-output models.

The interrelations between the economic and ecological system affect the flow of material inputs and outputs in many forms. Environmental degradation depends considerably on input quantities, which are taken from and transferred again to the environment in form of emissions and wastes. For the description of these relationships, the concepts of "industrial metabolism" and "societal metabolism" are important. These terms refer to the exchange of materials and energy between ecological and socio-economic systems. According to these concepts physical indicators can be differentiated with respect to input and output indicators.

The material input of a national economy is frequently regarded as a substantial indicator for environmental sustainability. The decrease of material flows and their decoupling from economic growth represent central goals of the Austrian strategy for sustainable development. Referring to the output side, CO_2 emissions reflect the most dominant output flow, showing a still increasing pattern in Austria, which clearly conflicts with the Kyoto goal of a reduction of greenhouse gases by 13% below 1990 levels by 2008–2012 for the Austrian economy. Therefore the Austrian sustainability strategy also demands climatic protection and thus the reduction of CO_2 emissions as the most important greenhouse gas.

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On the basis of these guidance goals fixed in the sustainability strategy, this paper examines which economic activities are directly as well as indirectly responsible for the material input and CO_2 emissions of the Austrian economy.

By using data on material input on the one hand and CO_2 emissions (undesired outputs) on the other hand we connect both an input- and an output-based indicator using the basic make-use tables of the input-output accounting framework in order to illustrate the interactions between environmental and socio-economic trends of the Austrian economy. This modelling approach allows accounting for flows of environmental commodities from the environment into the economy and of emissions and waste products from the economy back to the environment. It enables a comprehensive assessment of the considered indicators related to production and consumption activities of the Austrian economy. With this procedure we show which economic activities are directly and indirectly responsible for the use of natural resources and the generation of CO_2 emissions. Furthermore we investigate whether decoupling of resource use and CO_2 emissions from economic development took place in recent years.

In addition to the sustainability goals from an environmental point of view we refer to a high employment level, as one important aim for social sustainability in order to consider at least one essential aspect of social equality, by integrating employment in our model as social indicator. The parallel analysis of employment, environment and economy within the make-use-framework allows the comprehensive assessment of the considered indicators related to production and consumption activities of the Austrian economy. This analysis is supplemented by an evaluation of the sustainability of the Austrian economy by applying minimum conditions for sustainable development. With the help of this framework we investigate if the development of the Austrian economy fulfilled these minimum conditions in the time period 1995 to 2000.

Introduction

On a scientific as well as a political level, there is wide consensus today that the concept of sustainable development requires integrated approaches to illustrate the interactions between economic, social and environmental concerns. Input-output analysis is regarded as an appropriate framework to provide a comprehensive picture of these linkages as it allows combining bio-physical and social data with economic (monetary) input-output models. Input-output analysis is an empirical tool introduced by Leontief in the late 1930s and designed to analyse interdependencies of industries in the economy. It considers both direct and indirect effects of all economic activities. The starting point in input-output analysis is an input-output table, which describes the flows of goods and services through an economy in monetary terms.

Traditional national accounting only focuses on monetary transactions. Such an approach is not sufficient to study sustainable development as it does not adequately consider the physical flows of materials and energy from nature to the economy, as well as all transformation processes within the economy and the flows of wastes and emissions back to nature. According to Stahmer (2000), in the traditional framework, only about a 12th of the material flows are valued in monetary units, while all other transactions are neglected.[1]

However, the interrelations between the economic and environmental system affect the flow of inputs and outputs in many forms. Environmental degradation depends considerably on input quantities, which are taken from and transferred again to the environment in form of emissions or wastes. For the description of these relationships the concepts of "industrial metabolism" (Ayres et al. 1993) and "societal metabolism"[2] (Fischer-Kowalski, 1998a, b) are important, which refer to the exchange of materials and energy between environmental and socio-economic systems. According to these concepts physical indicators can be differentiated with respect to input and output indicators (Bringezu 1997).

The transformation towards a sustainable use of natural resources is closely related to the aim of decoupling of economic growth from the use of natural resources and environmental degradation (OECD 2002). While decoupling in relative terms decreases the resource intensity of economic processes, absolute de-linking is required from a sustainability point of view, highlighting the concept of dematerialization. A dematerialization strategy demands decreasing material and energy throughput of the socio-economic system in order to reduce environmental pressures in absolute terms. The material input of a national economy is therefore frequently seen as a substantial indicator for environmental sustainability. The decrease of materials flows and its decoupling from economic growth represent also a central goal of the Austrian strategy for sustainable development (Austrian Federal Government 2002).

Referring to the output side, CO_2 emissions reflect the most dominant outflow (Matthews et al. 2000), showing a still increasing pattern in Austria,[3] which clearly conflicts with the Kyoto goal of a reduction of greenhouse gases by 13% below 1990 levels by 2008–2012 for the Austrian economy. Therefore the Austrian sustainability strategy also demands climatic protection and thus the reduction of CO_2 emissions as the most important greenhouse gas (see Austrian Federal Government 2002, p. 44).

On the basis of these guidance goals fixed in the sustainable development strategy, this paper treats the question, which economic activities are directly as well as indirectly responsible for the material input and CO_2-emission patterns of the Austrian economy.

[1] Furthermore, all service flows within the household sector are not taken into account.

[2] Societal metabolism is a generalization of the concept of industrial metabolism to an entire socioeconomic system, which is described by the extent of its reliance on the physical environment (Fischer-Kowalski, 1998; Matthews et al. 2000).

[3] Austria's CO_2 emissions showed an increase of 24.4% from the base year 1990 to 2003 (Umweltbundesamt, 2005, p. 7).

By using data of material input on the one hand and CO_2 emissions (undesired outputs) on the other hand we connect both an input and output-based indicator with the basic make and use tables of the input-output accounting framework in order to illustrate the interactions between environmental and socio-economic trends of the Austrian economy. With this procedure we show which economic activities are directly and indirectly responsible for the use of natural resources and the generation of CO_2 emissions. Furthermore we investigate if a decoupling of resource use and CO_2 emissions from economic development took place in recent years.

In addition to the sustainability goals from an environmental point of view we refer to a high employment level as one important aim for social sustainability in order to consider at least one important aspect of social equality. While we recognize the fact that this narrow view is not able to deal with all relevant aspects of social sustainability, we have decided to restrict ourselves to this approach due to missing data for other social aspects. We integrate employment in the chosen framework by calculating employment multipliers, which show the quantity of labor in all sectors necessary to deliver the value of one output unit of a specific sector to final demand.

The parallel analysis of employment, environment and economy within the make-use framework allows the comprehensive assessment of the considered indicators related to production and consumption activities of the Austrian economy. This analysis is supplemented by an evaluation of the sustainability of the Austrian economy by applying minimum conditions for sustainable development. With the help of this framework we investigate whether the development of the Austrian economy fulfilled these minimum conditions in the time period 1995 to 2000.

The paper is structured as following: In section "The Concept of Sustainable Development" we introduce the concept of sustainable development. Section "Methodology" explains the theoretical approach, which comprises the description of the environmentally extended make-use framework and a possible approach of defining minimum conditions for sustainable development. We finish our contribution with an empirical application for the Austrian economy (section "Empirical Application").

The Concept of Sustainable Development

There is wide agreement today that sustainable development, since it is a normative-integrative concept, has to pursue environmental, economic and social objectives at the same time. In more recent debates, a fourth dimension – the institutional one – has been added to the scheme.

The following box (Box 34.1) describes the concept of sustainable development and its pillars, the viability (resilience) of environmental, economic and social systems.

Box 34.1 The Concept of Sustainable Development

The term "sustainable development" achieved world-wide recognition in 1987 with the publication "Our Common Future" of the World Commission on Environment and Development. The Brundtland Report defines sustainable development as "development that meets present needs without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 43). The report first articulated the concept of sustainable development systematically and captured widespread concerns about the state of the environment and poverty in many parts of the world by arguing that economic development requires a re-orientation, in order to consider environmental limits.

Concerning **economic sustainability** the predominance of economic growth and deregulation has been taken as given in most cases, instead of developing criteria for economic sustainability (Spangenberg 2004). Furthermore, the economic dimension focuses on competitiveness as a prerequisite for the development of new eco-efficient technologies (Hinterberger and Luks 2001). A few other economic sustainability criteria have been suggested, like innovativeness (Rennings 2000), or public debt (Bundeskanzleramt 2002). Although criteria like inflation or foreign trade balances are politically prominent, they are usually not linked to the debate on sustainable development (Spangenberg 2004). Again other, partly more traditional, criteria like aggregate demand, consumption levels and savings rates play a minor role in current discussions (Etxezarreta et al. 2003).

The **environmental dimension** of sustainability recognizes the indisputable fact that people are dependent upon the natural world, and that without the resources and ecosystems services it provides, life and development are impossible. In order to sustain the viability of ecological systems, development must not degrade or deplete them to an extent that destroys their ability to function effectively. Thus, the most important objectives of the environmental dimension include the long-term conservation of the ecosphere as a basis of human life, the sustainable utilization of renewable resources and minimized utilization of non-renewable resources (Daly 1991; Hinterberger et al. 1996).

Social sustainability focuses on personal assets like education, skills, experience, consumption, income and employment. The central objective is the fair distribution of opportunities both in intra-and inter-generation terms. A high employment level combined with high-quality jobs is an important link between the economic and social dimension.

Additionally, a fourth dimension, i.e. the institutional one, has increasingly been integrated into this concept (Spangenberg et al. 1999), although it is not part of modelling frameworks so far. **Institutional sustainability** aims at interpersonal processes like democracy and participation (institutional mechanisms), distributional and gender equity (institutional orientations) or independent and pluralistic sources of information (organisations). Obviously institutional settings often provide the opportunity space for social sustainability to develop; as a certain overlap cannot be avoided, institutional aspects will have to be taken into account when discussing social sustainability (Omann and Spangenberg 2002). The inclusion of

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Box 34.1 (continued)

the institutional dimension takes account of the fact that each economic activity is performed within an institutional framework that decisively influences the result of the activity (Hinterberger and Luks 2001). Therefore, socio-economic changes, such as the implementation of the sustainability concept, also require the further development of institutions.

In the literature considerable differences regarding the necessary conditions to satisfy sustainable development in all its dimensions are evident. These conditions apply to the capital base of an economy, with capital theory serving as an economic framework. In the context of sustainability, capital is defined broadly as the stock that provides current and future flows of services. Thus capital, which consists of physical (produced) capital, human capital and natural capital, is the basic source of quality of life (see Perman et al. 1997). Physical capital corresponds to the economic dimension, human capital to the social, while natural capital refers to the environmental dimension of sustainability. The institutional dimension is linked to the so called social capital, like social trust, norms and networks.[4]

A controversy determining much of the economic debate on sustainable development addresses the question whether each capital stock has to be maintained independently (Daly 1991), or whether the sum of all four capital stocks has to be non-declining (Pearce and Turner 1991). The assumptions about the substitution of the different kinds of capital have led to the opposite expressions of weak sustainability and strong sustainability (Neumayer 1999). Weak sustainability, one of the key features of the neoclassical approach, is about maintaining total capital stock, with one kind of capital being substitutable for another. Thus, weak sustainability allows for substitution between produced and natural capital. Proponents of weak sustainability argue that ongoing reductions in natural capital can be considered sustainable, provided that other capital like infrastructure, technology, knowledge and skills is developed to offer an equivalent function for society (Pearce et al. 1989).

Under the concept of strong sustainability different components of capital should be independently maintained. Strong sustainability means treating natural capital separately – on the assumption that natural resources are essential inputs in economic production, consumption and welfare and cannot be substituted by man-made capital. Therefore natural capital itself should be preserved for future generations in addition to the total aggregate capital stock. Its viability must be protected, as the unique services of natural systems have no substitute and irreversible harm or collapse can ensue (Hofkes and van den Bergh 1997, p. 7).

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[4] The social dimension represents the human (not the social) capital, which consists of the individual human assets such as skills, dedication, experiences and social attitudes. As in political science, 'institutions' (confusingly called 'social capital' in economics) refers to interpersonal systems of rules governing decision making, i.e. not only organisations, but institutional mechanisms and orientations as well (Spangenberg 2001).

Proponents of Ecological Economics affirm that human-made capital and natural capital are largely complements, and that natural capital is increasingly becoming the limiting factor for further development (Costanza and Daly 1992). Since human-made capital cannot be created and sustained without energy and natural resources, the natural capital stock must be maintained. A complete substitution of human-made capital for natural capital is not possible, because the existence of natural capital is a necessary prerequisite to produce human-made capital (Costanza and Daly 1992).

Representatives of the so called "London school" around Pearce present points of view, which lie between the two extremes of weak and strong sustainability (see Victor 1991, p. 201). They argue that despite the possible substitution between different capital components there also exists certain natural capital, for which no substitution is possible and/or allowed.

'Critical natural capital' may be defined "as natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital" (Ekins et al. 2003). This concept of 'critical nature capital' sees necessary conditions of sustainable development therefore both in the protection of these critical natural capital stocks and in the maintenance of the total capital stock. A substitution is only possible if natural capital is not scarce. If however it achieves its critical level, then no replacement by other kinds of capital is justifiable (see Pearce and Warford 1994, pp. 53ff.).

In the context of sustainability the distinction between growth and development is crucial. Daly (1987) noted that growth refers to the quantitative increase in the scale of the physical dimension of the economy, the rate of flow of matter and energy through the economy, and the stock of human bodies and artefacts, while development refers to the qualitative improvement in the structure, design, and composition of physical stocks and flows, that result from greater knowledge, both of technique and of purpose (see Costanza and Folke 1994).

Daly (1996) argued that there are potentials for a more efficient use of natural resources, recycling, and reduction of waste and pollutants. Hence economic progress should be based on development (qualitative improvement) rather than growth (quantitative improvement). According to Daly (1991) the economy is not a closed, isolated system; it is a sub-system of the biosphere, receiving and transforming matter and energy. The biosphere serves as both source and sink for the economy. In this context the decoupling discussion is interesting, which started with the question whether a continuous growth evolves along with increasing or decreasing use of nature. Various policy documents (e.g. the 6th Environmental Action Plan of the European Union, see European Commission 2001) emphasize decoupling economic development from use of nature as a precondition for sustainable development. Consequently a more systematic analysis of the decoupling phenomenon, that is a more disaggregated analysis going beyond the aggregated national economy, is needed.

A range of attempts have been made to formally analyse the interactions of all dimensions of sustainability in a single methodological framework. The input-output framework has received much attention in this respect (Van den Bergh 1996) and also serves as reference in our analysis. Input-output models promise to be useful tools for policy makers to connect economic, social and environmental policy in order to achieve sustainable development, since they are able to describe the structure of the socio-economic system and its interaction with the environment.

Numerous applications have already provided evidence that environmentally extended input-output tables and models are well suited to address a large number of environmental concerns, to evaluate policy measures and to identify future sustainable development options (for an overview see Luptacik and Stocker 2005). This is due to the fact that the parallel analysis of economic, environmental and social concerns in an input-output model provides a more complete representation of the real system, relates the production and consumption side, includes the illustration of indirect effects, enables the evaluation of direct and indirect substitution and improves the representation of the structural effects of policies. For these reasons it offers a comprehensive policy evaluating and information tool.

Methodology

The Make-Use Approach

The choice of the model for the analysis carried out in this paper was motivated by the Austrian data situation. Therefore we start this section with a presentation of the used data sets and then turn to the explanation of the modelling framework.

Data

Data on Austrian CO_2 emissions are provided by the system of NAMEA (National Account Matrix including Environmental Accounts). A time series (Umweltbundesamt 2000) includes data on direct CO_2 emissions induced by industries for the years 1995 and 2000. These data are arranged according to the NACE classification, i.e. related to industries (or activities). The Austrian input-output table in its standard version, however, is presented in the form of commodity by commodity. This symmetric table is derived from make and use tables, using the product technology assumption. Thus, the NAMEA data are not compatible with the symmetric input-output table, but correspond with the make-use framework. In order to relate the NAMEA data to industry output make and use tables have to be used.

We have selected the time period 1995 to 2000 because input-output tables are available for 1995 and 2000 in the same classification.[5] To enable comparisons over time all values for the year 2000 are expressed in prices of 1995.[6]

The Austrian statistical office publishes all tables in basic prices (excluding net commodity taxes and trade and transport margins), which enables a comparison of make and use table as well as the derivation of the analytical input-output table Statistik Austria 2001, 2004. Thus, the required transformation of use tables at purchaser's prices to use tables at basic prices by reallocating trade and transport margins to their respective sectors is provided.[7]

These make and use tables not only provide the economic information but also data on the employment situation (employed persons by industry).

With regard to assessing the material base and resource throughput of national economies, material flow accounting (MFA) is established as a widely applied methodological approach. The Austrian economy-wide MFA measures the material input with the indicator Direct Material Input (DMI). The DMI comprises "the flow of natural resource commodities that enter the industrial economy for further processing. Included in this category are grains used by a food processor, petroleum sent to a refinery, metals used by a manufacturer, and logs taken to a mill" (Adriaanse et al. 1997). The DMI covers primary extraction and imports, but does not consider so-called hidden flows (or ecological rucksacks).

A time series of material input from 1960 to 2001 (Petrovic 2003) is available for the Austrian Economy and was used to transform the input data provided by the economy-wide MFA into sector-specific information. The material input is divided into the main aggregates biomass, minerals and fossil fuels.

The direct attribution of **domestically** extracted resources to extracting industries is limited to a small number of production activities. Biomass is harvested by the production sectors agriculture, forestry and fisheries. Fossil fuel resources are extracted by the coal mining and crude oil and gas extracting industries.

The category of minerals contains metal ores, salts, industrial minerals and clay on the one side, and quarrying of sand, gravel and natural stone for construction on the other side (Petrovic 2003). They are extracted by the sector "Other mining and quarrying".

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[5] There is also a table for 1990, but it is not compatible with the other two.

[6] The official Austrian statistical office does not publish tables with constant prices. That is why we are very thankful to Kurt Kratena for providing us the necessary data.

[7] Producers and the users of a given product usually perceive its value differently, because of intervening transport costs, trade margins, taxes and subsidies on products. In order to achieve a standard common valuation, SNA 1993 and ESA 1995 recommend that outputs of products should be valued at basic prices, while inputs or final purchases should be valued at purchasers' prices. In the context of input-output analysis this means that the make table should be recorded in basic prices, whereas the use table should be valued in purchasers' prices. In order to make the use table consistent with the make table, the intermediate flow matrix needs to be transformed from purchasers into basic prices. In particular, this requires the exclusion of net commodity taxes and re-distribution of trade and transport margins (Ruiz, 2002).

Although the Austrian resource use is characterized by a high import share (39% in 2000, Petrovic 2003) imported material inputs are disregarded within this analysis, because at the time being the unambiguous attribution of imported material flows to the receiving sectors is not possible.

With the help of the modelling framework presented in the next section, the direct material input, CO_2 emissions and employment per sector are then re-attributed to final demanded products considering that for every final demanded good indirect effects were also induced via production of intermediate goods.

Environmental Extended Make-Use Framework

In order to be in alignment with the Austrian data situation, we use the basic commodity-by-industry framework (based on make and use tables)[8] instead of the common static Leontief model (based on symmetric input-output tables) to integrate socio-economic and environmental data.

We extend the basic commodity-by-industry framework with additional rows of environmental inputs (in our case direct material input) and columns of environmental outputs (in our case CO_2 emissions). In addition, employment is added on the input side. Figure 34.1 presents the structure of the model.

This framework, which was originally introduced by Victor (1972), allows accounting for flows of environmental commodities from the environment into the economy and of waste products from the economy back to the environment. It enables a comprehensive assessment of the considered indicators related to production and consumption activities and can easily be extended with other environmental data

	Commodities	Industries	Final demand	Total Output	Ecological Commodities
Commodities		Use matrix U	final demand matrix Y	Vector of commodity gross outputs q	R
Industries	Make matrix V			Vector of industry total outputs g	S
Value Added		Value Added	GNP		
Total inputs	q'	g'			
Employment	$l(q)$	$l(g)$			
Material inputs	P	T			

Fig. 34.1 Make-Use Framework, Extended with Environmental Indicators and Employment (Adapted from Miller and Blair 1985, p. 253)

[8] The analytical derivation of this model is provided in the contribution of Kagawa and Suh in Chapter 35 of this handbook.

such as land use data on the input side or waste water and other air emissions, as well as output flows of solid waste on the output side.

We integrate the social dimension of sustainable development in the same way as indicators on the input side by extending the framework with an additional row which contains the amount of jobs related either to industries l(g) or commodities l(p), comprising self-employed persons and employees (as annual averages).

From this modelling framework it is possible to calculate weighted multipliers that account for direct and indirect requirements or effects per unit of production in each economic sector and for the components of final demand (e.g. private consumption, public consumption, exports and investment). These multipliers can be interpreted as intensities with regard to resource-, emission-and labor-intensity of the production of services and commodities.

Referring to Chapter 35 for the derivation of the mathematical relationships of the make-use framework, we refrain here from explaining the formal model, which represent the economic part of the system and only cite the solution equations due to the industry technology assumption. There are two main technology assumptions in input-output analysis that deal with industry production of primary and secondary commodities and that are the basis for deriving homogeneous input-output tables from make and use tables: the product technology assumption and the industry technology assumption. The product technology assumption supposes that a given product is made with the same inputs no matter from which industry. Alternatively, the industry-based technology assumption assumes that industries produce both primary and secondary commodities with the same fixed industry input structure, no matter what type of commodity (Almon 2000). This implies that we treat all secondary products as by-products being manufactured with the same technology as the principal product of this industry.

While the Austrian symmetric input output table is derived using the product technology assumption, we have to apply the industry technology assumption for our environmentally extended analysis. This is due to the fact that the calculations with the product technology assumption led to negative coefficients, which are not interpretable in an economically reasonable way.

Generally, the product technology assumption raises the problem that some negative flows can appear when the model is solved because it requires computing the inverse of the matrix of industry output proportions (Matrix *C*). This problem can be solved using Almon's version of the product technology assumption (Almon 2000). This algorithm is able to avoid negatives in the **commodity by commodity** total requirements matrix $(I - BC^{-1})^{-1}$. Our analysis however has to be based on the **industry by commodity** total requirements matrix $C^{-1}(I - BC^{-1})^{-1}$ in order to deal with the Austrian environmental data classified by industries, not by commodities. For this matrix Almon's algorithm is not able to guarantee non-negativity, because one has to multiply the commodity by commodity total requirements matrix with the inverse matrix of *C*, which again may cause negatives. To avoid these negatives we have to use the industry technology assumption. This hypothesis, however, conflicts with the assumption of homogeneous production (i.e. every industry produces exactly one product and every product is produced by exactly one industry), which is the basis for deriving homogenous input-output tables.

Nevertheless, if we classify environmental goods as by-products that are technically related to the main production of goods and services then they seem to fit the industry-based technology assumption.

According to the industry technology assumption the solutions for commodity output q and industry output g are

$$q = (I - BD)^{-1} y \tag{34.1}$$

$$g = D(I - BD)^{-1} y \tag{34.2}$$

with y vector of final demand

q vector of commodity output
g vector of industry output
B input coefficients matrix
D market share matrix (matrix of commodity output proportions)
I identity matrix

The term $(I - BD)^{-1}$ is the commodity-by-commodity total requirement matrix, the element ij of this matrix shows the production of commodity i required to deliver a Euro's worth of commodity j to final demand.

The matrix $D(I - BD)^{-1}$ in Equation (34.2) represents the **industry-by-commodity total requirements matrix**, giving the industry output required per Euro of each commodity delivered to final users. It is this matrix that we have to use in order to relate the environmental to economic data.

We integrate material input and CO_2 emissions in the framework by combining the economic sub-system with the ecological subsystem.

The ecological subsystem is presented through four matrices (Miller and Blair 1985). For our purposes we only need two of them:

- CO_2 emissions can be integrated via matrix $S = [s_{jk}]$. s_{jk} represents the amount of environmental commodity output k discharged by industry j. Since we consider CO_2 as only emission category k is equal to one and we get a vector $s = [s_j]$.
- Material inputs are incorporated via matrix $T = [t_{kj}]$. t_{kj} shows the amount of environmental commodity k used by industry j. Since we also consider only one category of material inputs k is again equal to one and we can use the vector $t = [t_j]$.

Using these two vectors we can calculate **emission and material multipliers** that account for direct and indirect effects per unit of commodity in each economic sector and for the components of final demand. For this purpose we have to use the **solution equation of industry output *g*** and combine it with the vectors s and t, assuming a direct relationship between the two environmental indicators (measured in physical units) and monetary output.

The existing data on material input and CO_2 refer to direct requirements or emission generation of each industry.

Dividing the CO_2 emissions of sector j by the total industry output G_j leads to a vector of sectoral direct output coefficients (o_j).[9]

$$o_j = \frac{s_j}{G_j} \text{ With } o_j = \hat{O} \tag{34.3}$$

$\hat{O}$ is the diagonal matrix of environmental commodity **output** coefficients o_j. This matrix shows the direct CO_2 emissions of each sector, which is generated by producing one unit of (monetary) output of this sector. But it does not show the indirect CO_2 emissions of other sectors that are generated for producing one output unit that a specific sector provides for final demand.

If we multiply the diagonal matrix of environmental commodity output coefficients $\hat{O}$ with the industry by commodity total requirements matrix, we finally obtain the total CO_2 emissions intensity matrix M_o, which represents the total (direct and indirect) CO_2 intensities.

$$M_o = \hat{O}D(I - BD)^{-1} \tag{34.4}$$

The element m_{ij}^o of the weighted total requirement matrix M_o in Equation (34.4) illustrates the amount of CO_2 emissions of sector i generated to produce one additional unit of commodity output of sector j for final users.

The column sums of the weighted total requirements matrix finally give the CO_2 **multipliers**. The multipliers describe the total amount of CO_2 in all sectors of the economy that is generated if sector j provides the output necessary to satisfy a Euro's worth of final demand.

In order to calculate the total emissions S that are activated by final demand, the total requirements matrix M_o has to be post-multiplied with the vector of final demand y.

$$s = M_o y \tag{34.5}$$

$$s = \hat{O}D(I - BD)^{-1} \tag{34.5a}$$

With the help of this procedure it is possible to reveal the total CO_2 emissions per industry (direct plus indirect) that are generated to fulfil final demand.

For material inputs the same method can be applied with the only difference that we use the vector of "ecologic commodity **input** coefficients" $f = [f_j]$. We get these coefficients by dividing the components of the vector t by the total industry output of sector j.

$$f_j = \frac{t_j}{G_j} \text{ with } f_j = \hat{F} \tag{34.6}$$

[9] In our case k is equal to one, since we only consider CO_2.

$\hat{F}$ is the diagonal **matrix** of the ecologic commodity **input** coefficients f_j. This matrix shows the direct material input of each sector, which is necessary to produce one unit of (monetary) output of this sector.

If we multiply the direct material input coefficients with the total requirements matrix then we get the total material requirements matrix M_f, which shows the total (direct and indirect) material intensities.

$$M_f = \hat{F}D(I - BD)^{-1} \tag{34.7}$$

The element m_{ij} of the weighted total requirement matrix M_f illustrates the amount of material input of sector i used to produce one additional unit of commodity output j for final users.

The column sums of the weighted total requirements matrix M_f show the material input multipliers. We get the overall material input induced through final demand by post-multiplying the weighted total requirements matrix with the final demand vector.

$$t = M_f y \tag{34.8}$$

$$t = \hat{F}D(I - BD)^{-1} y \tag{34.8a}$$

We integrate the social dimension of sustainable development by calculating employment coefficients in the same way as we do for material input data. The direct labor coefficients e_j relate the amount of persons employed in sector j (l_j) to total industry output G_j.

$$e_j = \frac{l_j}{G_j} \text{ with } e_j = \hat{E} \tag{34.9}$$

Multiplying the diagonal matrix of direct labor coefficients $\hat{E}$ with the total requirements matrix leads to the total labor requirements matrix.

$$M_e = \hat{E}D(I - BD)^{-1} \tag{34.10}$$

If we post-multiply M_e with the vector of final demand, we get the total employment induced by final demand

$$l = M_e y, \tag{34.11}$$

In addition to the allocation of material inputs, CO_2 emissions and labor employment to aggregated final demand, we can also allocate resource requirements to specific categories of final demand. In this sense, the calculations provide the direct and indirect resource requirements for private consumption, public consumption, investments and exports respectively. For this purpose we simply replace the final demand vector y by the final demand matrix $Y = \{y_1, y_2, \ldots, y_k\}$.

In Chapter 4 of this handbook we use the described modelling framework to determine emission-and material-and employment-intensities of lifestyle and economic activities in Austria in recent years.

Minimum Conditions for Sustainable Development

The implementation of political strategies has to be evaluated by indicators in order to monitor whether defined sustainability goals are achieved within the determined timetables and whether trade-offs and links between them exist.

Regarding conflicts of interest, for example, economic growth is considered a necessary condition for providing income and employment on the one hand, while on the other hand sustained and unconditioned growth is considered a major threat to integrated sustainable development. Spangenberg (2001) points out that these tensions, unavoidable as they are in any multi-dimensional concept, clearly illustrate that sustainable development has no unambiguously defined optimum (as is usual when only two competing targets have to be taken into account). Instead, benchmarks need to be defined, distinguishing potentially sustainable from definitively unsustainable development trends.

In this chapter we describe a possible way to evaluate the sustainability of the Austrian economy for the period 1995 to 2000 by connecting indicators for all dimensions of sustainable development. With regard to sustainable economic development we choose the growth of gross domestic product (GDP) as a proxy indicator for human well being.[10] The social field is measured through employment. According to widely accepted norms in an economy, the values of these indicators are to be raised. These goals and indicators are of course not indisputable but widely used and can be taken as a general starting point. The Direct Material Input and CO_2 emissions are used as indicators reflecting the environmental pressures.

Resource productivity (derived from material input), CO_2 efficiency, labor productivity and economic growth can be related to each other via three inequations representing minimum conditions for sustainable development[11] (see for the following Spangenberg et al. 2002).

Minimum Condition for Environmental Sustainable Development

If we accept that we are already close to (or even beyond) the limits of nature's carrying capacity (on both the input and the output side, see for example WWF et al. 2004), following the precautionary principle industrial economies should reduce the total throughput of resources (R). Since the minimum condition for ecological sustainable development demands an absolute decoupling (dematerialization), it

[10] We share, however, the general agreement on the limitation of GDP growth as an indicator of societal well-being. As economic growth does not incorporate the external impacts on the environment, it is not compatible with environmental protection, and therefore sustainable development. Nevertheless GDP growth is still an accepted goal within economic policy. Taking GDP growth as one economic indicator allows us to show the trade-offs between and the links to different aims of sustainability.

[11] The formal derivation of the minimum conditions is explained in Appendix 2.

requires that the growth rate of GDP has to be smaller than the increase in resource productivity

$$dY < d(Y/R) \tag{34.12}$$

Consequently, with Y the Gross Domestic Output (GDP) and R the total volume of resources (physical flows[12]), Y/R is the *resource productivity*.

Following Spangenberg et al. (2002) we share the opinion that this criterion is a necessary condition for all environmentally sustainable strategies; it is not a sufficient criterion, since the rate and/or the speed of decoupling might be too slow to solve current and future environmental problems. This implies that economic growth can only lead to an environmentally sustainable path if it is accompanied by resource productivity increases at a higher rate than the rate of economic growth.[13]

As we analyse an input as well as an output related indicator, R stands for DMI and CO_2 respectively:

In order to reach a dematerialization or decoupling of material use and economic growth, the material intensity (MI/Y) must decrease or the material productivity (Y/MI) must increase stronger than Y.

$$dY < d(Y/MI) \tag{34.12a}$$

In order to reach a decoupling of CO_2 emissions and economic growth the CO_2 intensity (CO_2/Y) has to decrease, which means again the reciprocal (Y/CO_2) must increase stronger than Y.

$$dY < d(Y/CO_2) \tag{34.12b}$$

Both inequations have to be satisfied to fulfil the minimum condition of environmental sustainability.

Minimum Condition for Social Sustainable Development

The challenge of reducing unemployment is one of the most serious social concerns in Austria and has therefore to be considered when dealing with social sustainability.

The minimum criterion for social sustainability demands that the number of people employed L increases only if during a given period the economy grows faster than the average production per capita, that is if

$$dY > d(Y/L). \tag{34.13}$$

[12] Physical flows capture all resource inputs (such as energy, materials) or outputs (such as CO_2 emissions, acidifying emissions). Many physical flows are related to environmental problems.

[13] Furthermore, qualitative aspects of material flows are of crucial importance, as flows differ considerably with regard to their potential for negative environmental impacts. A quantitative reduction of natural resource inputs could theoretically even lead to an increase in environmental impacts, if the composition of material input changes towards higher polluting materials.

If we regard the creation of additional jobs as an indisputable precondition of social sustainability, this relation describes a **necessary, although not sufficient precondition for social sustainability**.[14]

This relationship is derived from the fact that total output Y can be written as the total active labor force L multiplied by the *labor productivity* Y/L, measured as the average per capita production. The production per capita is given as the average output per working hour Y/h multiplied by the average working hours per capita h/L. Since

$$Y/L = Y/h \times h/L \tag{34.14}$$

the labor productivity Y/L depends on the labor productivity per hour Y/h as well as on the number of working hours per capita (h/L). Equation (34.14) indicates that the labor productivity is increasing with growing labor productivity per hour and decreasing with reduced working times.

In equation (34.13) is only valid with strong economic growth.

As a condition for increasing employment is

$$dY > d(Y/L) = d(Y/h \times h/L) \tag{34.15}$$

ceteris paribus the increase in labor productivity per hour Y/h must be limited to $d(Y/h) < dY$, otherwise the working time h/L has to decrease sufficiently to offset increases in Y/h to keep the increase $d(Y/L)$ below the total economic growth *dY*.

Minimum Condition for Sustainable Economic Development[15]

Combining the two relations above, $dY > d(Y/L)$ and $dY < d(Y/R)$ (both include implicitly the economic dimension of sustainable development with dY) we can conclude that as a necessary precondition, sustainable growth is only possible, if

$$d(Y/L) < dY < d(Y/R) \tag{34.16}$$

We have to keep in mind that this condition is **a necessary but not sufficient prerequisite to attain sustainable development**. As a minimum condition, it helps to distinguish growth patterns that are definitely not sustainable from those that might be so.

We see that there is a trade-off between (34.12) and (34.13). (34.12) requires slow economic growth, which increases the chance for a sustainable path, whereas

[14] In addition to the quantity of jobs their quality is essential, comprising issues like job security, income, working conditions, Moreover, the differentiation of labor time (overtime, flexible working hours, time accounts, part time employment and early retirement,. . .) as well as the organisation and the division of labor are becoming increasingly important as well as informal labor (caring work, work in/for the community etc.).

[15] Spangenberg et al. (2002) call this criterion the *minimum condition of socio-environmental sustainability*.

(34.13) supports strong economic growth to reduce the unemployment rate. As said above, the growth of resource productivity is limited, so is economic growth to fulfil (34.12) and growth of labor productivity to fulfil (34.13). During the past 150 years, labor productivity has been steadily increasing (Spangenberg et al. 2002). From (34.14) we know that it is decreasing with reduced working time. Hence part time jobs, reduced yearly working time and other forms of working time reduction can be seen as a solution for this trade-off (Omann and Nordmann 2000).

Empirical Application

Applying the Make-Use Framework

This section illustrates the empirical application of the modelling approach described above for the Austrian economy. It refers to the results calculated within the project "Eco-efficiency and Sustainability" on behalf of the OeNB Anniversary Fund ("Jubiläumsfonds der Oesterreichischen Nationalbank"), which are partly listed in the tables of Appendix 1. Further results are presented in Luptacik and Stocker (2005).

We investigate different aspects of resource use, generation of CO_2 emissions and employment, comprising the description, calculation and comparison of direct and total absolute amounts and intensities. First, assuming that the material requirements of an industry are proportional to the industry's output, we relate the material input to output levels by industry. This relationship is expressed in terms of material input coefficients and indicates the direct material intensity.[16] Second, we calculate weighted total material requirements and multipliers[17] in order to quantify the indirect and total requirements, necessary to deliver a Euro's worth of output to final demand.

Third, we post-multiply the weighted total requirements matrix by a final demand vector in order to obtain for each industry the value of output induced by final demand. Using the matrix of final demand categories instead of the vector of total final demand finally enables the analysis of the amount, share and multipliers of resource use, CO_2 emissions and employment of the different categories of final demand.

Development over time for all of these figures are investigated in order to show whether a dematerialization, a reduction of CO_2 emissions and an increase in labor have taken place in the Austrian economy. Because of the data availability, the time period under consideration is 1995 to 2000.

[16] The same procedure applies for CO_2 emissions and labor requirements.

[17] The multiplier for sector j (column sum of the weighted total requirements matrix) describes the total value of material use in all sectors of the economy that is necessary for the production of sector j's output in order to satisfy a Euro's worth of final demand.

Results for Material Inputs

Concerning the resource use of the Austrian economy, it is important to mention that only domestic material extraction is considered, because an exact allocation of imported material inputs is not possible so far. However, ignoring imports is problematic for two reasons. First, the structure of the Austrian material inputs shows a high import share (39%). In 2000, for example, 87.5% of fossil fuels were imported. Second, it is not possible to show if a reduction of domestic material inputs results from importing more resource-intensive goods that require large amounts of materials in other countries (Petrovic 2003).

Table 34.1 lists the data on direct domestic material input by industry for the years 1995 and 2000, derived from the economy-wide MFA. Columns (1) and (3) represent the direct material input by industry in absolute amounts (in 1,000 t), columns (2) and (4) show the direct material intensities, i.e. the direct material input of a sector per unit of total output of this sector. The last two columns illustrate the difference between the years 1995 and 2000. The notation corresponds to the one used in the previous section.

The fact that only a small number of sectors extract material directly from nature clearly indicates the necessity of using structural approaches in providing valuable information for policy actions.

Considering the **amounts of material input** directly used, the sector "Other mining and quarrying" plays the most important role, followed by "Agriculture, forestry, fishing". Concerning the **material intensity** the situation changes slightly. The sector "Other mining and quarrying" has still the lead, but "Agriculture and Forestry" plays a less important role.

The changes of domestic material input between 1995 and 2000 reveal a small increase in material use and decrease in material intensity for the economy as a whole. The direct resource use of "Agriculture, forestry and fishing" was reduced between 1995 and 2000, while it increased for the sectors "Other mining and quarrying" and "Extraction of crude oil, natural gas and mineral or metal ores". The intensities declined in all sectors except for the case of "Mining of coal and lignite".

Table 34.1 Direct Material Input by Industry

	1995		2000		Difference	
	t_j	f_j	t_j	f_j	t_j	f_j
		1,000 t/million		1,000 t/million	t/million	1,000
Sectors	1,000 t	euro	1,000 t	euro	1,000 t	euro
Agriculture, forestry, fishing	37.990	6.00	36.150	5.27	−1.840	−0.73
Mining of coal and lignite	1.250	21.45	1.250	22.47	0	1.02
Extract. o. crude petrol. a. nat. gas, min. o. metal ores	4.460	17.94	4.710	14.71	250	−3.23
Other mining and quarrying	81.080	104.02	82.930	91.43	1.850	−12.59
Total	**124.780**	**0.45**	**125.040**	**0.36**	**260**	**−0.09**

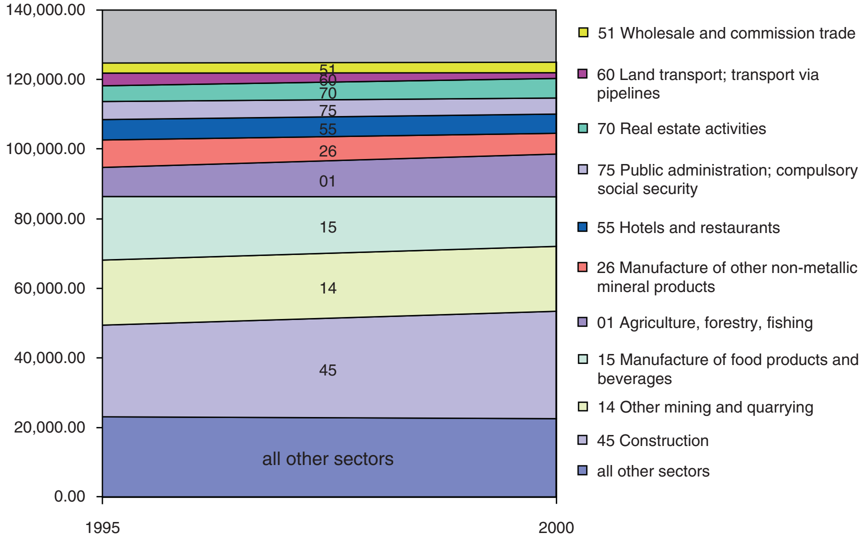

Fig. 34.2 Development of Total Material Input by Industry Between 1995 and 2000, in 1,000 t (Ten Most Material-Intensive Sectors, in 1,000)

Turning to the results for **total material (direct plus indirect) input** (Table 34.3 in Appendix 1), the sector with the highest amounts is "Construction", followed by "Other mining and quarrying" and "Food products and beverages". These results illustrate that the total material requirements of the direct extracting sectors are smaller than the direct intensities, although they are still considerably high. The sectors "Manufacture of other non-metallic mineral products", "Hotels and restaurants" and "Public administration, compulsory social security" do not extract materials directly from nature, but have high indirect amounts. This indicates that a lot of direct resource extraction is needed to provide intermediate commodities and services for other sectors, allowing them to produce their outputs. As the sectors with a high direct share produce mainly for intermediate products, they are not alone responsible for their material use.

The following figure (Fig. 34.2) shows the changes of total material input of the ten most resource intensive sectors over time. The development of the most important sector, Construction, shows no significant changes. The material use of the sector "Food products and beverages" declines, while it increases in "Agriculture".

Looking at the total intensities expressed by the multipliers (see columns 2 and 4 of Table 34.3) reveals that all direct extracting sectors also have a very high total material intensity.

Concerning the role of the different final demand categories (private consumption, public consumption, investments, exports) in activating resource use, the highest amounts of resource use are needed to satisfy private consumption (more than 41 million tons or 33% in 1995) and exports (around 37 million tons or nearly 30% in 1995). Investments in dwellings and other buildings (together around 28% in

1995 and 26% in 2000) also require a lot of material inputs. The share of exports increases over time, while the percentage of consumption and investments decreases.

Expressed in multipliers (that is if we relate the resource use to 1 million Euro's worth of a final demand category), the situation changes considerably, as now investments in dwellings and other buildings have the most prominent role. The development of the multipliers over time show slight decreases in almost all final demand categories.

Results for CO_2 Emissions

The data on direct CO_2 emissions by sector are provided by the Austrian NAMEA for air emissions (Umweltbundesamt 2000). The highest contributions to the generation of CO_2 are found in the sectors "Land transport and transport via pipeline services", "Electricity, gas, steam and hot water" and "Basic metals". These sectors also show high intensities, although the highest intensity is observed in the coal and lignite sector.

Referring to the total CO_2 emissions by sector it is evident that the sectors "land transport" (NACE 60), "Manufacture of basic metals" (NACE 27) and "Electricity, gas, steam and hot water supply" (NACE 40) have the highest values both in terms of absolute amounts and intensities. The development of the ten most polluting sectors is illustrated in Fig. 34.3. Here, the strong decrease in the sector 27 (Basic metals) between 1995 and 2000 is conspicuous. This decrease however is compensated by an increase in sector 28 "Manufacture of fabricated metal products" with an even higher magnitude (see Table 34.4 in Appendix 1).

The comparison between direct and total values reveals that in many sectors the direct CO_2 emissions are higher than the total emissions (see Table 34.5 in Appendix 1), again indicating the importance of using a structural model. This fact is especially true for land transport and electricity where the total values are half of the direct ones, albeit the total amounts are substantial. The converse effect can, for example, be observed in the construction sector, in the manufacture of food products and beverages and some service-oriented sectors.

It is also notable that many industries show higher indirect than direct CO_2 intensities.

With respect to categories of final demand, exports (22 million tons or 42% in 1995 and nearly 25 million tons or 46% in 2000) account for most emissions, followed by private consumption (37% in 1995 and 35.5% in 2000). Compared to material input the investments (about 12% in both years) are now less important.

Results for Employment

The analysis of employment is based on data of the input-output tables, which provide information about the number of jobs, by industries (annual average) comprising self-employed persons and employees.

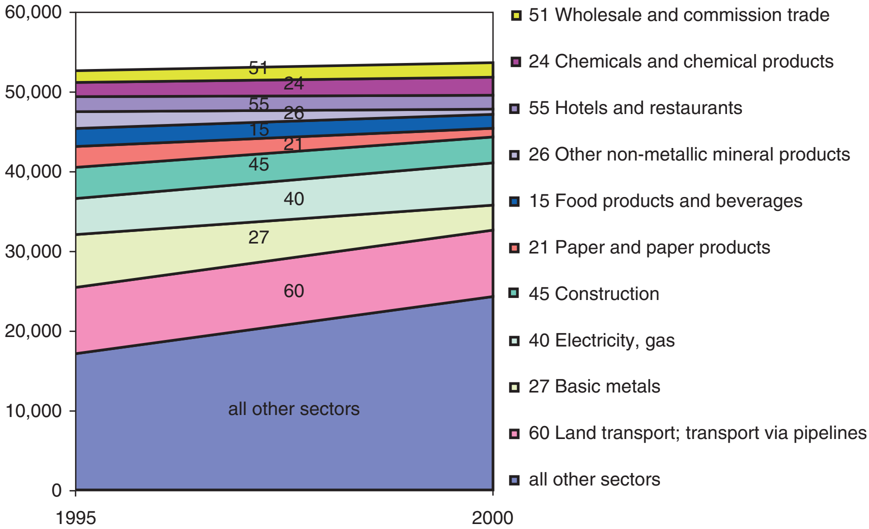

Fig. 34.3 Development of Total CO_2 Emissions per Sector Between 1995 and 2000, in 1,000 t (Ten Most CO_2-Intensive Sectors)

The situation of direct employment by industry reveals the prominent role of sector "Agriculture, forestry and fishing" especially with respect to both the high share of persons employed and the high degree in direct labor input intensity. Other leading sectors are "Construction", "Retail trade, repair of household goods" and "Health and social work".

Referring to total absolute amounts (Table 34.6 in Appendix 1) gives a different perspective on the outstanding position of labor. From this perspective, the sector "Manufacture of food products and beverages" employs most people in absolute terms, followed by "Construction", and "Hotels and restaurants". However, the sector with the highest total labor intensity is again "Agriculture, forestry and fishery".

Table 34.7 relates the direct, indirect and total labor intensities and shows that in many cases the indirect intensity exceeds the direct one.

An illustrative example of this situation is given by sector "Manufacture of food products and beverages", where the indirect intensity in 1995 is about five times higher than the direct intensity (in 2000 about four times).

According to Fig. 34.4, employment for the economy as a whole increased from 3,927.553 people in 1995 to 4,082.067 people in 2000. Considering the development in the most labor intensive sectors "manufacturing food products and beverages" has become less labor intensive, while employment in the sector "Health and social work" was increasing.

Concerning the distribution of labor to the different categories of final demand, again private consumption (1.75 million jobs or 44% in 1995; 1.7 million jobs or 42% in 2000) has the most prominent role, followed by exports (21% in 1995 and 24% in 2000). Public consumption accounts for 19% in 1995, and 20% in 2000.

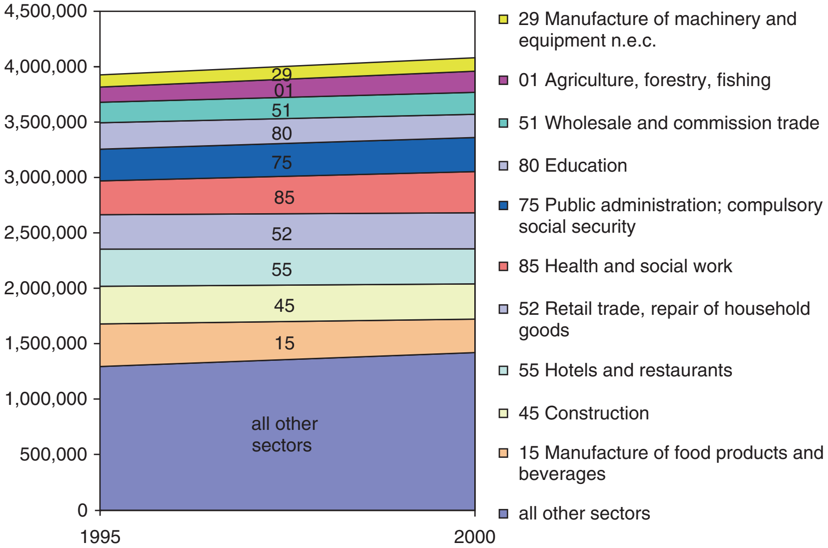

Fig. 34.4 Development of Total Labor by Sector Between 1995 and 2000, in Jobs (Ten Most Labor Intensive Sectors)

Table 34.2 Calculation of Minimum Condition for Social Sustainability

	Y	L	Y/L
	Million euro	Jobs	Million euro/million jobs
1995	190.175	3,927.553	48.421
2000	225.615	4,082.067	55.270
Difference	**35.439**	**154.514**	**6.849**

Evaluation of Austrian Sustainability: Minimum Conditions for Sustainable Development

In this section we present a first attempt to indicate the coherence between economic activity, employment and resource consumption for the Austrian economy on a disaggregated level. Applying the make-use framework, it is possible to compare resource consumption and employment by industries and thus detect structural trends and compare them to the above developed minimum sustainability criterion.

We investigate whether the developed minimum conditions of sustainable development (see Table 34.2) are valid for Austria by connecting the calculated figures of total material input, emissions and labor, induced by final demand, described in the last section to GDP.[18]

[18] As we only consider domestic figures, GDP is equal to final demand.

To evaluate the social and ecological sustainability we relate the change of final demand between 1995 and 2000 (dY) to the change of the reciprocal values of the total intensities of material input, CO_2 and labor between 1995 and 2000.

Regarding the criteria for social sustainability only an assessment on the level of the general economy make sense, since the demand for increasing employment in every sector – even in sectors with declining production or inefficiently large employment levels – rules out structural change in the economy. Table 34.2 shows that the minimum criterion for social sustainability (i.e. the number of people employed L increases only if during a given period the economy Y grows faster than the average production per capita Y/L) is valid for the Austrian economy as a whole over the considered time period 1995–2000.

While the goal of full employment only is applicable for the entire economy, the aims of dematerialization and reduction of CO_2 emissions are also reasonable for the sector level.

If we consider environmental sustainability, the growth rate of GDP has to increase slower than that of resource productivity d(Y/R). The calculation for material input (see Table 34.8) reveals that neither for the entire economy nor for most of the sectors this minimum condition is satisfied.[19] Exceptions are only those sectors, showing a decrease in Y over time, such as "Food products and beverages", or "Sale and repair of motor vehicles". In Table 34.9 the results for ecological sustainability with respect to CO_2 are presented, showing that the overall economy does not match this criterion, but more sectors do than in the case of material input.

Conclusions

This paper provided a straightforward example how ecological and social indicators can be integrated in economic modelling as well as in empirical studies. Exploring these approaches in more detail will help to discuss the effects and effectiveness of measures and policies for ecologically and socially sustainable development on all relevant macroeconomic variables. Further research is certainly needed to explore in more detail the structural, distributional, allocation and scale effects of such policies.

We have shown the importance of integrating physical flows in disaggregated economic modelling frameworks in order to adequately consider the relationship between the economic and the natural system. The evaluation of the sustainability of the Austrian economy by applying minimum conditions for sustainable development has shown that the necessary requirements for sustainable economic development were not fulfilled for the time period 1995 to 2000. The necessary absolute decoupling of resource use and CO_2 emissions from GDP did not occur.

[19] The term "Possible" in the last column of the tables indicate that fulfilling the minimum condition does not mean that the development was actually sustainable.

Only the criterion for social sustainability is fulfilled for nearly all sectors. However, the data for employment only relate to the number of jobs comprising self-employed persons and employees without considering the occupational breakdown or qualitative pattern. From a sustainability perspective an extended definition of the term "labor" itself is necessary, which comprises, in addition to the usual gainful employment, caring work, voluntary work in the community and parts of work as self-provider. Providing insight in these issues would significantly enhance the evaluation of social sustainability, but at the time being, the necessary data are not available in Austria. Still, the reduction of the unemployment rate can be regarded as an adequate indicator for social sustainable development, because formal work (traditional jobs) do play a role also in the concept of "mixed work" in the sense that people should work still in the formal economy (probably less hours per year on average) while working additionally in the informal sectors.

However, it is necessary to emphasize that neglecting imports is an important limitation of this analysis, because we are not able to distribute the data on material use to the sectors. Therefore, it is not possible to show if and how changes in domestic material extraction are related to changes in imports. Furthermore, all material flows are aggregated to one indicator. However, for the evaluation of changes in material flows it would be helpful to distinguish between different material groups with different environmental implications (e.g. biomass, fossil fuels, metallic resources, non-metallic minerals. This more disaggregated categorization is up to further research efforts.

The accuracy of data used, and the underlying assumptions considered may lead to different kinds of errors. Therefore, the results only provide rough estimates of the past development of material use, CO_2 emissions and employment in Austria.

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Appendix 1: Results

Results for Material Input

Table 34.3 Total Material Input

		1995		2000		Difference	
		M_f y	M_f	M_f y	M_f	M_f y	M_f
NACE	Commodities	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro
45	Construction	26.367	1.43	30.841	1.59	4.474	0.16
14	Other mining and quarrying	18.725	83.39	18.655	72.02	−70	−11.37
15	Food products and beverages	18.245	2.23	14.249	1.81	−3.996	−0.43
01	Agriculture, forestry, fishing	8.393	6.34	12.313	6.35	3.920	0.01
26	Other non-metallic mineral products	7.887	3.96	5.978	2.87	−1.910	−1.08
55	Hotels and restaurants	5.840	0.58	5.500	0.51	−340	−0.07
75	Public administration; compulsory social security	5.207	0.35	4.648	0.30	−559	−0.05
70	Real estate activities	4.532	0.34	5.611	0.38	1.079	0.04
60	Land transport; transport via pipelines	3.633	0.82	1.639	0.31	−1.994	−0.51
51	Wholesale and commission trade	2.879	0.29	3.030	0.24	151	−0.05
24	Chemicals and chemical products	2.399	0.69	1.787	0.36	−612	−0.32
21	Paper and paper products	2.301	0.88	2.823	0.79	522	−0.09
52	Retail trade, repair of household goods	1.996	0.18	2.260	0.18	264	0.00
85	Health and social work	1.957	0.15	2.629	0.20	672	0.05
20	Wood and of products of wood	1.920	0.94	1.693	0.61	−227	−0.33
29	Machinery and equipment n.e.c.	1.580	0.21	1.175	0.12	−405	−0.09
40	Electricity, gas, steam and hot water supply	1.389	0.55	2.430	0.76	1.041	0.20
74	Other business activities	1.187	0.31	720	0.15	−468	−0.16
36	Furniture; manufacturing n.e.c.	1.133	0.30	811	0.18	−322	−0.13

(continued)

Table 34.3 (continued)

27	Basic metals	1.073	0.33	898	0.19	−175	−0.14
23	Coke, refined petroleum products	798	1.13	200	0.28	−598	−0.85
80	Education	757	0.08	829	0.08	71	0.00
63	Supporting a. auxiliary transport activities; travel agencies	675	0.20	980	0.24	305	0.03
28	Fabricated metal products	497	0.17	471	0.12	−26	−0.05
50	Sale and repair of motor vehicles; retail sale of automotive fuel	483	0.10	677	0.15	194	0.05
31	Electrical machinery and apparatus	390	0.15	529	0.14	139	−0.02
91	Activities of membership organizations	389	0.18	502	0.21	113	0.03
34	Motor vehicles and trailers	385	0.09	379	0.05	−6	−0.03
92	Recreational, cultural and sporting activities	369	0.13	473	0.14	104	0.01
25	Rubber and plastic products	325	0.17	290	0.12	−35	−0.05
32	Radio, television equipment	306	0.10	337	0.08	31	−0.01
11	Extract. o. crude petrol. a. nat. gas, min. o. metal ores	248	18.52	92	16.42	−156	−2.10
19	Leather, leather products, footwear	230	0.33	244	0.29	14	−0.04
66	Insurance and pension funding, except social security	207	0.07	205	0.06	−2	−0.01
17	Textiles	188	0.11	166	0.08	−22	−0.03
65	Financial intermediation, except insur. a. pension funding	150	0.23	92	0.05	−58	−0.18
22	Publishing, printing and reproduction	144	0.19	189	0.11	45	−0.08
93	Other service activities	132	0.11	150	0.12	19	0.01
33	Manuf. of medical, precision, optical instruments, clocks	118	0.11	120	0.10	2	0.00
62	Air transport	100	0.17	139	0.12	40	−0.05
35	Other transport equipment	94	0.12	99	0.09	5	−0.03

(continued)

Table 34.3 (continued)

		1995		2000		Difference	
		M_f y	M_f	M_f y	M_f	M_f y	M_f
71	Renting of machinery and equipment without operator	87	0.13	93	0.11	5	−0.02
18	Wearing apparel	81	0.08	74	0.07	−7	−0.01
64	Post and tele-communications	64	0.03	295	0.08	231	0.04
90	Sewage and refuse disposal, sanitation and similar act.	62	0.58	153	0.91	91	0.34
72	Computer and related activities	61	0.14	141	0.10	80	−0.03
16	tobacco products	61	0.25	52	0.18	−9	−0.07
73	Research and development	33	0.13	41	0.09	8	−0.04
61	Water transport	15	0.20	14	0.20	−1	0.01
30	Office machinery and computers	5	0.09	26	0.05	22	−0.04
37	Recycling	3	0.14	3	0.10	0	−0.04
41	Collection, purification and distribution of water	0	0.34	0	0.32	0	−0.02
67	Activities auxiliary to financial intermediation	0	0.12	0	0.06	0	−0.06
95	Private households with employed persons	0	0.00	1	0.00	1	0.00
10	Mining of coal and lignite[a]	−1.323	21.71	−2.708	50.50	−1.384	28.79
	Total	124.780		125.040		260	

[a]In spite of the high positive multipliers of the sector "Mining of coal and lignite" the absolute figures are negative because the final demand of coal is negative. This is due to the fact, that this sector does not deliver to final demand, but is using its stocks.

Results for CO_2 Emissions

Table 34.4 Total CO_2 emissions

		1995		2000		Difference	
		M_o y	M_o	M_oy	M_o	M_oy	M_o
NACE	Commodities	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro
60	Land transport; transport via pipelines	8.320	1.87	8.330	1.56	10	−0.31
27	Basic metals	6.622	2.06	3.141	0.66	−3.480	−1.39
40	Electricity, gas, steam and hot water supply	4.549	1.81	5.320	1.65	771	−0.15
45	Construction	3.904	0.21	3.257	0.17	−647	−0.04
21	Paper and paper products	2.624	1.00	1.094	0.31	−1.530	−0.69
15	Food products and beverages	2.265	0.28	1.739	0.22	−526	−0.06
26	Other non−metallic mineral products	2.108	1.06	665	0.32	−1.443	−0.74
55	Hotels and restaurants	1.893	0.19	1.751	0.16	−142	−0.03
24	Chemicals and chemical products	1.773	0.51	2.256	0.46	483	−0.05
51	Wholesale and commission trade	1.471	0.15	1.829	0.14	357	0.00
75	Public administration; compulsory social security	1.424	0.10	1.262	0.08	−162	−0.01
29	Machinery and equipment n.e.c.	1.369	0.18	2.311	0.23	942	0.05
52	Retail trade, repair of household goods	1.294	0.12	1.366	0.11	73	−0.01
85	Health and social work	1.276	0.10	1.333	0.10	56	0.00
70	Real estate activities	1.189	0.09	1.151	0.08	−38	−0.01
28	Fabricated metal products	1.100	0.37	5.612	1.38	4.512	1.01
34	Motor vehicles and trailers	856	0.19	722	0.10	−133	−0.09
23	Coke, refined petroleum products	844	1.20	84	0.12	−760	−1.08
80	Education	748	0.08	449	0.04	−299	−0.03
63	Supporting a. auxiliary transport activities; travel agencies	740	0.22	730	0.18	−11	−0.05
36	Furniture; manufacturing n.e.c.	586	0.16	759	0.17	174	0.01
20	Wood and of products of wood	559	0.27	503	0.18	−56	−0.09

(continued)

Table 34.4 (continued)

		1995		2000		Difference	
		M_o y	M_o	M_o y	M_o	M_o y	M_o
NACE	Commodities	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro	1,000 t	1,000 t/million euro
25	Rubber and plastic products	533	0.28	1.070	0.43	537	0.15
50	Sale and repair of motor vehicles; retail sale of automotive fuel	513	0.11	504	0.11	−10	0.00
31	Electrical machinery and apparatus	490	0.19	770	0.20	280	0.01
17	Textiles	365	0.22	207	0.10	−158	−0.12
74	Other business activities	364	0.09	456	0.10	93	0.00
01	Agriculture, forestry, fishing	334	0.25	489	0.25	155	0.00
92	Recreational, cultural and sporting activities	329	0.12	391	0.12	62	0.00
32	Radio, television equipment	316	0.10	405	0.10	89	0.00
14	Other mining and quarrying	277	1.23	115	0.45	−162	−0.79
91	Activities of membership organizations n.e.c.	246	0.11	314	0.13	68	0.02
35	Other transport equipment	204	0.25	195	0.17	−9	−0.08
22	Publishing, printing and reproduction	180	0.24	1.110	0.66	930	0.42
66	Insurance and pension funding, except social security	159	0.05	169	0.05	10	−0.01
33	Manuf. of medical, precision, optical instruments, clocks	143	0.13	135	0.11	−8	−0.01
62	Air transport	117	0.20	159	0.13	43	−0.06
18	Wearing apparel	107	0.11	247	0.23	140	0.12
93	Other service activities	101	0.09	113	0.09	12	0.00
65	Financial intermediation, except insur. a. pension funding	96	0.15	69	0.04	−27	−0.11
64	Post and tele-communications	91	0.04	324	0.08	234	0.04
19	Leather, leather products, footwear	89	0.13	103	0.12	14	0.00
71	Renting of machinery and equipment without operator	78	0.12	93	0.11	15	0.00
73	Research and development	56	0.22	36	0.08	−21	−0.15

(continued)

Table 34.4 (continued)

72	Computer and related activities	52	0.12	76	0.06	25	−0.06
61	Water transport	41	0.54	42	0.62	1	0.08
16	Tobacco products	39	0.16	609	2.12	570	1.96
90	Sewage and refuse disposal, sanitation and similar act.	32	0.30	36	0.22	4	−0.08
11	Extract. o. crude petrol. a. nat. gas, min. o. metal ores	13	0.96	3	0.58	−10	−0.38
37	Recycling	6	0.25	6	0.22	0	−0.04
30	Office machinery and computers	6	0.11	205	0.40	200	0.29
41	Collection, purification and distribution of water	0	0.18	0	0.16	0	−0.02
67	Activities auxiliary to financial intermediation	0	0.09	0	0.07	0	−0.03
95	Private households with employed persons	0	0.00	0	0.00	0	0.00
10	Mining of coal and lignite	−228	3.74	−435	8.12	−207	4.38
	Total	52.659		53.682		1.022	

Table 34.5 Comparison of Direct, Indirect and Total CO_2 Intensities

NACE	Commodities	1995			2000		
		Direct o_j	Indirect $M_o - o_j$	Total M_o	Direct o_j	Indirect $M_o - o_j$	Total M_o
01	Agriculture, forestry, fishing	0.17	0.08	0.25	0.13	0.12	0.25
10	Mining of coal and lignite	3.58	0.16	3.74	3.54	4.58	8.12
11	Extract. o. crude petrol. a. nat. gas, min. o. metal ores	0.81	0.15	0.96	0.34	0.25	0.58
14	Other mining and quarrying	0.92	0.31	1.23	0.09	0.36	0.45
15	Food products and beverages	0.06	0.22	0.28	0.05	0.17	0.22
16	Tobacco products	0.04	0.12	0.16	2.31	−0.19	2.12
17	Textiles	0.10	0.12	0.22	0.00	0.09	0.10
18	Wearing apparel	0.03	0.08	0.11	0.20	0.03	0.23
19	Leather, leather products, footwear	0.03	0.10	0.13	0.03	0.10	0.12
20	Wood and of products of wood	0.07	0.20	0.27	0.00	0.18	0.18
21	Paper and paper products	0.69	0.32	1.00	0.07	0.24	0.31
22	Publishing, printing and reproduction	0.06	0.18	0.24	0.57	0.10	0.66
23	Coke, refined petroleum products	1.02	0.18	1.20	0.07	0.05	0.12
24	Chemicals and chemical products	0.23	0.28	0.51	0.29	0.17	0.46
25	Rubber and plastic products	0.13	0.15	0.28	0.27	0.16	0.43

(continued)

Table 34.5 (continued)

NACE	Commodities	1995 Direct o_j	1995 Indirect $M_o - o_j$	1995 Total M_o	2000 Direct o_j	2000 Indirect $M_o - o_j$	2000 Total M_o
26	Other non-metallic mineral products	0.71	0.35	1.06	0.08	0.24	0.32
27	Basic metals	1.65	0.41	2.06	0.45	0.22	0.66
28	Fabricated metal products	0.05	0.31	0.37	1.28	0.10	1.38
29	Machinery and equipment n.e.c.	0.02	0.16	0.18	0.03	0.20	0.23
30	Office machinery and computers	0.01	0.10	0.11	0.38	0.02	0.40
31	Electrical machinery and apparatus	0.02	0.17	0.19	0.02	0.18	0.20
32	Radio, television equipment	0.02	0.08	0.10	0.01	0.09	0.10
33	Manuf. of medical, precision, optical instruments, clocks	0.00	0.13	0.13	0.00	0.11	0.11
34	Motor vehicles and trailers	0.02	0.17	0.19	0.01	0.09	0.10
35	Other transport equipment	0.02	0.23	0.25	0.01	0.16	0.17
36	Furniture; manufacturing n.e.c.	0.00	0.16	0.16	0.00	0.16	0.17
37	Recycling	0.00	0.25	0.25	0.00	0.22	0.22
40	Electricity, gas, steam and hot water supply	1.17	0.63	1.81	1.18	0.48	1.65
41	Collection, purification and distribution of water	0.00	0.18	0.18	0.00	0.16	0.16
45	Construction	0.01	0.21	0.21	0.00	0.16	0.17
50	Sale and repair of motor vehicles; retail sale of automotive fuel	0.01	0.10	0.11	0.01	0.10	0.11
51	Wholesale and commission trade	0.01	0.13	0.15	0.01	0.14	0.14
52	Retail trade, repair of household goods	0.01	0.10	0.12	0.01	0.09	0.11
55	Hotels and restaurants	0.05	0.14	0.19	0.04	0.12	0.16
60	Land transport; transport via pipelines	1.91	−0.03	1.87	1.54	0.02	1.56
61	Water transport	0.42	0.13	0.54	0.49	0.13	0.62
62	Air transport	0.07	0.13	0.20	0.04	0.09	0.13
63	Supporting a. auxiliary transport activities; travel agencies	0.00	0.22	0.22	0.00	0.17	0.18
64	Post and tele-communications	0.01	0.04	0.04	0.00	0.08	0.08
65	Financial intermediation, except insur. a. pension funding	0.02	0.13	0.15	0.00	0.04	0.04
66	Insurance and pension funding, except social security	0.01	0.05	0.05	0.00	0.04	0.05

(continued)

Table 34.5 (continued)

67	Activities auxiliary to financial intermediation	0.01	0.09	0.09	0.00	0.06	0.07
70	Real estate activities	0.00	0.09	0.09	0.00	0.08	0.08
71	Renting of machinery and equipment without operator	0.00	0.12	0.12	0.00	0.11	0.11
72	Computer and related activities	0.00	0.11	0.12	0.00	0.06	0.06
73	Research and development	0.22	0.00	0.22	0.00	0.08	0.08
74	Other business activities	0.00	0.09	0.09	0.00	0.10	0.10
75	Public administration; compulsory social security	0.00	0.10	0.10	0.00	0.08	0.08
80	Education	0.03	0.04	0.08	0.00	0.04	0.04
85	Health and social work	0.02	0.08	0.10	0.00	0.10	0.10
90	Sewage and refuse disposal, sanitation and similar act	0.07	0.23	0.30	0.07	0.15	0.22
91	Activities of membership organizations n.e.c.	0.00	0.11	0.11	0.00	0.13	0.13
92	Recreational, cultural and sporting activities	0.03	0.09	0.12	0.02	0.09	0.12
93	Other service activities	0.00	0.09	0.09	0.00	0.09	0.09
95	Private households with employed persons	0.00	0.00	0.00	0.00	0.00	0.00

Results for Employment

Table 34.6 Total Labor Employment (Absolute and Intensities)

		1995		2000		Change	
NACE	Commodities	$M_l y$ Jobs	M_l Jobs/million euro	$M_l y$ Jobs	M_l Jobs/million euro	M_l y Jobs	M_l Jobs/million euro
15	Food products and beverages	384.676	47.09	301.399	38.25	−83.277	−8.84
45	Construction	339.956	18.50	318.329	16.46	−21.627	−2.04
55	Hotels and restaurants	334.468	33.42	316.656	29.47	−17.813	−3.96
52	Retail trade, repair of household goods	310.621	27.98	323.897	25.23	13.276	−2.75
85	Health and social work	304.366	23.69	370.996	28.70	66.630	5.00
75	Public administration; compulsory social security	286.379	19.14	308.692	19.83	22.314	0.69
80	Education	238.676	24.21	209.292	20.30	−29.384	−3.92
51	Wholesale and commission trade	184.945	18.40	197.497	15.63	12.552	−2.77
01	Agriculture, forestry, fishing	137.469	103.76	190.644	98.24	53.175	−5.52

(continued)

Table 34.6 continued

NACE	Commodities	1995 $M_l y$ Jobs	1995 M_l Jobs/million euro	2000 $M_l y$ Jobs	2000 M_l Jobs/million euro	Change M_l y Jobs	Change M_l Jobs/million euro
29	Machinery and equipment n.e.c.	110.014	14.50	122.068	12.12	12.055	−2.38
70	Real estate activities	99.312	7.49	125.748	8.58	26.437	1.09
60	Land transport; transport via pipelines	96.195	21.65	104.924	19.67	8.729	−1.98
50	Sale and repair of motor vehicles; retail sale of automotive fuel	83.786	17.90	79.920	17.54	−3.866	−0.37
36	Furniture; manufacturing n.e.c.	81.594	21.93	75.719	16.48	−5.874	−5.45
74	Other business activities	72.603	18.76	95.101	20.05	22.499	1.29
20	Wood and of products of wood	61.036	29.74	55.185	19.83	−5.851	−9.91
28	fabricated metal products	51.470	17.13	55.334	13.58	3.864	−3.56
92	Recreational, cultural and sporting activities	51.115	18.39	64.440	19.10	13.325	0.71
63	Supporting a. auxiliary transport activities; travel agencies	47.481	14.18	51.651	12.40	4.170	−1.78
91	Activities of membership organizations n.e.c.	47.270	21.71	50.588	21.48	3.318	−0.24
93	Other service activities	45.950	39.76	49.013	38.75	3.064	−1.00
66	Insurance and pension funding, except social security	42.348	14.40	41.668	11.91	−680	−2.49
24	Chemicals and chemical products	40.747	11.63	43.403	8.85	2.655	−2.78
34	Motor vehicles and trailers	39.628	9.02	49.083	6.90	9.455	−2.11
21	Paper and paper products	38.422	14.67	45.211	12.69	6.788	−1.97
31	Electrical machinery and apparatus n.e.c.	38.223	14.82	44.942	11.49	6.719	−3.32
27	Basic metals	37.534	11.66	41.610	8.80	4.076	−2.86
32	Radio, television equipment	37.415	11.73	36.962	8.99	−454	−2.74
26	Other non−metallic mineral products	31.941	16.02	28.682	13.78	−3.259	−2.24
17	Textiles	27.775	16.49	25.116	11.80	−2.658	−4.69

(continued)

Table 34.6 (continued)

65	Financial intermediation, except insur. a. pension funding	27.253	42.36	14.362	8.48	−12.890	−33.89
25	Rubber and plastic products	26.338	13.77	28.449	11.44	2.111	−2.33
64	Post and tele−communications	24.835	12.13	46.597	11.98	21.762	−0.15
18	Wearing apparel	23.328	23.32	16.442	15.43	−6.886	−7.89
40	Electricity, gas, steam and hot water supply	21.709	8.62	21.264	6.61	−446	−2.00
33	Medical, precision, optical instruments, clocks	20.042	17.80	19.066	15.98	−977	−1.82
19	Leather, leather products, footwear	14.396	20.35	12.582	14.97	−1.814	−5.38
22	Publishing, printing and reproduction	12.191	16.13	18.483	11.02	6.292	−5.11
35	Other transport equipment	9.011	11.08	10.894	9.55	1.883	−1.53
95	Private households with employed persons	7.411	17.35	9.433	23.27	2.022	5.92
62	Air transport	7.237	12.14	11.097	9.38	3.859	−2.77
72	Computer and related activities	7.090	15.78	20.566	15.02	13.476	−0.76
71	Renting of machinery and equipment without operator	6.610	10.04	7.610	9.32	1.001	−0.72
73	Research and development	4.278	17.00	6.798	14.52	2.521	−2.48
14	Other mining and quarrying	3.334	14.85	3.517	13.58	183	−1.27
23	Coke, refined petroleum products	3.302	4.70	2.025	2.86	−1.277	−1.83
16	Tobacco products	2.926	12.21	2.684	9.34	−242	−2.87
90	Sewage and refuse disposal, sanitation and similar act.	1.638	15.20	2.812	16.79	1.174	1.59
61	Water transport	1.041	13.81	904	13.45	−137	−0.35
30	Office machinery and computers	766	14.99	3.466	6.82	2.700	−8.17
37	Recycling	347	15.40	223	8.55	−124	−6.85
11	Extract. o. crude petrol. a. nat. gas, min. o. metal ores	188	14.09	64	11.42	−125	−2.67
41	Collection, purification and distribution of water	0	11.94	0	14.93	0	2.99
67	Activities auxiliary to financial intermediation	0	28.65	0	20.48	0	−8.17
10	Mining of coal and lignite	−1.132	18.57	−1.040	19.39	93	0.82
	Total	3,927.553		4,082.067		154.514	

Table 34.7 Comparison of direct, indirect and total labor intensities

NACE	Commodities	1995 direct e_j	1995 indirect $M_l - e_j$	1995 total M_l	2000 direct e_j	2000 indirect $M_l - e_j$	2000 total M_l
01	Agriculture, forestry, fishing	96.59	7.17	103.76	80.31	17.93	98.24
10	Mining of coal and lignite	11.86	6.71	18.57	6.40	12.99	19.39
11	Extract. o. crude petrol. a. nat. gas, min. o. metal ores	8.35	5.73	14.09	5.43	5.99	11.42
14	Other mining and quarrying	7.41	7.44	14.85	6.43	7.14	13.58
15	Food products and beverages	7.98	39.11	47.09	7.98	30.27	38.25
16	Tobacco products	4.26	7.94	12.21	3.81	5.53	9.34
17	Textiles	11.23	5.27	16.49	8.20	3.60	11.80
18	Wearing apparel	18.97	4.35	23.32	10.86	4.57	15.43
19	Leather, leather products, footwear	12.06	8.29	20.35	7.18	7.79	14.97
20	Wood and of products of wood	10.48	19.25	29.74	7.25	12.58	19.83
21	Paper and paper products	4.45	10.22	14.67	3.80	8.89	12.69
22	Publishing, printing and reproduction	9.45	6.68	16.13	5.58	5.44	11.02
23	Coke, refined petroleum products	1.35	3.34	4.70	0.86	2.01	2.86
24	Chemicals and chemical products	5.67	5.97	11.63	3.26	5.59	8.85
25	Rubber and plastic products	8.96	4.81	13.77	6.69	4.75	11.44
26	Other non-metallic mineral products	8.92	7.10	16.02	7.69	6.09	13.78
27	Basic metals	5.91	5.75	11.66	4.38	4.42	8.80
28	Fabricated metal products	11.53	5.61	17.13	8.91	4.66	13.58
29	Machinery and equipment n.e.c.	8.95	5.55	14.50	7.74	4.38	12.12
30	Office machinery and computers	8.55	6.45	14.99	2.61	4.21	6.82
31	Electrical machinery and apparatus.	10.34	4.48	14.82	7.09	4.40	11.49
32	Radio, television equipment	7.29	4.43	11.73	4.81	4.19	8.99
33	Medical, precision, optical instruments, clocks	14.08	3.72	17.80	11.88	4.10	15.98
34	Motor vehicles and trailers	5.14	3.87	9.02	3.20	3.70	6.90
35	Other transport equipment	5.45	5.63	11.08	4.59	4.96	9.55
36	Furniture; manufacturing n.e.c.	14.12	7.81	21.93	11.47	5.02	16.48
37	Recycling	9.86	5.54	15.40	3.82	4.73	8.55
40	Electricity, gas, steam and hot water supply	3.86	4.75	8.62	2.98	3.63	6.61

(continued)

Table 34.7 (continued)

411	Collection, purification and distribution of water	7.07	4.88	11.94	10.25	4.69	14.93
45	Construction	11.99	6.51	18.50	10.78	5.67	16.46
50	Sale and repair of motor vehicles; retail sale of automotive fuel	14.01	3.90	17.90	13.45	4.09	17.54
51	Wholesale and commission trade	11.64	6.76	18.40	9.94	5.69	15.63
52	Retail trade, repair of household goods	24.55	3.43	27.98	22.14	3.09	25.23
55	Hotels and restaurants	21.44	11.98	33.42	19.43	10.03	29.47
60	Land transport; transport via pipelines	18.50	3.15	21.65	15.21	4.46	19.67
61	Water transport	5.20	8.61	13.81	3.47	9.98	13.45
62	Air transport	4.17	7.97	12.14	3.38	6.00	9.38
63	Supporting a. auxiliary transport activities; travel agencies	7.17	7.01	14.18	6.42	5.98	12.40
64	Post and tele-communications	11.04	1.09	12.13	6.76	5.22	11.98
65	Financial intermediation, except insur. a. pension funding	29.67	12.70	42.36	5.55	2.93	8.48
66	Insurance and pension funding, except social security	8.41	5.99	14.40	6.85	5.06	11.91
67	Activities auxiliary to financial intermediation	15.17	13.48	28.65	13.52	6.96	20.48
70	Real estate activities	1.64	5.85	7.49	3.02	5.56	8.58
71	Renting of machinery and equipment without operator	4.09	5.94	10.04	4.47	4.85	9.32
72	Computer and related activities	8.17	7.62	15.78	9.20	5.82	15.02
73	Research and development	14.56	2.44	17.00	11.05	3.47	14.52
74	Other business activities	14.34	4.42	18.76	15.64	4.41	20.05
75	Public administration; compulsory social security	14.61	4.54	19.14	15.33	4.51	19.83
80	Education	22.60	1.61	24.21	18.63	1.67	20.30
85	Health and social work	19.57	4.13	23.69	23.08	5.61	28.70
90	Sewage and refuse disposal, sanitation and similar act	8.96	6.24	15.20	9.53	7.26	16.79
91	Activities of membership organizations n.e.c.	15.93	5.79	21.71	16.25	5.22	21.48
92	Recreational, cultural and sporting activities	12.85	5.54	18.39	13.02	6.08	19.10
93	Other service activities	35.24	4.51	39.76	34.42	4.33	38.75
95	Private households with employed persons	17.35	0.00	17.35	23.02	0.25	23.27

Table 34.8 Ecological Sustainability (Material Input)

NACE	Commodities	d Y Million Euro	d Y/MI Million Euro/ Million tons	Ecol. sustainable d Y < d(Y/MI)
01	Agriculture, forestry, fishing	616	0.00	No
10	Mining of coal and lignite	7	−0.03	No
11	Crude petroleum, natural gas, metal ores	−8	0.01	Possible
14	Other mining and quarrying	34	0.00	No
15	Manufacture of food products and beverages	−289	0.11	Possible
16	Tobacco products	48	1.61	No
17	Textiles	444	3.86	No
18	Wearing apparel	65	2.06	No
19	Leather, leather products, footwear	133	0.37	No
20	Wood and of products of wood	731	0.58	No
21	Paper and paper products	942	0.12	No
22	Publishing, printing and reproduction	921	3.62	No
23	Coke, refined petroleum products	4	2.66	No
24	Chemicals and chemical products	1.401	1.28	No
25	Rubber and plastic products	574	2.70	No
26	Other non-metallic mineral products	88	0.10	No
27	Basic metals	1.510	2.27	No
28	Fabricated metal products	1.071	2.60	No
29	Machinery and equipment n.e.c	2.488	3.77	No
30	Office machinery and computers	457	8.40	No
31	Electrical machinery and apparatus n.e.c	1.331	0,78	No
32	Radio, television equipment	920	1.78	No
33	Medical, precision, optical instruments, clocks	67	0.42	No
34	Motor vehicles and trailers	2.715	7.33	No
35	Other transport equipment	328	2.92	No
36	furniture; manufacturing n.e.c	873	2.38	No
37	Recycling	4	2.51	No
40	Electricity, gas, steam and hot water supply	695	−0.49	No
45	Construction	966	−0.07	No
50	Sale and repair of motor vehicles: retail sale of automotive fuel	−123	−2.96	Possible
51	Wholesale and commission trade	2.586	0.68	No

Table 34.9 Ecological Sustainability (CO_2)

NACE	Commodities	d Y Million Euro	d Y/CO2 Million Euro/1,000 tons	ecol. Sustainable d Y $<$ d(Y/CO_2)
01	Agriculture, forestry, fishing	616	5	No
10	Mining of coal and lignite	7	−144	No
11	Crude petroleum, natural gas, metal ores	−8	676	Possible
14	Other mining and quarrying	34	1.436	Possible
15	Manufacture of food products and beverages	−289	925	Possible
16	Tobacco products	48	−5.685	No
17	Textiles	444	5.659	Possible
18	Wearing apparel	65	−5.019	No
19	Leather, leather products, footwear	133	169	Possible
20	Wood and of products of wood	731	1.863	Possible
21	Paper and paper products	942	2.258	Possible
22	Publishing, printing and reproduction	921	−2.687	No
23	Coke, refined petroleum products	4	7.605	Possible
24	Chemicals and chemical products	1.401	198	No
25	Rubber and plastic products	574	−1.266	No
26	Other non−metallic mineral products	88	2.185	Possible
27	Basic metals	1.510	1.019	No
28	Fabricated metal products	1.071	−2.004	No
29	Machinery and equipment n.e.c.	2.488	−1.182	No
30	Office machinery and computers	457	−6.613	No
31	Electrical machinery and apparatus n.e.c	1.331	−182	No
32	Radio, television equipment	920	63	No
33	Medical, precision, optical instruments, clocks	67	933	Possible
34	Motor vehicles and trailers	2.715	4.707	Possible
35	Other transport equipment	328	1.876	Possible
36	Furniture; manufacturing n.e.c.	873	−305	No
37	recycling	4	647	Possible
40	Electricity, gas. steam and hot water supply	695	50	No
45	Construction	966	1.232	Possible

Appendix 2: Formal Derivation of Minimum Conditions

As starting point we write the resource flow R as the product of resource intensity R/Y times the gross national product Y.

$$R = \left(\frac{R}{Y}\right) Y \tag{A2.1}$$

If we bring Y on the left hand side we get

$$Y = \left(\frac{Y}{R}\right) R \tag{A2.2}$$

From Equation (A2.2) we define the change of Y over the time as

$$dY = d\frac{Y}{R} + dR - d\frac{Y}{R}dR \tag{A2.3}$$

Simplifying leads to

$$dY = d\frac{Y}{R} + dR\left(1 - d\frac{Y}{R}\right) \tag{A2.4}$$

Now we can consider the following special cases:

(a) For the case of a complete coupling, which means $Y = R$ and $Y/R = 1$, the deviation becomes

$$d\left(\frac{Y}{R}\right) = 0 \tag{A2.5}$$

Substituting Equation (A2.5) in Equation (A2.4) leads to:

$$dY = dR \tag{A2.6}$$

Equation (A2.6) is the marginal condition for material intensity increases and weak dematerialization.

(b) For the case of a complete decoupling (R is constant) we have

$$dR = 0 \tag{A2.7}$$

Substituting Equation (A2.7) in Equation (A2.4) leads to

$$dY = d\left(\frac{Y}{R}\right) \tag{A2.8}$$

which is the marginal condition of strong (and weak) dematerialization.

If R decreases over time, i.e. $R(t) > R(t+n)$ for all $t, n > 0$ then Y/R increases and the in equation

$$d\left(\frac{Y}{R}\right) > dY \tag{A2.9}$$

is fulfilled and guarantees an absolute decoupling.

Chapter 35
Multistage Process-Based Make-Use System

Shigemi Kagawa and Sangwon Suh

Introduction

The System of National Accounts (United Nations 1968, 1993) is a useful tool for measuring not only the effects of technological changes, input composition changes, product-mix changes, and consumption shifts as fundamental structural elements (e.g., Afrasiabi and Casler 1991; Rose and Casler 1996; Dietzenbacher and Los 1998, 2000 for the exposition of structural change analyses) but also the efficiency indices consistent with neoclassical economic theory such as total factor productivity growth and labor productivity growth (e.g., ten Raa 1994,1995a; ten Raa and Mohnen 1994).[1] The key to the system's utility rests on the structural elements provided.

In analyzing environmental consequences of productive systems, the emphasis has been generally on microscopic level, where process-based Life Cycle Assessment (LCA) may be a representative tool (Guinée et al. 2002). The analysis measures physical energy and material requirements for the processes of the product system in question *inside* a well-defined system boundary and provides very detailed inventories of environmental emissions and resources use. Hybrid Life Cycle Assessment model, where the standard input-output model and the process-LCA model are combined, additionally enables us to cover the indirect intermediate inputs *outside* the process-based system boundary (e.g., Moriguchi et al. 1993;

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[1] Input-output structural decomposition analyses and index decomposition analyzes have often been used to examine the sources of structural changes (e.g. Ang and Zhang, 2000; Hoekstra and van den Bergh, 2003 for the survey papers). We think both methodologies would also be powerful tools in the field of industrial ecology.

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

Suh 2004; Suh et al. 2004). In this case, the concept of a sector outside the system boundary no longer relates to a process but to a standard commodity or an industry.

On the other hand, several economics research papers have discussed productivity growth at the firm and process level such as total factor productivity and technological efficiency. An interesting example is the fragmentation problem in international economics (e.g., Venables 1999; Deardorff 2001a, b; Arndt and Kierzkowski 2001; Kohler 2004a, b). International economists treat the efficient vertical and horizontal production stage divisions at the industry and firm level under multi-country scenarios and often discuss optimal resource allocations taking into account competitive conditions, social welfare gain and induced commodity trade. Although the input-output analysis has also been used in practical treatments such as the Heckscher–Ohlin–Vanek test, it sometimes seems irrelevant because of its focus on only the commodity and industry technologies and because it is difficult to understand differences in *production systems* among multi-countries, for example between a developing country and a developed country.

The international fragmentation problem should be focused on the process units, as when considering a real case such as Japanese automobile firms transferring their superior assembly processes to China and directly selling automobiles to the Chinese people. The fragmentation consequently influences not only the activity levels of the Japanese assembly process but also automobile exports from Japan to China under an assumption of fixed final demand in both countries, while it may promote materials imports from Japan and from other countries to China.

A process-based make-use system is proposed herein to quantitatively evaluate the more microscopic production system and flow mentioned above. The present paper separates the production technology matrix into an intermediate input matrix for the manufacturing processes and a process activity level matrix with the outputs of representative unfinished materials from the commodity production processes. The static make-use model was constructed by connecting the separated production technology matrix with the product-mix matrix, and separating in the same way (see Fig. 35.1 for the concept for the automobile production). As economic and environmental inventories, the comparative static multipliers would also be useful for capturing the effects of temporal fluctuations in process activity levels for commodity production and process-based input composition as the microscopic structural elements and examining the critical components of a life cycle chain and its shifts.

The present paper is organized as follows. Following the introduction, the second section on Standard Make-Use Models formulates the standard make-use models based on commodity and industry technology assumptions, and derives the pollution generation models. The third section on the Allocation Problem explains about the relationship between allocation problem in LCA and make-use model, while the sections on Multistage Process-Based Make-Use Models and the Application to Hybrid LCA formulate the discrete process-based make-use models followed by a section providing the numerical example. Finally, the last section presents the conclusion.

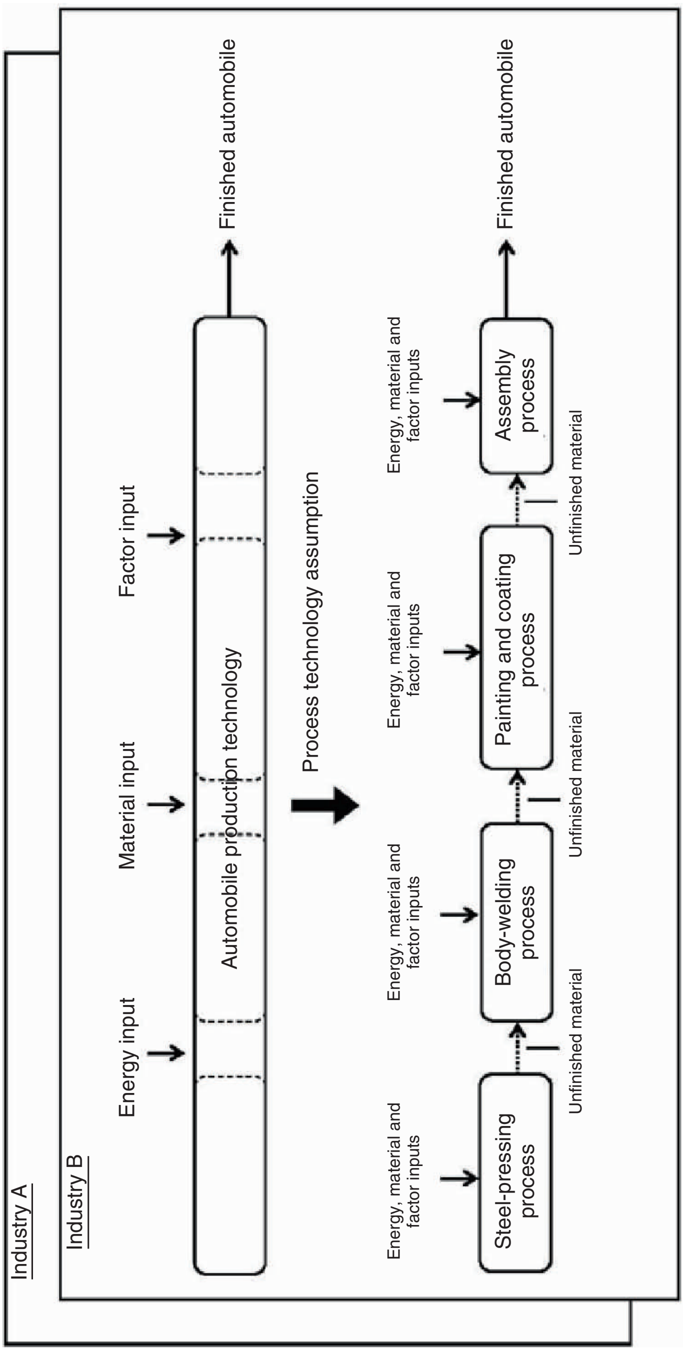

Fig. 35.1 Concept Applied to Automobile Production

The Standard Make-Use Models[2]

Commodity Technology Model

Table 35.1 shows a standard competitive-imports type make-use table.

Table 35.1 Standard Competitive-Imports Type Make-Use Table

	Commodity	Industry	Final demand	Imports	Total
Commodity	$\mathbf{X}$	$\mathbf{U}$	$\mathbf{f}$	$-\mathbf{m}$	$\mathbf{Q}$
Industry	$\mathbf{V}$				$\mathbf{g}$
Value added	$\mathbf{Z}$	$\mathbf{y}$			
Total	$\mathbf{q}^{\mathrm{T}}$	$\mathbf{g}^{\mathrm{T}}$			

where

$\mathbf{X} = \left(X_{ij}\right)$: Intermediate input matrix representing an input requirement of commodity i used for a production activity of commodity j
$\mathbf{V} = \left(V_{ij}\right)$: Output matrix representing an output of commodity j produced by industry i
$\mathbf{U} = \left(U_{ij}\right)$: Intermediate input matrix representing an input requirement of commodity i used for a production activity of industry j
$\mathbf{q} = (q_i)$: Gross domestic commodity output column vector
$\mathbf{g} = (g_i)$: Gross domestic industry output column vector
$\mathbf{f} = (f_i)$: Final demand column vector
$\mathbf{m} = (m_i)$: Import column vector
$\mathbf{z} = \left(z_j\right)$: Commodity value added row vector
$\mathbf{y} = \left(y_j\right)$: Industry value added row vector
Superscript T: Transposition of matrices or vectors.

Comparing the input-output table, named the Leontief table, shown in the gray color of Table 35.1 with the make-use table, it can be seen that the industry by commodity make table (V table) and the commodity by industry use table (U table) are newly introduced and maintain the input-output balance. This is an important feature of the make-use scheme. Diagonal elements of the V table represent industry outputs of "primary products" and off-diagonal elements represent industry outputs of "secondary outputs" and/or "by-products". It should be noted that the by-products are *jointly* produced by the production activities in question. The Leontief table presumes the "Production Activity Principle", in the sense that all the commodities produced by industries can be grouped from the point of view of technological nature, whereas the make-use table relaxes the principle using the concept of both commodity and industry sectors.

[2] See United Nations (1968), van Rijckeghem (1967), Gigantes (1970), Fukui and Senta (1985), Kop Jansen and ten Raa (1990),ten Raa and Rueda-Cantuche (2003).

In formulating the standard make-use models, we have to choose relevant technology assumption(s) and model. As highlighted in ten Raa and Rueda-Cantuche (2003), nine main technology models exist: (1) *Transfer model of outputs*, (2) *By-product technology model*, (3) *European System of Integrated Economic Accounts model*, (4) *Lump-sum transfer model*, (5) *Commodity technology model*, (6) *Industry technology model*, (7) *Activity technology model*, (8) *Mixed technology model I based on commodity and industry technology assumption* (9) *Mixed technology model II based on commodity and by-product technology assumption* (see ten Raa et al. 1984, for (9)). Although we understand that the choice of the technology assumption can embed several problems, such as construction biases of estimated technical coefficients, theoretical shortcoming of the demand-driven commodity technology model and desirable properties of technical coefficients (see Rainer and Richter 1992; de Mesnard 2004; Kop Jansen and ten Raa 1990), we extend the model's utility further, concentrating on the two representative models (5) and (6). In what follows, we formulate the two models and explain the relationship between them.

The commodity technology assumption implies that even if the commodity in question is produced by various industries, the commodity has it own technology, regardless of primary and secondary products. Theoretically the commodity technology assumption better corresponds to the original Leontief system where each product is assumed to be produced by one unique technology (Konijn 1994).[3] In this case, from the V table of Table 1, the product-mix matrix $\mathbf{C} = \left(c_{ij}\right)$representing the output of primary or secondary product i per unit of output of industry j is defined as $\mathbf{C} = \mathbf{V}^{\mathrm{T}}\hat{\mathbf{g}}^{-1}$ where $\hat{\mathbf{g}}$ is the diagonal matrix with the elements of domestic industry output vector $\mathbf{g}$ and, from the U table, the input coefficient matrix $\mathbf{B} = \left(b_{ij}\right)$ representing the input of commodity i required for a unit of output of industry j is defined as $\mathbf{B} = \mathbf{U}\hat{\mathbf{g}}^{-1}$. Here, it should be noted that we completely ignore the by-product.

From the material balance, which implies gross output minus intermediate input is equal to net output, we can write

$$\mathbf{V}^{\mathrm{T}}\mathbf{i} - \mathbf{U}\mathbf{i} = \mathbf{f} - \mathbf{m} \tag{35.1}$$

where $\mathbf{i}$ denotes a column vector for which all elements are one. By substituting the two relationships $\mathbf{V}^{\mathrm{T}}\mathbf{i} = \mathbf{C}\mathbf{g}$ and $\mathbf{U}\mathbf{i} = \mathbf{B}\mathbf{g}$ into the left-hand side of Equation (35.1) we have

$$\mathbf{C}\mathbf{g} - \mathbf{B}\mathbf{g} = \mathbf{f} - \mathbf{m} \tag{35.2}$$

[3] In practice, the commodity technology assumption possesses difficulties when applied as it is known to produce small negative values in the technology matrix. In many cases where production of technology matrix through commodity technology model is necessary, statistical bureaus employ iteratively adjust the coefficients based largely on expert opinions. See also Konijn et al. (1997), Hoekstra (2003), and Joosten (2001) for application of commodity technology assumption for mixed-unit systems.

Arranging Equation (35.2) yields

$$\mathbf{g} = (\mathbf{C} - \mathbf{B})^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.3}$$

From Equation (35.3), we can estimate the gross industry outputs directly and indirectly induced by the commodity final demand. Furthermore, considering the commodity output balance Equation $\mathbf{q} = \mathbf{V}^{\mathrm{T}}\mathbf{i} = \mathbf{Cg}$, which implies that total commodity output is the sum of commodity outputs produced by industries, the gross commodity outputs directly and indirectly induced by the final demand of a commodity in question can be estimated by using

$$\begin{aligned} \mathbf{q} &= \mathbf{C}(\mathbf{C} - \mathbf{B})^{-1} (\mathbf{f} - \mathbf{m}) . \\ &= \left(\mathbf{I} - \mathbf{BC}^{-1}\right)^{-1} (\mathbf{f} - \mathbf{m}) \end{aligned} \tag{35.4}$$

where $\mathbf{I}$ denotes the identity matrix. Thus, a similar formulation with the well-known open Leontief formula $\mathbf{q} = (\mathbf{I} - \mathbf{A})^{-1} (\mathbf{f} - \mathbf{m})$ is obtained, where $\mathbf{A} = \left(a_{ij}\right)$ is the technical coefficient matrix representing the input of commodity i required for a unit of output of commodity j. In other words, since the commodity technology assumption implies that the production technology for the commodity produced by the industry in question completely coincides with the production technologies for the homogenous commodities produced by the other industries, then the input of commodity i required for unit of output of industry k, say b_{ik}, can be formulated as $b_{ik} = \sum_{j=1}^{m} a_{ij} c_{jk}$ or $\mathbf{B} = \mathbf{AC}$ in algebraic form, considering the economic situation that industry k produces commodity j per unit of output which amounts to c_{jk}, and that the technical coefficient a_{ij} representing the input of commodity i required for a unit of output of commodity j can be well defined. Hence, we have the well-known relationship: $\mathbf{A} = \mathbf{BC}^{-1}$, avoiding the singularity of $\mathbf{C}$, and it can be seen that Equation (35.4) coincides with the competitive imports type Leontief formula. If the commodity technology assumption is satisfied in the real world and the singularity problem can be avoided, Equation (35.4) can be interpreted as the Leontief system and also expressed as $\mathbf{q} = (\mathbf{I} - \mathbf{A}(\mathbf{B}, \mathbf{C}))^{-1} (\mathbf{f} - \mathbf{m})$ where $\mathbf{A}(\mathbf{B}, \mathbf{C})$ represents the technical coefficient matrix based on the commodity technology assumption, as in Kop Jansen and ten Raa (1990).

The interpretation problem is also important for environmental input-output analyses. The problem might arise in the construction of environmental inventory data. In performing environmental input-output analysis, we have to clarify whether the inventory data is based on commodity units or industry units. When the inventory data is industry units, Equation (35.4) is obviously unsuitable. More concretely, when observing pollution emission directly generated by unit production of industry j under the commodity technology assumption and by defining the pollution emission row vector $\mu_c(\mathbf{B}, \mathbf{C}, \mathbf{\Gamma})$ with element $(\mu_c)_j$, which denotes the direct pollution emission coefficient of industry j influenced by the commodity technology condition $(\mathbf{B}, \mathbf{C})$ and the pollution emission conversion condition Γ, the pollution generation model can be formulated from Equation (35.3) as

$$Q_c = \boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{g} = \boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,(\mathbf{C}-\mathbf{B})^{-1}\,(\mathbf{f}-\mathbf{m}) \tag{35.5}$$

where subscript c represents the commodity technology assumption and $\boldsymbol{\Gamma}$ represents the appropriate mapping used to transform intermediate energy and non-energy inputs into net pollution emissions.[4] In the same way, defining the pollution emission directly generated by unit production of commodity j as row vector $\boldsymbol{\lambda}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})$ yields from Equation (35.4).[5]

$$Q_c = \boldsymbol{\lambda}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{q} = \boldsymbol{\lambda}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\left(\mathbf{I}-\mathbf{B}\mathbf{C}^{-1}\right)^{-1}(\mathbf{f}-\mathbf{m}) \tag{35.6}$$

Since Equation (35.5) can be rewritten as

$$\begin{aligned} Q_c &= \boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{C}^{-1}\left(\mathbf{I}-\mathbf{B}\mathbf{C}^{-1}\right)^{-1}(\mathbf{f}-\mathbf{m}) \\ &= \boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{C}^{-1}\mathbf{q}, \end{aligned} \tag{35.7}$$

we have the relationship $\boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma}) = \boldsymbol{\lambda}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{C}$ by comparing Equation (35.6) with (35.7). Finally, the industry- and commodity-production oriented pollution emission vectors can be written as

$$\boldsymbol{\mu}_c = \boldsymbol{\lambda}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{C}, \tag{35.8}$$

and

$$\boldsymbol{\lambda}_c = \boldsymbol{\mu}_c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})\,\mathbf{C}^{-1}, \tag{35.9}$$

respectively.[6]

Industry Technology Model

Although the industry technology model is conceptually largely different from the commodity technology model, the formulations are very similar. The commodity technology model assumes that each commodity has its own technology, while the industry technology model assumes that all commodities produced within an industry utilize the same industry technology and that market shares of commodities

[4] In the tradition of LCA computations (e.g. Heijungs and Suh 2002), environmental interventions are exogenously given reflecting the actual situation where environmental data are collected from individual facilities instead of being calculated using input materials.

[5] Let us rewrite $\boldsymbol{\lambda}^c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})$ as $\boldsymbol{\lambda}^c\,(\mathbf{A},\boldsymbol{\Gamma})$, considering $\mathbf{A} = \mathbf{B}\mathbf{C}^{-1}$. Then, it is clear that the changes in the technical energy input coefficients clearly affect the direct carbon emission coefficients. Furthermore, the energy requirements of industries which use the production technology also fluctuate due to the technical changes; this consequently can be read as $\boldsymbol{\mu}^c\,(\mathbf{B},\mathbf{C},\boldsymbol{\Gamma})$.

[6] In most cases environmental data are gathered at the level of industry or installation, which leads to form μ_c instead of $\boldsymbol{\lambda}_c$.

are fixed. Under the industry technology assumption, the market-share matrix $\mathbf{D} = \left(d_{ij}\right)$, representing the market share of industry j which produces commodity i is defined as $\mathbf{D} = \mathbf{V}\hat{\mathbf{q}}^{-1}$ from the V table in Table 35.1 where $\hat{\mathbf{q}}$ is the diagonal matrix with the elements of domestic commodity output vector $\mathbf{q}$. The relationships $\mathbf{g} = \mathbf{D}\mathbf{q}$ or $\mathbf{q} = \mathbf{D}^{-1}\mathbf{g}$ can be formulated by avoiding singularity and invertibility problems of the market-share matrix D. From the definitions of the market-share matrix and the product-mix matrix, it can be understood that the inverses of the market-share matrix and the product-mix matrix play the same mathematical role in transforming industry outputs into commodity outputs. The material balance as shown in Equation (35.1) can be obtained as

$$\mathbf{D}^{-1}\mathbf{g} - \mathbf{B}\mathbf{g} = \mathbf{f} - \mathbf{m}, \tag{35.10}$$

and hence solving Equation (35.10) in terms of $\mathbf{g}$ yields

$$\begin{aligned} \mathbf{g} &= \left(\mathbf{D}^{-1} - \mathbf{B}\right)^{-1} (\mathbf{f} - \mathbf{m}) \\ &= \mathbf{D}\,(\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}\,(\mathbf{f} - \mathbf{m}) \end{aligned} \tag{35.11}$$

Substituting Equation (35.11) into the right-hand side of $\mathbf{q} = \mathbf{D}^{-1}\mathbf{g}$, we have

$$\mathbf{q} = (\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}\,(\mathbf{f} - \mathbf{m})\,. \tag{35.12}$$

If the industry technology assumption is satisfied in the real world, Equation (35.12) can be interpreted as the Leontief system and also expressed as $\mathbf{q} = (\mathbf{I} - \mathbf{A}\,(\mathbf{B}, \mathbf{D}))^{-1}\,(\mathbf{f} - \mathbf{m})$ where $\mathbf{A}\,(\mathbf{B}, \mathbf{D})$ represents the technical coefficient matrix based on the industry technology assumption.

Similarly with Equations (35.8) and (35.9), the industry- and commodity-production oriented pollution emission vectors can be written as

$$\boldsymbol{\mu}_s = \boldsymbol{\lambda}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,\mathbf{D}^{-1}, \tag{35.13}$$

and

$$\boldsymbol{\lambda}_s = \boldsymbol{\mu}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,\mathbf{D} \tag{35.14}$$

respectively, where $\boldsymbol{\mu}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})$ $(\boldsymbol{\lambda}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma}))$ is the industry units- (commodity units-) pollution emission row vector with element $(\mu_s)_j$ $((\lambda_s)_j)$ denoting the *direct* pollution emission coefficient of industry j (commodity j) influenced by the industry technology condition $(\mathbf{B}, \mathbf{D})$ and the pollution emission condition. The pollution generation models under the industry technology assumption can thus be formulated as

$$Q_s = \boldsymbol{\lambda}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,\mathbf{q} = \boldsymbol{\lambda}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,(\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}\,(\mathbf{f} - \mathbf{m}) \tag{35.15}$$

and

$$Q_s = \boldsymbol{\mu}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,\mathbf{g} = \boldsymbol{\mu}_s\,(\mathbf{B}, \mathbf{D}, \boldsymbol{\Gamma})\,\mathbf{D}\,(\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}\,(\mathbf{f} - \mathbf{m}) \tag{35.16}$$

where the subscript s denotes the industry technology assumption.

Allocation Problem in LCA and Make-Use Model

It is notable that the basic concept of the make and use framework very much resembles what has been done in dealing with allocation problem in the domain of LCA. Allocation in LCA refers to the distribution of environmental emissions and resources use as well as materials inputs of the process that produces more than one functional outputs (Huppes 1994; ISO 1998). For instance, a Zinc mining process produces not only Zinc but also other non-ferrous metals such as Cadmium, and an LCA practioner needs to figure out how to distribute the environmental emissions and resources use as well as input materials such as mining machineries and fuel over the multiple outputs.

There are various method proposed and used to deal with the allocation problem in LCA (Huppes 1994; Azapagic and Clift 1999a, b; Werner and Richter 2000; Frischknecht 2000;Weidema 2001; Borg et al. 2001; Vogtländer 2001). General concept of allocation, however, can be categorized as two basic groups, namely *partitioning* and *system expansion* (ISO 1998). In partitioning method, environmental burdens and material inputs of a process are distributed over its multiple outputs based on certain criteria such as monetary value (or estimated revenue or cost), energy content, mass, etc., of the multiple output of a process. In system expansion, the amount of environmental burdens and material inputs to produce the outputs that are not used within the product system under study are subtracted referring to the process that produces only these materials.[7]

The commodity technology model described in the previous section corresponds to the system expansion method, while the industry technology model does the partitioning method in LCA (Suh and Huppes 2002). Let us denote a technology matrix used in LCA as $\tilde{\mathbf{A}} = (\tilde{a}_{ij})$ (hereafter tilde ($\tilde{}$) is used for matrices and vectors used in LCAs). In LCA a technology matrix may be rectangular and usually in mixed-physical units such as kg, kWh, m^3, kBq, etc., (see e.g., Heijungs and Suh 2002 for a general description of LCA computation). Furthermore, a technology matrix in LCA describes both consumption and production of commodities by processes distinguished by its signs (negative for consumption, positive for production). Let us define $\tilde{\mathbf{V}} = (\tilde{v}_{ij})$ such that $\tilde{v}_{ij} = \tilde{a}_{ji}$ for $\tilde{a}_{ji} > 0$ otherwise $\tilde{v}_{ij} = 0$ for all i and j. Similarly $\tilde{\mathbf{U}} = (\tilde{u}_{ij})$ is defined such that $\tilde{u}_{ij} = -\tilde{a}_{ij}$ for $\tilde{a}_{ij} < 0$ otherwise $\tilde{u}_{ij} = 0$ for all i and j. Let us further define $\tilde{\mathbf{g}}$ and $\tilde{\mathbf{q}}$ as total process output and total commodity output, respectively. Note that $\tilde{\mathbf{g}}$ may not be appropriately defined when units are mixed. System expansion implies

$$\tilde{\mathbf{q}} = (\mathbf{I} - \tilde{\mathbf{B}}\tilde{\mathbf{C}}^{-1})^{-1}\tilde{\mathbf{f}} \tag{35.17}$$

[7] An extension from this line of method is made under consequential LCA school, where the amount of environmental burdens avoided by producing co-products through substituting existing products are subtracted from the calculation of Life Cycle Inventory (LCI) (see e.g. Weidema 2001). Azapagic and Clift (1999c) introduce marginal allocation using process-specific information on the relationship between the inputs and outputs and linear programming.

where $\tilde{\mathbf{B}} = \tilde{\mathbf{U}}\hat{\tilde{\mathbf{g}}}^{-1}$, $\tilde{\mathbf{C}} = \tilde{\mathbf{V}}^{\mathrm{T}}\hat{\tilde{\mathbf{g}}}^{-1}$ and $\tilde{\mathbf{f}}$ is the functional unit of the product system. Needless to say, system expansion method does not apply when the technology matrix is non-square. Note also that multiple outputs of each process need to have the same unit in order to properly define $\tilde{\mathbf{g}}$.[8] Nevertheless, the system expansion method is independent of the units applied and thus is capable of being used for mixed unit tables such as those used in LCA.[9] The system expansion method requires that all of the multiple products in the system needs to be produced at least one another process. In other words, if there is no other process that produces the multiple product of which the environmental burdens and materials input need to be subtracted from the process in question, system expansion method cannot be applied as there is no process to refer to in subtracting such portion. Industry technology assumption implies

$$\tilde{\mathbf{q}} = (\mathbf{I} - \tilde{\mathbf{B}}\tilde{\mathbf{D}})^{-1}\tilde{\mathbf{f}} \tag{35.18}$$

where $\tilde{\mathbf{D}} = \tilde{\mathbf{V}}\hat{\tilde{\mathbf{q}}}^{-1}$. Note also that the multiple outputs of each process needs to have the same unit, and, furthermore, unlike system expansion, the choice of appropriate unit may change the result. In partitioning method the numerical values of the multiple outputs in $\tilde{\mathbf{D}}$ work as partitioning factors, and, therefore, any unit changes affecting $\tilde{\mathbf{D}}$ changes the result. The unit of each multiple output process is in fact the basis of allocation. For instance, if the monetary value of the output is used as a unit, the allocation is done using so called economic allocation principle.

Multistage Process-Based Make-Use Models

Multistage Process-Based Commodity Technology Model

Since the standard technology models formulated above do not definitely consider the production process chain, it may sometimes be hard to capture the engineering relationship between intermediate inputs and outputs. As Lin and Polenske (1998) pointed out, an entrepreneur might be interested in the more microscopic, intermediate input structure to attain cost-saving and energy-saving activity. It seems to us that applied economists are increasingly tending to focus on the microscopic behavior, at the level of the firm and product, as environmental and natural scientists already do. In this section, we show that the standard make-use model can be interpreted as a microscopic process chain model and can thus provide fruitful inventory analysis.

In what follows, let us focus on the commodity technology model to explain about the advantage of the process-based make-use model. The U table implicitly

[8] If units of the multiple outputs of a process differ, a vector of conversion factors can be applied without changing the results.

[9] This can be easily proven by showing the existence of the arbitrary vector that converts units of each row without changing the results.

includes the intermediate input requirements for processes operated in order to produce the commodity in question. As outlined in the enterprise input-output framework of Lin and Polenske (1998), by considering the chain of intermediate processes with the main outputs of unfinished materials and the final process with the finished product, the intermediate input of a commodity required for a unit of industry output can be defined as the sum of the intermediate inputs for the process units. In order to explain this formulation, let us assume l commodities $\times$ m industries $\times\, n_l$ manufacturing processes with the appropriate sector numbers (orders). This implies for example that the industry in question ($j = 2$) produces two commodities ($i = 2, 5$) by operating n_2 processes for commodity 2 and n_5 processes for commodity 5 and hence operates a total of $n_2 + n_5$ processes. More generally, let N be the total number of such manufacturing processes and let us partition the manufacturing processes into n_i manufacturing processes for each commodity $i = 1, \cdots, l$. Furthermore, we assume the more rigid commodity technology assumption that each commodity has its own complex process network and process technologies. This may be called a process technology assumption. In this situation, if the $(N \times l)$ process activity matrix can be defined as[10]

$$\mathbf{A}_c^{pc} = \begin{array}{c} \text{Processes 1} \\ \text{Processes 2} \\ \vdots \\ \text{Processes } N \end{array} \begin{bmatrix} \mathbf{a}_1^{pc} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{a}_2^{pc} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{a}_l^{pc} \end{bmatrix} \text{ with } \mathbf{a}_i^{pc} = \begin{bmatrix} \mathbf{a}_{1i}^{pc} \\ a_{2i}^{pc} \\ \vdots \\ a_{n_i i}^{pc} \end{bmatrix} \quad (i=1,2,\cdots,l) \tag{35.19}$$

where $\mathbf{a}_i^{pc}$ represents the n_i-dimensional process activity column vector with element a_{ki}^{pc} $(i = 1, \cdots, l; k = 1, \cdots, n_i)$ denoting the physical output of *unfinished* material of kth process per unit of monetary or physical output of commodity i, and $\mathbf{0}$ is the zero column vector with appropriate dimension, then industry j producing l commodities needs to operate a total of N processes. Considering the product-mix matrix, the $(N \times m)$ industrial process activity matrix can be formulated as

$$\begin{bmatrix} \mathbf{b}_{11}^{ps} & \mathbf{b}_{12}^{ps} & \cdots & \mathbf{b}_{1m}^{ps} \\ \mathbf{b}_{21}^{ps} & \mathbf{b}_{22}^{ps} & \cdots & \mathbf{b}_{2m}^{ps} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{b}_{l1}^{ps} & \mathbf{b}_{l2}^{ps} & \cdots & \mathbf{b}_{lm}^{ps} \end{bmatrix} = \begin{bmatrix} \mathbf{a}_1^{pc} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{a}_2^{pc} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{a}_l^{pc} \end{bmatrix} \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1m} \\ c_{21} & c_{22} & \cdots & c_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{l1} & c_{l2} & \cdots & c_{lm} \end{bmatrix} \tag{35.20}$$

[10] It is also notable that, in LCA, commodity-by-process framework is generally used. LCA researchers use a transposition of the process activity matrix.

$$
= \begin{array}{c c}
 & \begin{array}{cccc} \text{Ind.1} & \text{Ind.2} & \ldots & \text{Ind. } l \end{array} \\
\begin{array}{c} \text{Processes for Com. 1} \\ \text{Processes for Com. 2} \\ \vdots \\ \text{Processes for Com.} l \end{array} &
\begin{bmatrix} c_{11}\mathbf{a}_1^{pc} & c_{12}\mathbf{a}_1^{pc} & \cdots & c_{1m}\mathbf{a}_1^{pc} \\ c_{21}\mathbf{a}_2^{pc} & c_{22}\mathbf{a}_2^{pc} & \cdots & c_{2m}\mathbf{a}_2^{pc} \\ \vdots & \vdots & \ddots & \vdots \\ c_{l1}\mathbf{a}_l^{pc} & c_{l2}\mathbf{a}_l^{pc} & \cdots & c_{lm}\mathbf{a}_l^{pc} \end{bmatrix}
\end{array} \tag{35.21}
$$

or $\mathbf{B}_c^{ps} = \mathbf{A}_c^{pc}\mathbf{C}$ in algebraic form. Here, the element b_{ijk}^{pc} $(i = 1, \cdots, l; j = 1, \cdots, m; k = 1, \cdots, n_i)$ of the column vector $\mathbf{b}_{ij}^{ps}$ represents the activity level of the kth process needed for the commodity i production per unit of output of industry j.

Subsequently, defining the $(l \times N)$ process technology matrix showing the intermediate input of commodity i per unit of output of unfinished material from manufacturing process k as

$$
\begin{array}{cc}
 & \begin{array}{cccc} \text{Processes for Com.1} & \text{Processes for Com.2} & \ldots & \text{Processes for Com.} l \end{array} \\
\mathbf{A}_c^{cp} = \text{Com.} & \begin{bmatrix} \mathbf{a}_1^{cp} & \mathbf{a}_2^{cp} & \cdots & \mathbf{a}_l^{cp} \end{bmatrix}
\end{array} \tag{35.22}
$$

where $\mathbf{a}_i^{cp}$ $(i = 1, 2, \cdots, l)$ represents the $(l \times n_i)$ process technology sub-matrix for the commodity i technology, then we can formulate the $(l \times m)$ industrial input coefficient matrix showing the intermediate input of commodity i required for a unit of output of industry j, that is b_{ij}, as

$$
\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{l1} & b_{l2} & \cdots & b_{lm} \end{bmatrix} = \begin{bmatrix} \mathbf{a}_1^{cp} & \mathbf{a}_2^{cp} & \cdots & \mathbf{a}_l^{cp} \end{bmatrix} \begin{bmatrix} c_{11}\mathbf{a}_1^{pc} & c_{12}\mathbf{a}_1^{pc} & \cdots & c_{1m}\mathbf{a}_1^{pc} \\ c_{21}\mathbf{a}_2^{pc} & c_{22}\mathbf{a}_2^{pc} & \cdots & c_{2m}\mathbf{a}_2^{pc} \\ \vdots & \vdots & \ddots & \vdots \\ c_{l1}\mathbf{a}_l^{pc} & c_{l2}\mathbf{a}_l^{pc} & \cdots & c_{lm}\mathbf{a}_l^{pc} \end{bmatrix} \tag{35.23}
$$

or

$$
\mathbf{B} = \mathbf{A}_c^{cp}\mathbf{B}_c^{ps} = \mathbf{A}_c^{cp}\mathbf{A}_c^{pc}\mathbf{C}. \tag{35.24}
$$

If we notice that $\mathbf{A} = \mathbf{A}_c^{cp}\mathbf{A}_c^{pc}$ holds under our process technology assumption, it can be seen that Equation (35.24) coincides with $\mathbf{A} = \mathbf{A}_c^{cp}\mathbf{A}_c^{pc} = \mathbf{B}\mathbf{C}^{-1}$ from the standard commodity technology model, assuming the number of commodities is equal to the number of industries and the non-singularity of the product-mix matrix. Our main idea is to separate the standard technical matrix into the process technology matrix and the process activity matrix and to construct the make-use model from the structural elements.

Since substituting Equation (35.24) into Equations (35.3) and (35.4) yields

$$
\mathbf{g} = \left(\mathbf{C} - \mathbf{A}_c^{cp}\mathbf{B}_c^{ps}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.25}
$$

and

$$\mathbf{q} = \left(\mathbf{I} - \mathbf{A}_c^{cp}\mathbf{B}_c^{ps}\mathbf{C}^{-1}\right)^{-1}(\mathbf{f} - \mathbf{m}), \tag{35.26}$$

respectively, the pollution generation model under the commodity technology assumption can be formulated as

$$Q_c = \boldsymbol{\mu}_c\left(\mathbf{A}_c^{cp}, \mathbf{B}_c^{ps}, \mathbf{C},\right)\mathbf{g} = \boldsymbol{\mu}_c\left(\mathbf{A}_c^{cp}, \mathbf{B}_c^{ps}, \mathbf{C},\right)\left(\mathbf{C} - \mathbf{A}_c^{cp}\mathbf{B}_c^{ps}\right)^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.27}$$

and

$$Q_c = \boldsymbol{\lambda}_c\left(\mathbf{A}_c^{cp}, \mathbf{B}_c^{ps}, \mathbf{C},\right)\mathbf{q} = \boldsymbol{\lambda}_c\left(\mathbf{A}_c^{cp}, \mathbf{B}_c^{ps}, \mathbf{C},\right)\left(\mathbf{I} - \mathbf{A}_c^{cp}\mathbf{B}_c^{ps}\mathbf{C}^{-1}\right)^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.28}$$

Multistage Process-Based Industry Technology Model

The theoretical difference between the commodity technology model and the industry technology model is that the former assumes that each industry uses available commodity technologies and produce commodities, while the latter assumes that each industry uses an industry production technology. Hence, although the multistage process-based commodity technology model considered the case that industries use the commodity-oriented production processes, for the multistage process-based industry technology model, we need to consider industry-oriented manufacturing processes. Let M be the total number of such manufacturing processes and let us partition the manufacturing processes into p_j manufacturing processes for each industry $j = 1, \cdots, m$ where m is the number of industries. Similar with the multistage process-based commodity technology model, if we further assume the rigid industry technology assumption that each industry has its own process network and process technologies, irrespective of its product-mix, the $(M \times m)$ industrial process activity matrix can be defined as

$$\mathbf{B}_s^{ps} = \begin{bmatrix} \bar{\mathbf{b}}_1^{ps} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \bar{\mathbf{b}}_2^{ps} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \bar{\mathbf{b}}_m^{ps} \end{bmatrix} \tag{35.29}$$

where the kth element b_{kj}^{ps} of the p_j-dimensional column vector $\mathbf{b}_j^{ps}$ represents the activity level of the kth process needed for the unit production of industry j. Subsequently, defining the $(l \times M)$ process technology matrix showing the intermediate input of commodity i per unit of output of unfinished material from industry-oriented process k as

$$\begin{array}{rccccc} & \text{Processes} & \text{Processes} & & \text{Processes} & \\ & \text{for Ind.1} & \text{for Ind.2} & \ldots & \text{for Ind.}m & \\ \mathbf{A}_s^{cp} = \text{Com.} \Big[& \bar{\mathbf{a}}_1^{cp} & \bar{\mathbf{a}}_2^{cp} & \cdots & \bar{\mathbf{a}}_m^{cp} & \Big] \end{array} \tag{35.30}$$

where $\bar{\mathbf{a}}_j^{cp}$ $(j = 1, 2, \cdots, m)$ represents the $\left(l \times p_j\right)$ process technology sub-matrix for the industry j technology, then we can formulate the $(l \times m)$ industrial input coefficient matrix showing the intermediate input of commodity i required for a unit of output of industry j, as

$$\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{l1} & b_{l2} & \cdots & b_{lm} \end{bmatrix} = \left[\, \bar{\mathbf{a}}_1^{cp} \; \bar{\mathbf{a}}_2^{cp} \cdots \bar{\mathbf{a}}_m^{cp} \,\right] \begin{bmatrix} \bar{\mathbf{b}}_1^{ps} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \bar{\mathbf{b}}_2^{ps} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \bar{\mathbf{b}}_m^{ps} \end{bmatrix} \tag{35.31}$$

or

$$\mathbf{B} = \mathbf{A}_s^{cp} \mathbf{B}_s^{ps}. \tag{35.32}$$

Recalling the relationship under the industry technology assumption: $\mathbf{A}\left(\mathbf{B}, \mathbf{D}\right) = \mathbf{BD}$, we have the following relationship:

$$\mathbf{A}\left(\mathbf{B}, \mathbf{D}\right) = \mathbf{A}_s^{cp} \mathbf{B}_s^{ps} \mathbf{D} \tag{35.33}$$

Substituting Equation (35.33) into Equations (35.11) and (35.12) yields

$$\mathbf{g} = \mathbf{D}\left(\mathbf{I} - \mathbf{A}_s^{cp} \mathbf{B}_s^{ps} \mathbf{D}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.34}$$

and

$$\mathbf{q} = \left(\mathbf{I} - \mathbf{A}_s^{cp} \mathbf{B}_s^{ps} \mathbf{D}\right)^{-1} (\mathbf{f} - \mathbf{m})\,. \tag{35.35}$$

Finally, the pollution generation models can be formulated as

$$Q_s = \boldsymbol{\mu}_s \left(\mathbf{A}_s^{cp}, \mathbf{B}_s^{ps}, \mathbf{D}, \boldsymbol{\Gamma}\right) \mathbf{g} = \boldsymbol{\mu}_s \left(\mathbf{A}_s^{cp}, \mathbf{B}_s^{ps}, \mathbf{C}, \boldsymbol{\Gamma}\right) \mathbf{D}\left(\mathbf{I} - \mathbf{A}_s^{cp} \mathbf{B}_s^{ps} \mathbf{D}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.36}$$

and

$$Q_s = \boldsymbol{\lambda}_s \left(\mathbf{A}_s^{cp}, \mathbf{B}_s^{ps}, \mathbf{D}, \boldsymbol{\Gamma}\right) \mathbf{q} = \boldsymbol{\lambda}_s \left(\mathbf{A}_s^{cp}, \mathbf{B}_s^{ps}, \mathbf{D}, \boldsymbol{\Gamma}\right) \left(\mathbf{I} - \mathbf{A}_s^{cp} \mathbf{B}_s^{ps} \mathbf{D}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.37}$$

Application to Hybrid LCA

The practical difficulties in applying the method presented above for a full IO system are mainly twofold. The first is how define the process technology matrix. In order to precisely define the process technology matrix, we need detailed information from the vertical and horizontal process networks and the intermediate energy and material inputs and outputs of unfinished materials flowing downstream to other processes in the physical base, as described in Lin and Polenske (1998) and Albino et al. (2003); such a task is understandably very difficult. The second is whether it is possible to perform the tasks on the level of the enormous existing production processes in the real world, which again is very difficult to do.

However, if we focus on a limited number of key commodity production technologies, it may be possible to define the processes composing the commodity technology.[11] Such an anatomy is similar to the well-known hybrid LCA, which uses both process inventory and input-output models (Moriguchi et al. 1993; Suh 2004; Suh 2004). Our process-based make-use model can be applied to this kind of special model.

Here, let us focus on the production technology of commodity j and formulate the column-specific process model, presuming that we have process data only for commodity j. Then, since intermediate input of commodity i required for the commodity j processes per unit of output of industry k, $b_{ik}(j)$, can be obtained as

$$\begin{bmatrix} b_{11}(j) & b_{12}(j) & \cdots & b_{1l}(j) \\ b_{21}(j) & b_{22}(j) & \cdots & b_{2m}(j) \\ \vdots & \vdots & \ddots & \vdots \\ b_{l1}(j) & b_{l2}(j) & \cdots & b_{lm}(j) \end{bmatrix} = [\mathbf{0} \cdots \mathbf{0}\ \mathbf{a}_j^{cp}\ \mathbf{0} \cdots \mathbf{0}] \begin{bmatrix} \mathbf{0} & & & & & \\ & \ddots & & & \mathbf{0} & \\ & & \mathbf{0} & & & \\ & & & \mathbf{a}_j^{pc} & & \\ & & & & \mathbf{0} & \\ & \mathbf{0} & & & & \ddots & \\ & & & & & & \mathbf{0} \end{bmatrix} [\mathbf{C}] \tag{35.38}$$

or in algebraic form

$$\mathbf{B}(j) = \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j) = \mathbf{A}_c^{cp}(j)\mathbf{A}_c^{pc}(j)\mathbf{C} \tag{35.39}$$

where $\mathbf{a}_j^{cp}$ and $\mathbf{a}_j^{pc}$ represent the $(l \times n_j)$ process technology sub-matrix and the $(n_j \times 1)$ process activity sub-vector for the commodity j production, respectively. The industrial input coefficient matrix $\mathbf{B}$ can be decomposed as $\mathbf{B}^*$ and $\mathbf{B}(j)$, where $\mathbf{B}^* = (\mathbf{b}_{ik}^*)$ represents the intermediate input of commodity i required for all the other processes per unit of output of industry k. In this case, it holds that $\mathbf{B} = \mathbf{B}^* + \mathbf{B}(j) = \mathbf{B}^* + \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j) = \mathbf{B}^* + \mathbf{A}_c^{cp}(j)\mathbf{A}_c^{pc}(j)\mathbf{C}$. By substituting the decomposition formula into Equations (35.3) and (35.4), we have

$$\mathbf{g} = (\mathbf{C} - \mathbf{B}^* - \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j))^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.40}$$

and

$$\mathbf{q} = (\mathbf{I} - \mathbf{B}^*\mathbf{C}^{-1} - \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\mathbf{C}^{-1})^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.41}$$

respectively. Considering the more general decomposition formula $\mathbf{B} = \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)$ $\mathbf{B}_c^{ps}(j)$, we have the mathematically equivalent relationships

[11] Definition of key technologies may vary depending on the goal and scope of a study. In LCA context, for instance, key technologies are those contribute the most of the environmental impacts of the system and have the largest potential to reduce the impacts.

$$\mathbf{g} = \left(\mathbf{C} - \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.42}$$

and

$$\mathbf{q} = \left(\mathbf{I} - \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\mathbf{C}^{-1}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.43}$$

and the generalized pollution generation models can be modified as

$$Q_c = \boldsymbol{\mu}_c \left(\sum_{j=1}^{l} \mathbf{A}_c^{cp}(j), \sum_{j=1}^{l} \mathbf{B}_c^{ps}(j), \mathbf{C}, \boldsymbol{\Gamma}\right) \left(\mathbf{C} - \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.44}$$

and

$$Q_c = \boldsymbol{\lambda}_c \left(\sum_{j=1}^{l} \mathbf{A}_c^{cp}(j), \sum_{j=1}^{l} \mathbf{B}_c^{ps}(j), \mathbf{C}, \boldsymbol{\Gamma}\right) \left(\mathbf{I} - \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\mathbf{C}^{-1}\right)^{-1} (\mathbf{f} - \mathbf{m}) \tag{35.45}$$

Equations (35.44) and (35.45) are crucial for measuring the impacts of manufacturing process innovations for commodity j on the pollution emissions, and Equations (35.42) and (35.43) provide information about the large-scale economic impacts of the microscopic process innovations of firms. It should be noted that it holds that

$\mathbf{A}_c^{cp} = \sum_{j=1}^{l} \mathbf{A}_c^{cp}(j)$ and $\mathbf{B}_c^{ps} = \sum_{j=1}^{l} \mathbf{B}_c^{ps}(j)$ and the proof is straightforward.

If intermediate input of commodity i required for the industry j processes of per unit of output of commodity k, $a_{ik}(j)$, can be obtained as

$$\begin{bmatrix} a_{11}(j) & a_{12}(j) & \cdots & a_{1l}(j) \\ a_{21}(j) & a_{22}(j) & \cdots & a_{2l}(j) \\ \vdots & \vdots & \ddots & \vdots \\ a_{l1}(j) & a_{l2}(j) & \cdots & a_{ll}(j) \end{bmatrix} = \begin{bmatrix} \mathbf{0} \cdots \mathbf{0} \ \bar{\mathbf{a}}_j^{cp} \ \mathbf{0} \cdots \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{0} & & & & & \\ & \ddots & & & \mathbf{0} & \\ & & \mathbf{0} & & & \\ & & & \bar{\mathbf{b}}_j^{pc} & & \\ & & & & \mathbf{0} & \\ & \mathbf{0} & & & & \ddots & \\ & & & & & & \mathbf{0} \end{bmatrix} [\mathbf{D}] \tag{35.46}$$

or in algebraic form

$$\mathbf{A}(j) = \mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\mathbf{D} \tag{35.47}$$

where $\bar{\mathbf{a}}_j^{cp}$ and $\bar{\mathbf{b}}_j^{ps}$ represent the $(l \times p_j)$ process technology sub-matrix and the $(p_j \times 1)$ process activity sub-vector for the industry j production, respectively. In this case, the multistage process-based industry technology models can be formulated as

$$\mathbf{g} = \mathbf{D}\left(\mathbf{I} - \sum_{j=1}^{m} \mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\mathbf{D}\right)^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.48}$$

and

$$\mathbf{q} = \left(\mathbf{I} - \sum_{j=1}^{m} \mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\mathbf{D}\right)^{-1}(\mathbf{f} - \mathbf{m}), \tag{35.49}$$

and the generalized pollution generation models based on the industry technology assumption can be modified as

$$Q_s = \boldsymbol{\mu}_s\left(\sum_{j=1}^{ms} \mathbf{A}_s^{cp}(j), \sum_{j=1}^{m} \mathbf{B}_s^{ps}(j), \mathbf{D}, \boldsymbol{\Gamma}\right)\mathbf{D}\left(\mathbf{I} - \sum_{j=1}^{m} \mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\right)^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.50}$$

and

$$Q_s = \boldsymbol{\lambda}_s\left(\sum_{j=1}^{m} \mathbf{A}_s^{cp}(j), \sum_{j=1}^{m} \mathbf{B}_s^{ps}(j), \mathbf{D}, \boldsymbol{\Gamma}\right)\left(\mathbf{I} - \sum_{j=1}^{m} \mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\mathbf{D}\right)^{-1}(\mathbf{f} - \mathbf{m}), \tag{35.51}$$

noting that the relationship under the commodity technology assumption: $\mathbf{A}_c^{cp}(j)\mathbf{B}_c^{ps}(j)\mathbf{C}^{-1}$ corresponds to the relationship under the industry technology assumption: $\mathbf{A}_s^{cp}(j)\mathbf{B}_s^{ps}(j)\mathbf{D}$.

Numerical example

In what follows, we explain about how the multistage process-based make-use system works, using the Miller and Blair's example (see Tables 35.5–35.9 of Miller and Blair [1985]). Table 35.2 shows the example and assumes as follows.

Table 35.2 Summary of Make-Use Table

	Commodity 1	Commodity 2	Industry 1	Industry 2	Final demand	Total
Commodity 1			10	10	80	100
Commodity 2			10	7	83	100
Industry 1	90	0				90
Industry 2	10	100				110
Value added			70	93		
Total	100	100	90	110		

Industry 1 uses \$10 million each of commodities 1 and 2 and \$70 million worth of value added inputs in producing \$90 million worth of output assigned to industry 1. Industry 2 uses \$10 million of commodity 1, \$7 million of commodity 2, and \$93 million of value-added inputs in producing \$110 million worth of output assigned to industry 2. Finally, let us assume that final demands for commodities 1 and 2 are \$80 million and \$83 million, respectively (see p. 161 of Miller and Blair [1985]).

Now recalling the definitions of the industrial input coefficient matrix and the product-mix matrix, we have:

$$\mathbf{B} = \mathbf{U}\hat{\mathbf{g}}^{-1} = \begin{bmatrix} 10 & 10 \\ 10 & 7 \end{bmatrix} \begin{bmatrix} \frac{1}{90} & 0 \\ 0 & \frac{1}{110} \end{bmatrix} = \begin{bmatrix} 0.111 & 0.091 \\ 0.111 & 0.064 \end{bmatrix} \tag{35.52}$$

$$\mathbf{C} = \mathbf{V}^{\mathrm{T}}\hat{\mathbf{g}}^{-1} = \begin{bmatrix} 90 & 10 \\ 0 & 100 \end{bmatrix} \begin{bmatrix} \frac{1}{90} & 0 \\ 0 & \frac{1}{110} \end{bmatrix} = \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix} \tag{35.53}$$

Then, the technical coefficient matrix based on the commodity technology assumption can be estimated as

$$\mathbf{A} = \mathbf{B}\mathbf{C}^{-1} = \begin{bmatrix} 0.111 & 0.091 \\ 0.111 & 0.064 \end{bmatrix} \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix}^{-1} = \begin{bmatrix} 0.111 & 0.089 \\ 0.111 & 0.0593 \end{bmatrix} \tag{35.54}$$

Since the commodity-by-commodity intermediate input matrix can be formulated as $\mathbf{X} = \mathbf{A}\hat{\mathbf{q}}$, we have the following commodity transaction matrix (table).

$$\mathbf{X} = \mathbf{A}\hat{\mathbf{q}} = \begin{bmatrix} 0.111 & 0.089 \\ 0.111 & 0.0593 \end{bmatrix} \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \approx \begin{bmatrix} 11 & 9 \\ 11 & 6 \end{bmatrix} \tag{35.55}$$

Here let us assume under the commodity-oriented process technology assumption that two manufacturing processes, say process 1–1 and process 1–2, are operated in order to produce commodity 1 and the process activity levels expressed in physical unfinished material outputs are 30 units (process 1–1) and 40 units (process 1–2) respectively, in producing \$100 million worth of output assigned to commodity 1. We further assume that process 1–1 uses \$7 million of commodity 1 and \$3 million of commodity 2, while process 1–2 uses \$4 million of commodity 1 and \$8 million of commodity 2, respectively. It should be noted that the intermediate input requirements of commodities 1 and 2 required for both processes are \$11 million and it is consistent with the first column of the commodity transaction matrix.[12]

[12] Even if we don't employ a commodity technology assumption or an industry technology assumption, we can directly estimate the technical coefficients for commodities through the observation for the production processes. In fact, Japanese input-output tables have been estimated by the observation method. However, whether the estimated technical coefficients satisfy the commodity technology equation or industry technology equation is still questionable. Here we propose to

In this situation, the process technology sub-matrix $\mathbf{a}_1^{cp}$ and process activity sub-vector $\mathbf{a}_1^{pc}$ for commodity 1 production can be obtained as

$$\mathbf{a}_1^{cp} = \begin{bmatrix} \frac{7}{30} & \frac{4}{40} \\ \frac{3}{30} & \frac{8}{40} \end{bmatrix} \text{ and } \mathbf{a}_1^{pc} = \begin{bmatrix} \frac{30}{100} \\ \frac{40}{100} \end{bmatrix} \tag{35.56}$$

Hence, from Equation (35.27), the *partial* intermediate input requirements of industries operating the commodity 1 production processes can be estimated as

$$\begin{aligned} \mathbf{B}(1) &= \begin{bmatrix} \mathbf{a}_1^{cp} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{a}_1^{pc} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{C} = \mathbf{A}_c^{cp}(1)\,\mathbf{A}_c^{pc}(1)\,\mathbf{C} \\ &= \begin{bmatrix} \frac{7}{30} & \frac{4}{40} & 0 \\ \frac{3}{30} & \frac{8}{40} & 0 \end{bmatrix} \begin{bmatrix} \frac{30}{100} & 0 \\ \frac{40}{100} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix} \approx \begin{bmatrix} 0.111 & 0.010 \\ 0.111 & 0.010 \end{bmatrix} \end{aligned} \tag{35.57}$$

Then, we have the following decomposition formula.

$$\mathbf{B} = \mathbf{B}(1) + \mathbf{B}^* \Rightarrow \begin{bmatrix} 0.111 & 0.091 \\ 0.111 & 0.064 \end{bmatrix} = \begin{bmatrix} 0.111 & 0.010 \\ 0.111 & 0.010 \end{bmatrix} + \begin{bmatrix} 0 & 0.081 \\ 0 & 0.054 \end{bmatrix} \tag{35.58}$$

The first term on the right-hand side represents the industrial intermediate input coefficients for the commodity 1 production and the second term represents that for the commodity 2 production. From the first column of the first term, it can be understood that industry 1 uses \$111,000 each of commodities 1 and 2 in producing a million dollars worth of commodity 1 output assigned to industry 1. The second column of the first term shows that industry 2 uses \$10,000 each of commodities 1 and 2 in producing \$91,000 worth of commodity 1 output assigned to industry 2 (see the product-mix matrix computed above). Similarly, we can interpret the second term. Furthermore, the industrial process activity matrix relating to the commodity 1 production can be estimated from the following relationship.

$$\begin{aligned} \mathbf{B}_c^{ps}(1) &= \mathbf{A}_c^{pc}(1)\,\mathbf{C} \\ &= \begin{bmatrix} \frac{30}{100} & 0 \\ \frac{40}{100} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix} = \begin{bmatrix} 0.3000 & 0.0273 \\ 0.4000 & 0.0364 \\ 0 & 0 \end{bmatrix} \end{aligned} \tag{35.59}$$

decompose the technical coefficients estimated by the technology assumptions into the process-level technical coefficients through the *relevant* observation.

The first column shows that industry 1 operates processes 1–1 and 1–2 at the activity levels of 0.3 and 0.4, respectively in producing a million dollars worth of output assigned to industry 1, while the second column shows that industry 2 operates processes 1–1 and 1–2 at the activity levels of 0.0273 and 0.0364, respectively in producing \$91,000 worth of commodity 1 output assigned to industry 2.

Substituting the following matrices $\mathbf{B}^*$, $\mathbf{C}^{-1}$, $\mathbf{A}_c^{cp}(1)$, $\mathbf{B}_c^{ps}(1)$ and the final demand vector shown in Table 35.2 into Equations (35.29) and (35.30) yields

$$\begin{aligned}\mathbf{g} &= (\mathbf{C} - \mathbf{B}^* - \mathbf{A}_c^{cp}(1)\mathbf{B}_c^{ps}(1))^{-1}(\mathbf{f} - \mathbf{m}) \\ &= \left(\begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix} - \begin{bmatrix} 0 & 0.081 \\ 0 & 0.054 \end{bmatrix} - \begin{bmatrix} \frac{7}{30} & \frac{4}{40} & 0 \\ \frac{3}{30} & \frac{8}{40} & 0 \end{bmatrix} \begin{bmatrix} 0.3000 & 0.0273 \\ 0.4000 & 0.0364 \\ 0 & 0 \end{bmatrix} \right)^{-1} \begin{bmatrix} 80 \\ 83 \end{bmatrix} \\ &\approx \begin{bmatrix} 90 \\ 110 \end{bmatrix} \end{aligned} \tag{35.60}$$

and

$$\begin{aligned}\mathbf{q} &= \left(\mathbf{I} - \mathbf{B}^*\mathbf{C}^{-1} - \mathbf{A}_c^{cp}(1)\mathbf{B}_c^{ps}(1)\mathbf{C}^{-1}\right)^{-1}(\mathbf{f} - \mathbf{m}) \\ &= \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0.081 \\ 0 & 0.054 \end{bmatrix} \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix}^{-1} - \begin{bmatrix} \frac{7}{30} & \frac{4}{40} & 0 \\ \frac{3}{30} & \frac{8}{40} & 0 \end{bmatrix} \begin{bmatrix} 0.3000 & 0.0273 \\ 0.4000 & 0.0364 \\ 0 & 0 \end{bmatrix} \right. \\ &\qquad \left. \begin{bmatrix} 1.000 & 0.091 \\ 0 & 0.909 \end{bmatrix}^{-1} \right)^{-1} \begin{bmatrix} 80 \\ 83 \end{bmatrix} \approx \begin{bmatrix} 100 \\ 100 \end{bmatrix} \end{aligned} \tag{35.61}$$

The important point is that the result estimated by the generalized make-use model coincides with the result by the standard make-use model. Finally, we prove the equivalence relationships based on the commodity technology assumption:

$$\mathbf{g} = (\mathbf{C} - \mathbf{B}^* - \mathbf{A}_c^{cp}(1)\mathbf{B}_c^{ps}(1))^{-1}(\mathbf{f} - \mathbf{m}) = (\mathbf{C} - \mathbf{B})^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.62}$$

and

$$\mathbf{q} = (\mathbf{I} - \mathbf{B}^*\mathbf{C}^{-1} - \mathbf{A}_c^{cp}(1)\mathbf{B}_c^{ps}(1)\mathbf{C}^{-1})^{-1}(\mathbf{f} - \mathbf{m}) = \left(\mathbf{I} - \mathbf{B}\mathbf{C}^{-1}\right)^{-1}(\mathbf{f} - \mathbf{m}) \tag{35.63}$$

using the numerical example. Although the model is self-contained, we believe that our accounting model is useful in evaluating the effects of the microscopic process innovations on the large-scale domestic economy.

Conclusion

Great efforts have already been made by input-output researchers to progress the theoretical and practical basis of input-output analyses, while LCA researchers have also greatly contributed to modeling the production system and evaluating global and local environmental problems. However, it is sometimes frustrating to face the empirical results from inventory and structural analyses, especially when the *socio-economic* role of production processes of firms and products is often masked due to aggregation and structural issue. From the point of view of *structural economics*, it seems to us that part of the frustration and confusion arise from the concept and definition of a sector and from the choice of technology assumptions considering economic foundation such as Johansen (1972) and ten Raa (1995b).

For the first cause, we clarified the relationship among structural elements such as a commodity, industry, and a manufacturing process. This enables us to describe the industrial system where multiple processes are involved in producing commodities on the basis of more consistent make-use framework. The advantages are mainly twofold. First, it is possible to observe the activity levels of the manufacturing processes and capture the process scale effects. Certain process-level changes such as product miniaturization, for instance, and corresponding effects may not be properly observed using traditional input-output framework, unless it accompanies changes in economic value. The framework presented in this chapter is capable of capturing such effects by extending the traditional input-output framework toward multi-stage process models. The second is that it is also possible to describe microscopic process technologies and capture not only economic circuit induced by intermediate inputs required for the process technologies but also the process innovation effects.

For the second cause, the present paper contributes to not only providing a make-use framework for allocation in LCA but also formulating multistage process-based make-use models (quantity model) under the commodity and industry technology assumption. In employing partitioning method and system expansion method, a technology assumption is implicitly chosen. We clarified that if the partitioning method is employed, it presumes an industry technology assumption and an industry-oriented process technology assumption. If the system expansion method is employed, it presumes a commodity technology assumption and a commodity-oriented process technology assumption.

Taking this point, the benefits of the process-based Life Cycle Assessment methods and the input-output analyses can be integrated within the established theoretical and mathematical foundations of the two. Such integration can be further explored for the analyses in the field of industrial ecology, where the inter-relationships between industries through producing and absorbing commodities and the role of process level innovation are among the central concerns, providing both detailed process-level insights and a more broader, industry level information.

Future outlooks in this line of developments: Identifying effective strategies for linking process models with economic models needs further development. There is variety of models used by engineers for simulating industrial processes ranging from linear process-flow sheeting to complex non-linear dynamic models (see e.g., Westerberg et al. 1979; Bequette 1998). The process model covered in this chapter is among the simplest ones and may not be adequate for certain type of applications. Nevertheless a number of basic strategies to link different classes of models may be possible including toolbox approach, full integration and hybridization (Udo de Haes, et al. 2004). Depending on the specifics of the study different strategies may be identified as the best.

Hybrid-unit input-output system for modeling materials and energy flows in industrial ecology needs further exploitation. As shown by Hoekstra (2003) and Joosten (2001) hybrid-unit systems can play an important role in modeling materials and energy flows free from the price inhomogeneity and the pitfalls of single-mass unit Physical Input-Output Tables. As the detailed process level flows, especially for the unfinished intermediate goods, do not have prices, the use of physical and mixed units for modeling the process part is inevitable, which leads to the use of mixed unit system. Such developments have just started, and there are choices to be made in actual implementation.

Finally, building reliable data to back up the model presented and implementing case studies are in need. Many LCA databases are structured in such a way that they can be utilized in the framework delineated in the current work. Linking such databases with input-output tables and using the linked databases are yet to be explored.

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Chapter 36
Input-Output Analysis and Linear Programming

Klaus-Ole Vogstad

Introduction

Input-output analysis of inter-industry exchange has proved to be useful in LCA. Input-output has a long history in economics. Less known, is that input-output influenced *linear programming* (LP) in its early development. In fact, Input-output models can be regarded as special cases of *linear programming* problems. Linear programming is the most useful practical tool in helping us to make the best use of scarce resources when faced with complex decision problems. Firms routinely use linear programming and other optimization techniques in planning their activities, for example in logistics of supply chains, production scheduling, and resource allocation in general. In this chapter, we show the historical relationship of input-output analysis and linear programming. Next, we show that an input-output model is a special case of an LP formulation. Through a series of examples, we show how an LP formulation more generally can tackle situations with multifunctional units and multiple technologies. Furthermore, we show how a detailed LP model of an industry sector can be linked with an aggregated IO model. The last section of this chapter provides a brief survey of applications where LCA and input-output analysis has been integrated with optimization models.

Environmental Decision Support Models

Numerous models for environmental analysis have evolved over time. The usefulness of a model should not be judged after how closely it represents reality, but it's relevance for the decisions to be made. One must therefore reflect upon the type of

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

Table 36.1 Decision Support Tools, their Scope and Type of Decision Support

Tool	System level	Decision type
IO, general equilibrium	Economy (country, region)	Government planning
Partial equilibrium, LP	Industry, government planning	Government planning
LP, optimization	The firm	Planning of activities. Supply chain management, logistics, production scheduling
LCA	Process tree over lifetime	Product improvement Comparison of substitutable products

decision to be made when choosing the appropriate modeling approach. Table 36.1 shows different levels of decision-making and different types of models.

- **National level:** General equilibrium models for the economy and industry sectors are used for decision support. These models typically include optimization to find equilibrium or optimal development paths. Examples are computable general equilibrium models (CGE) for economies and IO models.
- **Industry sector:** Detailed LP is in use for important sectors of the economy. These models are partial equilibrium models and linear programming models. As an example, MARKAL (Market Allocation) model is the most widely used energy model for analysis of energy policies.
- **The firm:** Companies frequently use optimization models in routinely planning their activities. Examples are logistics of supply chains, transport and production scheduling.
- **Process level:** LCA describes the processes involved in providing a certain product or a function. Traditional LCA trace the energy- and material flows required for the production, use and disposal of a product at a detailed process level. As an example, Franklin Associates conducted the first LCA study in 1969 for Coca-Cola to determine which beverage containers had the lowest releases to the environment.

The distinction is not as sharp as depicted in Table 36.1. For instance, process LCA can in some cases be used as input to both firms (for example the beverage study), and authorities, and optimization models are also used at the process level.

Of importance here, is that the model is relevant for the decisions. An input-output model aggregates technologies into sectors (or products into commodities). It is well suited to analyze the environmental impact of how an increase in transport increase emissions in other sectors through inter-industry exchanges. However, it is not able to distinguish the environmental performance between specific technologies within the transport sector, for which detailed process LCA is well suited. Detailed process LCA based on site-specific data are on the other hand too detailed to be generalized to efficient national policy making. In addition, omission of higher-order upstream resource requirements can be in the order of 50% (Lenzen 2000). LCA is now increasingly being integrated with LP and other optimization tools, as shown in the survey in the last section of this chapter. In addition, detailed models of important industry sectors (i.e. energy) needs to be linked with economic models as well.

The Beginning of Linear Programming and Its Relationship with Input-Output

George B. Dantzig is known as the father of linear programming (Albers et al. 1986). After WWII, he worked for the US air force on mechanizing the planning process of their activities. He had learned about the inter-industry model developed by Leontief around 1932.

The advantage of Leontief's input-output approach was its mathematical simplicity that made it practical for planning purposes. At that time, calculations were carried out by mechanical desk calculators. The input-output approach represented the economy as a network of industries, where each industry produced unique, non-substitutable goods over a predefined time interval. The input-output approach applies in general to the organization of industry sectors, firms or any other level of organization.

For Dantzig's planning problems however, the Leontief model had to be generalized. Firstly, a firm have can produce their items in many different ways. The planning problem is characterized by a large number of feasible ways of providing the same output. This lead to the *Leontief substitution model* (Albers et al. 1986). Before the simplex method was developed (i.e. the search algorithm that solves the LP problem), there were no systematic way of evaluating all the alternative ways of producing the same output, and planning was conducted in a heuristic, ruled-based manner (Dantzig 1963) Second, practical planning problems were stage wise and highly dynamic, requiring an extension from static to dynamic models. Over time, products could be stored from one period to the other, and demand can vary over longer periods as well. This extended the original Leontief model into a *dynamic Leontief substitution model* (Dantzig 1949, 1963).

Dantzig developed the Simplex algorithm that proved to be extremely efficient in solving linear programming problems. With this method, it was now possible to find optimal solutions to planning problems in a systematic and efficient way.

Input-Output and Linear Programming Problems

First we describe a simple two-industry economy as an input-output model, and its underlying assumptions. Then we are going to show how the input-output model can be represented as an LP formulation. Finally, we are going to relax the underlying assumptions of the input-output model that often cause problems in LCA analyses, and show how LP overcomes these problems.

A Simple IO Model

Recall the definition of an input-output economy described under the previous section *environmental decision support models*. For convenience, we restate the assumptions of an IO table here in mathematical terms. Table 36.2 shows a simple two-industry economy where:

- Each industry produces exactly one commodity.
- Each commodity produced is non-substitutable.

In LCA jargon, the first assumption states that there are no multifunctional production processes. For instance, the *paper and pulp* industry delivers paper and paper only. The latter assumption assumes there is only one technology or industry that produces the good, i.e. paper can only be produced by the *paper* industry, and no other sector can deliver substitutes for paper.

In addition, each industry generates emissions. The corresponding mathematical definition is as follows:

Let $i = 1, 2$ denote the set of goods, $j = 1,2$, the set of industries and $k = 1 \ldots 3$, the set of emissions.

x_i – total output of commodity i, where $x_j \geq 0$ for all j. [GNOK/year]
x_{ij} – input requirement of goods i, to industry j. [GNOK/year]
d_i – final demand in for good i. [GNOK/year]
e_{kj} – emissions of type k in physical units from industry j. [mass units/year]
q_k – total emissions of type k.[mass units/year]
x_0 – total output in of *labor services* [GNOK/year]
x_{0j} – input requirement of *labor services* to sector j [GNOK/year]
w – wage rate for *labor services* [GNOK/year/GNOK/year]

Table 36.2 contains the corresponding IO table for the above coefficients.

Labor services (x_{0j} in Table 36.2) is the only *primary input factor* to the economy. *Labor services* represent the only cost to the economy at a wage rate w. We shall use this information when re-interpreting the IO model into an LP problem.

Table 36.2 Input-Output of Simple Two Industries Economy

	Outputs			
Inputs [GNOK/year]	Industry, x_{i1} (a_{i1})	Paper, x_{i2} (a_{i2})	Final demand, d_j	Total outputs, x_j
Industry goods	358 (0.268)	21 (0.288)	957	1,337
Paper goods	37 (0.028)	11 (0.151)	26	74
Labor x_{0j} (a_{0j})	942 (0.705)	41 (0.554)	–	984
Emissions (mass units)	b_{k1} (e_{k1})	b_{k2} (e_{k2})		
CO_2[Mt/GNOK]	49 (0.037)	0.4 (0.005)		50
CH_4 [kt/GNOK]	300 (0.224)	27 (0.363)	–	327
Cd [kg/GNOK]	790 (0.591)	179 (2.406)		969

There is no final demand for *Labor services*. *Emissions* can be treated similar to *primary input factors*, with an associated external cost to the economy.

We derive the input-output coefficients from the IO table:

$$a_{ij} = x_{ij}/x_j,\ b_{kj} = e_{kj}/x_j,\ a_{0j} = x_{0j}/x_j \tag{36.1}$$

The input-output coefficients are shown in parenthesis in Table 36.2. Table 36.2 can be represented as a set of equations:

$$\sum_j a_{ij}x_j + d_i = x_i \tag{36.2}$$

$$\sum_j b_{kj}x_j = q_k \tag{36.3}$$

$$\sum_j a_{0j}x_j = x_0 \tag{36.4}$$

In matrix notation:

$$Ax + d = x \tag{36.5}$$

$$Bx = q \tag{36.6}$$

$$a_0x = x_0 \tag{36.7}$$

Solving the set of equations:

$x = (I - A)^{-1} \cdot d$ yields an industrial output of $x_1 = 1337$ [GNOK/year] and paper output of $x_2 = 74.7$ [GNOK/year]. The environmental stress is $q = B \cdot x$, giving $q_1 = 50\,\mathrm{Mt\,CO_2}$, $q_2 = 327\,\mathrm{kt\ CH_4}$ and $q_3 = 970\,\mathrm{kg\,Cd}$. To make sure there is enough labor available, Equation (36.7) must hold, or there must at least be more labor available than required. To verify, we find that $a_0x = [0.705, 0.554] \cdot [1337, 41]^{\mathrm{T}} = 984$, which is equal to x_0 (see Table 36.2).

IO Model as a Special Case of an LP model

The IO model in the previous section represents the simplest Leontief system with a unique solution. The IO model can be viewed as a special case of a linear program (Dorfman et al. 1987), in fact linear programming was influenced by input-output analysis (Dantzig 1963, pp. 16–20; Albers et al. 1986). A standard LP formulation contains a linear objective function to optimize over, subject to a set of linear constraints, and a set of nonnegative decision variables (36.8):

$$\begin{aligned} \min z &= c^{\mathrm{T}}x \\ Ax &\le d \\ x &\ge 0 \end{aligned} \tag{36.8}$$

By constraints, we consider both equality and inequality constraints (i.e. $=, \leq, \geq$). The problem is solved by finding the set of variables $\boldsymbol{x}$ that optimize z subject to constraints by means of the *Simplex* search algorithm. Starting with our IO model in the previous section, (36.5) can be rewritten to:

$$(I - A)x = d \tag{36.9}$$

Denoting $\tilde{A} = (I - A)$, we get

$$\tilde{A}x = d \tag{36.10}$$

The left hand side of Equation (36.10) states that *net* production of commodities must equal demand. We can relax this assumption to say that *net* production of commodities must be *greater or equal to demand*:

$$\tilde{A}x \geq d \tag{36.11}$$

The Input-output model provides a simple form of a Walrasian general equilibrium model of the economy. In a meaningful economy, there are no free goods. In our IO model, the primary input factor *Labor* is the only cost of production. If we define w_j as the *wage rate* of industry j, the unit cost of production for product j is:

$$w_j a_{0j} x_j \tag{36.12}$$

Hence the minimum cost at which the society satisfies final demand can be stated as:

$$Min\ z = wa_0x \tag{36.13}$$
$$\tilde{A}x \geq d \tag{36.14}$$
$$a_0x \leq x_0 \tag{36.15}$$
$$x \geq 0 \tag{36.16}$$

Emissions q are here externalities (i.e. the cost of emissions are not internalized in the economy), and does not influence the attainment of equilibrium. It is thus not specified in the minimization problem (36.13–36.16).

$$Bx = q \tag{36.17}$$

The total output column x_j can be added across the goods i to reflect the total cost of the economy, and we can alternatively replace (36.13) with (36.18) to minimize output rather than minimizing costs:

$$Min\ z = \sum_j x_j \tag{36.18}$$

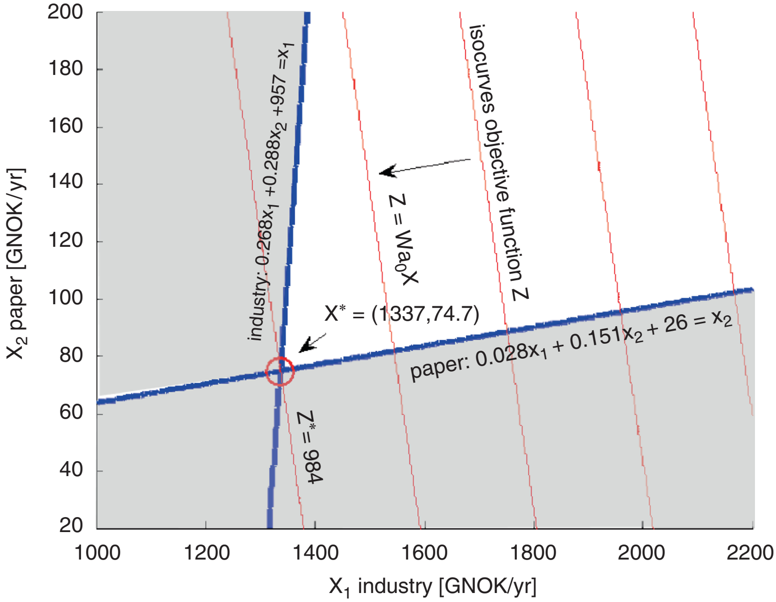

Fig. 36.1 Graphical Solution to the LP Problem. The Shaded Region Represents Infeasible Solutions, While the Upper Right Region is Feasible, but Will Provide Goods in Excess of Demand

The Leontief model can only provide relative prices. For simplicity, we assign the wage rate equally $w = 1$ [monetary units] for the two industries.

The solution to the LP problem is: $x_1 = 1,337$ and $x_2 = 74.7$ GNOK/year. The solution obtained from our optimization problem, is the same as derived from by the simple IO model in the previous section. Emissions q follows from Equation (36.17). Figure 36.1 shows the graphical solution to the minimization problem. The two equations representing the demand for each product provide lower bounds for the solution (x_1,x_2). The cost isocurves shows the objective function (Equation (36.13)), whose optimum is at the intersection of the isocurve $z^* = 856$ and the two demand constraints (see Fig. 36.1).

Cost minimization in Equation (36.13) plus the demand constraints, Equation (36.14) in the LP formulation is equivalent to the stronger assumption of demand balance (Equation (36.5)) in the IO model in the previous section. Thus, we have shown that the LP formulation is a generalized form of the IO model.

Of course, solving the IO model by matrix inversion is much simpler. This example merely serves to show that an IO model is a special case of a *linear programming problem*, and that their underlying assumptions are fully coherent. (Dorfman et al. 1987).

Problems with Multifunctional Outputs

When an industry or process produces more than one item, the problem of how much environmental burden should be attributed to each of the processes arise. For example, if we want to estimate emissions from 1 t of paper produced, the paper industry also produce heat as a by-product which substitutes alternative provision of heat (oil, for instance). The problem is then: how do we account for emissions for the paper production? The problem is known as the *allocation problem* and much work is devoted to this topic within LCA.

Heijungs and Frischknecht (1998) and Heijungs and Suh (2002) provides a mathematical treatment of the problem. Mathematically, systems with multiple products generate matrices with more rows than columns. Hence, matrix inversion is not possible.

Chemical pulping usually generate large amounts of waste heat that can be used for district heating or other processes. In Table 36.3, we have added another row, comprising a 3-by-2 commodity-sector industry.

The objective function is as before:

$$Minz = w \cdot \sum_j a_{0j} \cdot x_j \tag{36.19}$$

The equations are now modified into:

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + d_1 &\le x_1 \\ a_{21}x_1 + a_{22}x_2 + d_2 &\le x_2 \\ a_{31}x_1 + a_{32}x_2 + d_3 &\le 0.19x_2 \end{aligned} \tag{36.20}$$

where the last row states that the industry purchases 0.008 monetary units of heat for each unit output. The *Paper and pulp* industry's own heat demand is 0.028 per (monetary) unit output, while the final demand is 0 in this example. Heat services

Table 36.3 3-by-2 Commodity-Sector Industry

	Outputs [1] Industry, x_1 (a_{i1})	[GNOK/year] Paper, x_2 (a_{i2})	[GNOK/year] Final demand, d_j	Total outputs, x_j
Industry goods	0.262	0.291	957	1,326
Paper goods	0.028	0.125	26	72
Heat	0.008	0.028	0	0.19 x_2
Labor x_{0j} (a_{0j})	0.702	0.568	–	972
CO_2 [Mt/GNOK]	0.037	0.006		50
CH_4 [kt/GNOK]	0.226	0.374	–	327
Cd [kg/GNOK]	0.596	2.482		969

from the paper sector, is constrained to 19% of the paper output, which introduces a third constraint in 36.20. The rest of the problem remains the same as in our previous section:

$$\begin{aligned} b_{11}x_1 + b_{12}x_2 &= q_1 \\ b_{21}x_1 + b_{22}x_2 &= q_2 \\ b_{31}x_1 + b_{32}x_2 &= q_3 \end{aligned} \tag{36.21}$$

$$a_0 x \leq x_0 \tag{36.22}$$

$$x_i \geq 0 \tag{36.23}$$

The solution to this problem is an output of $x_1 = 1,325$ GNOK industrial goods and $x_2 = 72.1$ t of paper at a total cost of $z = 971$ GNOK/year. The corresponding environmental stress is $q = Bx$, which yields $q_1 = 50$ Mt CO_2,$q_2 = 326$ kt CH_4 and $q_3 = 969$kg Cd.

Figure 36.2 shows the three constraints as lines. In this multifunction system, there is a feasible region where the demand constraints are satisfied, bounded by the *Industry goods demand* from the left, and the *paper demand* restriction from below. The optimal solution, $x^* = (1,325, 72.1)$ with respect to costs lies at the intersection of the two constraining curves and the isocurve of the objective function.

Apparently, there are excess heat production from the *paper and pulp* sector, as the industry and paper constraints are binding at the optimum.

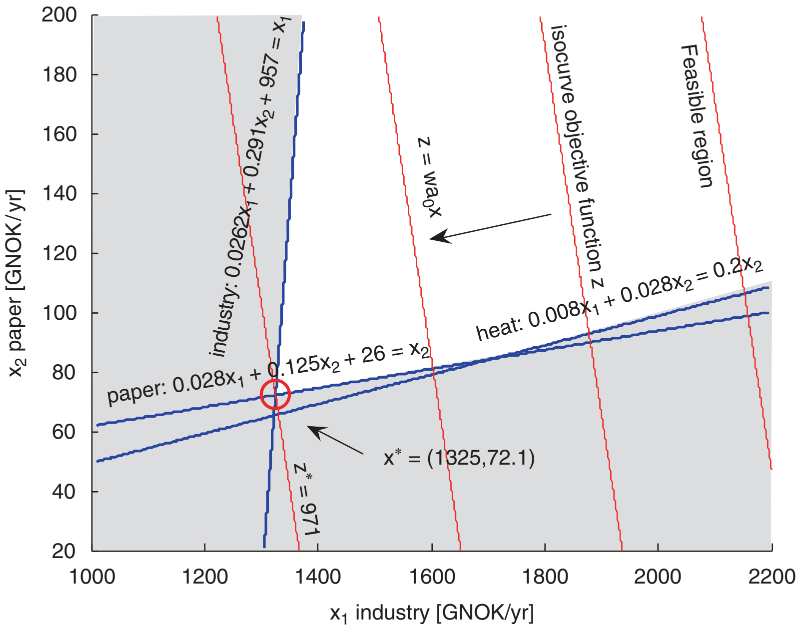

Fig. 36.2 Graphical Solution Multifunctional System

Table 36.4 External Costs of Emissions

Emissions, k	External costs, c_k [NOK/t]	Comments
CO_2	160	(ExternE 2005; Nord Pool 2008)
CH_4	3,360	GWP $CH_4 = 21 \times$ GWP CO_2
Cd	624,000	(Espreme 2008)

If the industry goods production (x_1) should jump to 1,800 GNOK/year of output, heat production from paper and pulp becomes the binding constraint and so heat becomes the primary product. This occurs at the intersection of the paper and the heat constraint in Fig. 36.2.

To minimize the environmental impact of our model, we need a single objective to make the emission types comparable. The LCA approach would be to multiply the emission inventory with environmental impact categories (Global Warming Potential, Human Toxicity Potential etc.) and use a weighting scheme such as the EPS method or Ecoindicator (ISO 2000).

The problem with this approach is the omission of costs. Most people would agree that costs matter also when making decisions concerning the environment. Recall Tables 36.1 and 36.2 that lists labor (in monetary units) as a *primary input factor* to the economy. The emissions can also be interpreted as *primary input factors*, representing *external costs* to the economy. The external costs listed in Table 36.4 are based on ExternE (2005), Nord Pool (2008) and the Espreme project (2008). External costs are often used in socio-economic valuation and cost-benefit analyses of projects by regulating authorities.

We can now define the objective function as

$$\min\ z = \sum_k c_k \cdot q_k \tag{36.24}$$

where c_k represents the external costs of emission k. The optimal solution turns out to be identical to our cost minimization, i.e. $x^* = (1,325, 72.1)$, with an environmental costs of $z = 9.0$ GNOK/year. Even better, we can internalize the external costs by adding the external cost term in 36.24 to the original cost function (36.19), which in this case give the same result as before:

$$\min\ z = w \cdot \sum_j a_{0j} \cdot x_j + \sum_k c_k \cdot q_k \tag{36.25}$$

Azapagic and Clift (1999) propose the use of *dual values* in linear programming to allocate environmental burden, and suggest that linear programming should be used to capture the whole system under study. A *dual value* is the marginal change in the objective function from relaxing a constraint by one unit. Dual values are then interpreted as prices or costs (if costs are the objective function). In our example, the dual values are listed in Table 36.5.

Table 36.5 Dual Values from Minimizing External Cost

Sector, j	Industry	Paper goods	Heat
Dual values [GNOK/GNOK]	0.0093	0.0056	0

Table 36.6 Expanded IO Model Two Industries with Alternative Technologies

	Inputs to Industry	Inputs to paper and pulp		Final demand d_i	Total outputs
	a_{i1} b_{i1} a_{01}	TMP a_{i2}	CP a_{i3}		x_i q_k x_0
Industry	0.39	0.05	0.09	100	x_1
Paper [GNOK/year]	0.02	0.02	0.04	50	$x_2 + x_3$
CO_2 [Mt]	0.28	0	0	–	q_1
SOx [kt]	0.03	0	0.04	–	q_2
Labor [GNOK/year]	0.56	0.07	0.11	–	x_0

If we increase the demand of paper goods by, say 1 GNOK, then the associated external cost (given by the objective function 36.24) increases by 5.6 MNOK, but if we increase the demand of heat by 1 GNOK – there is no increase in the environmental costs. As pointed out earlier, there is an excess supply of heat, which is a by-product of paper production. If we demanded more than 1.08 GNOK of heat per year, each extra demanded GNOK of heat would increase external costs by 30 MNOK per year. Paper goods would now become a by-product in excess of demand and a corresponding dual value of 0.

Leontief Substitution Systems

Suppose that we expand our IO model to include several *alternative* technologies for the paper and pulp industry. Two technologies are available for production of paper: Thermo-mechanical (TMP) and chemical pulping (CP). As shown in Table 36.6, Chemical pulping requires more wood per kg output than mechanical pulping, and the emissions characteristics for the two pulping technologies differ as well. We assume no direct emission of CO_2 and SO_2 in the case of Norwegian thermomechanical pulping, while chemical pulping emits 4% SO_2 per unit output.

We formulate the system as an LP problem, having $i = 2$ rows, one for each commodity, and $j = 3$ columns representing the production from each technology, where technology 2 and 3 (TMP and CP) are substitutes:

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + d_1 &\le x_1 \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + d_2 &\le x_2 \end{aligned} \tag{36.26}$$

$$\begin{aligned} b_{11}x_1 + b_{12}x_2 + b_{13}x_3 &\leq q_1 \\ b_{21}x_1 + b_{22}x_2 + b_{23}x_3 &\leq q_2 \end{aligned} \tag{36.27}$$

The objective function can then be stated as:

$$\min z = w \cdot a_0 \cdot x \tag{36.28}$$

$$Ax + d \leq x \tag{36.29}$$

$$Bx = q \tag{36.30}$$

$$a_0 x_0 \leq x_0 \tag{36.31}$$

$$x_0 \geq 0 \tag{36.32}$$

The solution of the problem is $x_1 = 170, x_2 = 54$ and $x_3 = 0$ with corresponding emissions $q_1 = 47, q_2 = 5.6$ for CO_2 [Mt] and SO_2 [kt] respectively. The preferred pulping technology $i = 2$ is thermo-mechanical pulping in terms of costs. This example shows that the LP formulation is able to tackle the representation of alternative technologies.

Detailed LP Models in an IO Model

Detailed models of important industry sectors are often used for decision support. Major changes in one industry sector can induce repercussions from other sectors, and the potential influence on other sectors can be analyzed by linking detailed industry models to economy-wide models. This "hybrid approach" of linking detailed models with aggregated, economy-wide models is currently a focus of research in LCA. In particular IOLCA and process LCA can be linked to combine their strengths (Suh 2004). In the following example, we show how IO and a more detailed LP model of a sector can be integrated.

Following Dantzig's approach (Dantzig, 1976), we elaborate our previous example into a slightly more detailed LP model of the paper and pulp industry while capturing the economy-wide induced emission effects by linking its upstream- and downstream exchanges to an aggregated IO model.

Suppose that we possess a more detailed LP model of the *paper and pulp* sector, and a more aggregated IO model of the other sectors being *Energy*, *Industry* and *Services*. The paper and pulp industry has the set of technologies $T \in \{TMP, CP, DIP\}$ denoting *thermo-mechanical*, *chemical* and *de-inked pulp* from recycling. These technologies can be mixed to produce paper products $p \in \{pp, np, hy, bo\}$, denoting *print paper*, *newspaper*, *hygienic paper* and *cardboard*.

Table 36.7 and the corresponding Table 36.8 display

1. The three-sector IO model in the upper left
2. Inputs from sector i to other the detailed LP model for each technology T in the upper right part
3. Inputs of paper products p to the IO model in the lower left

Table 36.7 Hybrid IO Linear Programming

	Other industry sectors			Paper and Pulp				
	Service	Industry	Energy	TMP	CP	DIP	Final demand	Total output
Service	0.209	0.098	0.041	0.171	0.17	0.3	957	1, 322
Industry	0.053	0.267	0.026	0.08	0.10	0.10	342	586
Energy	0.009	0.023	0.075	0.10	0.07	0.02	375	74
Printpaper	0.005	0.005	0.01	0.01	0.01	0.01	6.9	
Newspaper	0.0035	0.001	0.01	0.02	0.02	0.02	12.7	
Hygienic	0.004	0.005	0.03	0.02	0.02	0.05	2.7	
Cardboard	0.0055	0.01	0.001	0.01	0.01	0.02	3.7	
CO_2 [Mt]	3.6E–3	5.2E–2	1.9E–3	0.007	0.008	0.003		50
CH_4 [kt]	7.7E–3	8.2E–2	7.7E–4	0.034	0.104	0.151		327
Cd [kg]	1.8E-3	8.6E–3	3.8E–4	0.683	0.963	3.528		969
Labor [GNOK/year]	0.711	0.262	0.282	0.026	0.003	0.04		

Table 36.8 Equations Used in Hybrid IO Linear Programming

	Other industry sectors j			Paper and pulp T			Final demand	Total output
	Energy	Industry	Forestry	TMP	CP	DIP		
Energy services, i		$\sum_j a^{11}_{ij} \cdot x^1_j$			$\sum_T a^{12}_{iT} \cdot x^2_T$		d^1_i	x^1_i
Paper products, p		$\sum_j a^{21}_{pj} \cdot x^1_j$			$\sum_T a^{22}_{pT} \cdot x^3_p$		d^2_p	x^3_p
Emissions, j		$\sum_j b^1_{kj} x^1_j$			$\sum_T b^2_{kT} x^3_T$			q_k
Labor services		$a^1_{0j} x^1_j$			$a^2_{0T} x^2_T$			x_0

4. Parts of the detailed LP model in the lower right (i.e. the demand constraints)
5. The primary input factors (labor, emissions) for each sector and each pulping technology as the lowermost rows of the table

The unknowns, x^1_j, x^2_T, x^3_p represents total outputs of goods j, pulp production allocated to technology T, and production of paper type p respectively. Equations (36.33)–(36.42) define the whole model:

First, the total output x^1_i of goods i must be greater or equal to intermediate demand from sectors j, the technologies T, and final demandd^1_i:

$$\text{Goods demand}: \sum_j a^{11}_{ij} \cdot x^1_j + \sum_T a^{12}_{pT} \cdot x^2_T + d^1_i \leq x^1_i \tag{36.33}$$

Similarly, the total output x_p^3 of paper products must be greater or equal to intermediate demand from sectors j, the technologies T, and final demand d_p^2:

$$\text{Paper demand}: \sum_j a_{ij}^{11} \cdot x_j^1 + \sum_T a_{pT}^{22} \cdot x_p^3 + d_p^2 \leq x_p^3 \tag{36.34}$$

Emissions and labor constraints are as follows:

$$\text{Emissions constraints}: \sum_j b_{kj}^1 x_j^1 + \sum_j b_{kT}^2 x_T^2 = q_k \tag{36.35}$$

$$\text{Labor constraints}: \sum_j a_{0j}^1 x_j^1 + \sum_T a_{0T}^2 x_T^2 \leq x_0 \tag{36.36}$$

The problem for the paper and pulp sector is to find the most cost-effective mix of pulping technologies to produce the desired output of paper products subject to quality- and material constraints. This problem is formulated in the LP problem below. Let u_{pT} be the $p\ x\ T$ decision variable of allocating pulp produced by technology T to production of the paper type p. Minimize cost of production:

$$Min\ z = w\left(\sum_j a_0^1 x_j^1 + \sum_T a_{0T}^2 x_T^2\right) + \sum_k c_k \cdot q_k \tag{36.37}$$

The three terms in the objective function now represents costs of providing goods from the economic sectors, costs of the pulping technologies and the external costs of emissions. We set the wage rate equal to 1. For convenience, x_T^2 and x_p^3 defines total output from the pulping technologies, for each technology and paper type respectively:

$$\text{Pulp output}: x_T^2 = \sum_p u_{pT} \qquad \forall T \tag{36.38}$$

$$\text{Paper output}: x_p^3 = \sum_T u_{pT} \qquad \forall p \tag{36.39}$$

Furthermore, each paper type has upper limits for each type of pulp:

$$\text{Quality constraints}: u_{pT} \leq \eta_{Tp} \cdot x_p^3 \qquad \forall p, T \tag{36.40}$$

While thermo-mechanical and chemical pulp obtain wood from the forestry sector, de-inked pulp utilizes recycled paper as resource, except hygienic paper. Recycled paper is available from each sector j, pulping technology T, and final demand – which sums up to x_p^3 according to the paper demand constraint in Equation (36.34). Thus the available amount of recycled paper is:

$$\text{Recycling constraints}: x_{DIP}^2 \leq \sum_{p \neq hy} x_p^3 \tag{36.41}$$

$$\text{Non-negativity}: \; u_{pT}, x_i^1, x_T^2, x_p^3, d_i^1, d_p^2 \geq 0 \tag{36.42}$$

Quality constraints η_{pT} for paper technologies are shown in Table 36.9. The numbers indicate maximum share of pulp from technology T that can be used for production of paper type p.

Let's define the functional unit of final demand of paper products to be as in Table 36.10. Demand of other goods and services, d_j^1 is now set to 0. Minimizing costs of the total economy yields the following allocation of technologies T to the production of each paper type p (see Table 36.10).

We find that thermo-mechanical pulp is the preferred pulping technology with respect to costs. However, chemical pulping is required due to the quality constraints for some of the paper products. Table 36.11 shows the services purchased by the paper and pulp sector from other sectors, and Table 36.12 shows the induced emissions from the total of the background economy and the paper and pulping technologies.

The paper and pulp LP model described through equations 36.38–36.42 contains three technologies that can produce four types of paper products. The model allocates paper products to each technology in the most cost effective way subject to demand and quality constraints. The model is linked to a three-sector IO model

Table 36.9 Quality Constraints η_{pT} for Paper Technologies

η_{pT}	TMP	CP	DIP
Pp	0	1	0
Np	1	1	0.4
Hy	0.3	0.4	1
Bo	1	1	1

Table 36.10 Optimal Solution with Respect to Total Costs. Allocation of Pulp and Paper Production

Paper type p	TMP	CP	DIP	Final demand [GNOK/year]	Total output, p [GNOK/year]
Pp	0	7.2	0	6.9	7.2
Np	13.5	0	0	12.7	13.5
Hy	0.9	1.2	0.9	2.7	3
Bo	3.9	0	0	3.7	3.9
Total	18.3	8.4	0.9	26	27.6

Table 36.11 Goods and Services Purchased from Paper and Pulp Sector (Optimal Solution, Cost Minimization)

Sector	Service	Industry	Energy
[GNOK/year]	6.76	3.87	2.87

Table 36.12 Total Emissions, Optimal Solution (Cost Minimization)

Emissions per year	CO_2[Mt]	CH_4 [kt]	Cd [kg]
	0.49	3.37	28.63

through equations 36.33–36.36, which captures total costs and emissions through equations 36.35–36.36. As there are multiple products and multiple technologies that can provide the same demand, the model chooses the best allocation of production of paper type p to technology T according to the objective function (Equation (36.37)).

To minimize the environmental impact, we re-introduce Equation (36.24) as the objective function:

$$\text{Min } z = \sum_k c_k \cdot q_k \tag{36.43}$$

Based on the external costs in Table 36.4 and the magnitude of demand, we notice that CO_2 is the major contributor to external costs.

Minimization of emissions yields the following results in Tables 36.13 through 36.15. We observe that *de-inked pulp*, (i.e. recycling) is the preferred technology, though chemical pulping and thermo-mechanical pulping is still required. The two paper types with the lower grades (hygienic paper and paperboard), are however produced by 100% recycled paper, while production from the CO_2-intensive chemical pulping technology is reduced to a minimum (see Table 36.13). Dual values in Table 36.13 represent the percentage increase of environmental costs from increasing the demand of each paper type.

Table 36.14 shows a corresponding change in purchases of services from the paper and pulp sector, due to the new allocation of production technologies. Purchases from services increase, while consumption of energy is reduced, as de-inking requires less energy than virgin pulping technologies.

Finally, we observe that CO_2 emissions are reduced by approximately 9%. Unfortunately the release of cadmium doubles, and CH_4 emissions increase by 30%.

Table 36.13 Optimal Solution with Respect to External Costs. Allocation of Pulp and Paper Production

Paper type p	TMP	CP	DIP	Dual values [%]	Final demand [GNOK/year]	Total output, p [GNOK/year]
Pp	0	7.2	0	4.08	6.9	7.2
Np	8.1	0	5.4	3.78	12.7	13.5
Hy	0	0	3.0	3.86	2.7	3
Bo	0	0	3.95	3.66	3.7	4.0
Total	8.1	7.2	12.4		26	27.7

Table 36.14 Goods and Services Purchased from Paper and Pulp Sector (Minimization of External Costs)

Sector	Service	Industry	Energy
[GNOK/year]	8.6	4.2	1.9

Table 36.15 Total Emission, Optimal Solution (Minimization of External Costs)

Emissions per year	CO_2 [Mt]	CH_4 [kt]	Cd [kg]
	0.448	4.9	61.7

Applications of LCA in Optimization Models

Optimization is usually performed under economic criteria. Lately, environmental criteria have been introduced in optimization problems, either as the only objective or combined with the economic objectives in optimizations tasks. This section merely presents a sample selection of work that combines linear programming and LCA. For a more extensive survey, see Bloemhof-Ruwaard et al. (1995a).

Bloemhof-Ruwaard et al. (1995b) combined linear programming and LCA on fat blends and have later on combined LCA and operations research on various management problems.

Azapagic et al. (1995, 1999, 2000) combined economic and environmental objective functions based on LCA, yielding a multi objective optimization problem. At the same time Kniel et al. (1996) applied the same technique in optimization of a nitric acid plant. The economic objective function is formulated based on the incomes and expenditures of the system, whereas the environmental objective function can be formulated based on an LCA of the system. In optimization of chemical processes the profit and environmental burden are the objective functions, mass and energy balances the equality constraints, and material availability, heat requirements, production capacity etc. are the inequality constraints. Azapagic and Clift (1995, 1999) and Kniel et al. (1996) used linear programming in their approach.

Various optimization techniques are proposed to solve the multi objective problem. Azapagic et al. (1995, 1999, 2000), Kniel et al. (1996) and Alexander et al. (2000) produced a set of optimum solutions which yield Pareto-optimal surfaces.

Björk and Rasmuson (2002) showed that LCA can be used for environmental optimization of energy systems; Song et al. (2002) introduces LCA to optimize a refinery. Diwekar (2002) and Gielen et al. (2001) combined LCA and nonlinear optimization of chemical processes and modelling of material policies, respectively.

Azapagic et al. also discuss a method to overcome the problem with allocation when more than one product is produced, as was demonstrated in this chapter. By use of LP and a holistic process description, the problem can be avoided or calculated by use of dual variables.

The different approaches for optimization of processes given above, all include the life cycle perspective of the processes, they differ, however, in the scope of use.

The MARKAL model was used in optimization of industrial sectors. Authorities typically want to analyse the impact of new regulations and environmental policies.

The refinery process by Song et al. (2002) is an example of optimization of an industrial plant, whereas Diwekar and Small (2002) are optimizing models of industrial processes. In these cases, a companies or departments within companies would be interested in finding cost-effective ways to comply with environmental regulations. This shows that LCA and optimization is a powerful tool which can be adapted at all levels in design and evaluation of industrial processes.

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Chapter 37
Time Use and Sustainability: An Input-Output Approach in Mixed Units

Jan Christoph Minx and Giovanni Baiocchi

Introduction

Industrial Ecology as coined by Frosch and Gallopoulos (1989)[1] has proven to be one operational and holistic concept for successfully 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 (Jänicke 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).[2]

Researchers have responded to this criticism by adjusting their policy approaches. Much more emphasise 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).

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[1] The idea of Industrial Ecology has evolved from the 1960s onwards (see Erkman 1997, among others), but it did not attract widespread attention until Frosch and Gallopoulos' (1989) contribution to Scientific America. This is, therefore, often seen as the ultimate take-off of the Industrial Ecology movement.

[2] 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).

S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

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 integrated quantitative frameworks opens a whole new array of possibilities for sustainability research for doing so. 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).

The section on Time Use Data gives an introduction to time use data and outlines four unique properties that allow social and behavioural aspects to be better represented in quantitative frameworks. The section on Comprehensive Sustainability Research proposes to integrate data in monetary, physical and time units in one comprehensive framework before the section on Integrating Time Use Data 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 on "Magic Triangle" through the Results section.

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) of 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 37.1 (see United Nations 1975). Data is usually collected through the diary method (most often 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 (Fig. 37.1). 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

Table 37.1 Basic Information Content of Time Use Data

Cross-sectional data	The following information can be analysed when referring to a single reporting period: 1. The activities realised in the course of a representative day for different purposes 2. The duration of these activities 3. The allocation or distribution of these activities during the day 4. Differences in activity patterns between social strata
Longitudinal Data	As soon as at least two comparable time budget surveys are available, the analysis can be extended to address: 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

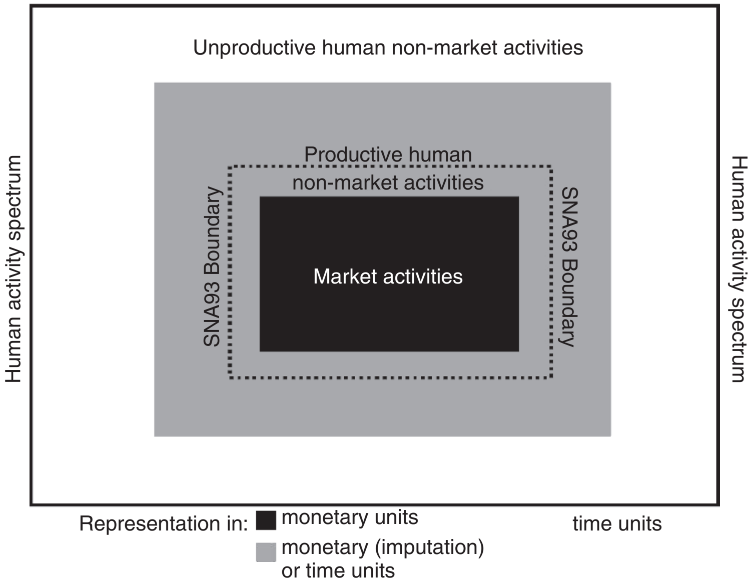

Fig. 37.1 Relationship Between Monetary and Time Use Data for the Representation of Human Activities

during a given reporting period (i.e. time cannot be hoarded – this is the *24 h add-up property*), time use data has the unique capability to capture *all* human activities under *equal coverage*[3] *of the whole population*.

To extend the scope of quantitative models, time use data can be applied not only as a standalone, but also as a basic data input for imputing the value of non-

[3] "Equal coverage" means that every citizen is represented as well as any other. This is a direct consequence of the 24 h add-up property of human time.

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 can also be depicted in money terms, as shown in Fig. 37.2. The appropriate representation depends on the research purpose.[4]

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 an 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

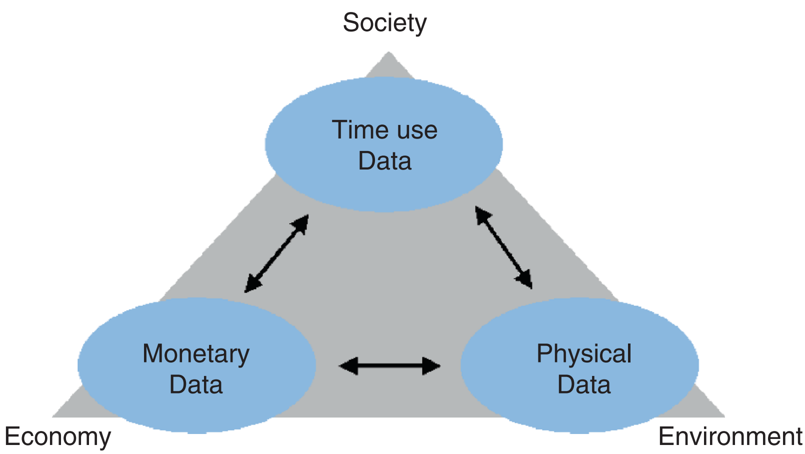

Fig. 37.2 A Magic Triangle for Quantitative Sustainability Research

[4] Note that the SNA93 production boundary also comprises some productive non-market activities (see UN, 1993a; Kendrick, 1996).

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, p. 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; UNST 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 have much more focussed on the study of human activities and behaviour from a societal angle.

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.[5] but as *instrumental* 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 either one of them. This is shown in Fig. 37.2. It is a particular strength of such a data framework that monetary and non-monetary phenomena are conceptually and numerically interlinked "without relying

[5] 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.

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*.

Unfortunately, sustainability studies have only very rarely applied data in all three different units (e.g. Schipper et al. 1989; Jalas 2002; Stäglin and Schintke 2002; Stahmer et al. 2003c, 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, 2000; Kazemier et al. 1999), published by the Statistical Offices of Germany and the Netherlands respectively, are notable and visionary exceptions.

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 household's 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. Wiedmann et al. 2006; 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

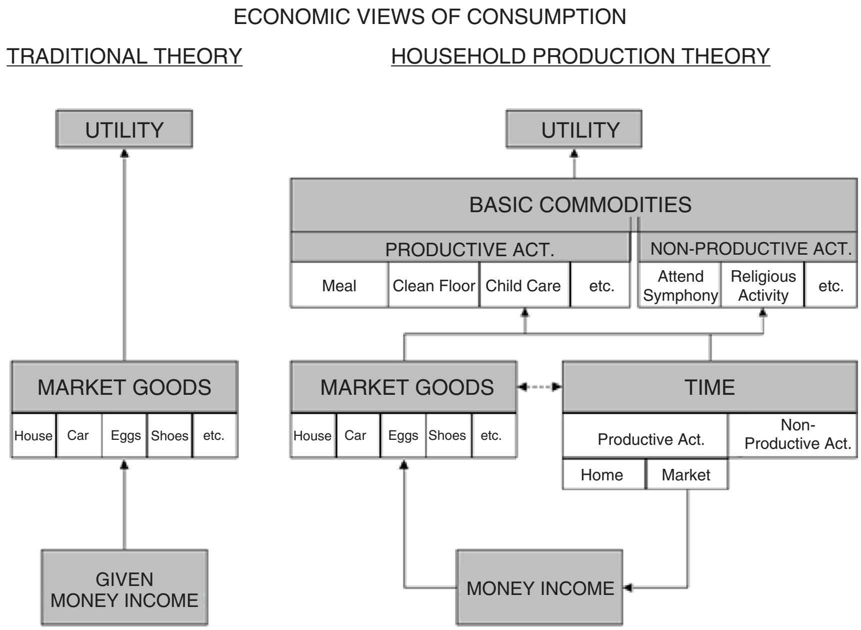

Fig. 37.3 Two Distinct Views of Household Consumption (Adapted from Hawrylyshyn [1977])

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 Fig. 37.3.

However, goods are usually best perceived not as ends in themselves,[6] 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 independent of involvement in an activity (Juster et al. 1981). Time is certainly another indispensable input for any human activity, as already argued in the section on Time Use Data. 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", 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 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 Fig. 37.3.

[6] 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.

Because households can substitute between time and market goods,[7] 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, 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 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.

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[7] 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.

> Once a time dimension is introduced, the field expands considerably: commodities might be consumed once 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 life-cycle 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 2002). 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 2002). The availability of time use data also allows expression of resource use not only per unit of money spent, but also per hour of activity engagement (Van der Werf 2002; Jalas 2002). 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 for addressing topics such as the material well-being, poverty or income inequality of different lifestyle groups and their relationship to resource use much more appropriately than 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, or health data[8] 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 modeled (Ehling 1999). Because activities are not only rooted in time, but also in space, time use data might also facilitate a more comprehensive introduction of the space dimension into input-output modelling. Inspirations might be taken from scholars in Geography, who have been using time use and spatial data in combination for quite a while (see Carlstein et al. 1978a–c). A first attempt has already been undertaken by Schaffer (2003).

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.

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. (2003b).

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 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

[8] 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).

Table 37.2 Household Activities Distinguished in This Study

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

Budget Survey (see Ehling 1999), exogenously as final demand like in the traditional MIOT.[9] They are listed in Table 37.2.

We further aggregated the ten household activity fields of the present study into four basic categories of time use, as is 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 Fig. 37.4.

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 37.6). 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.[10] 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

[9] In contrast, the extended MIOT records all goods and services used by households as intermediate inputs in the spirit of the household production literature.

[10] Stahmer et al. (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.

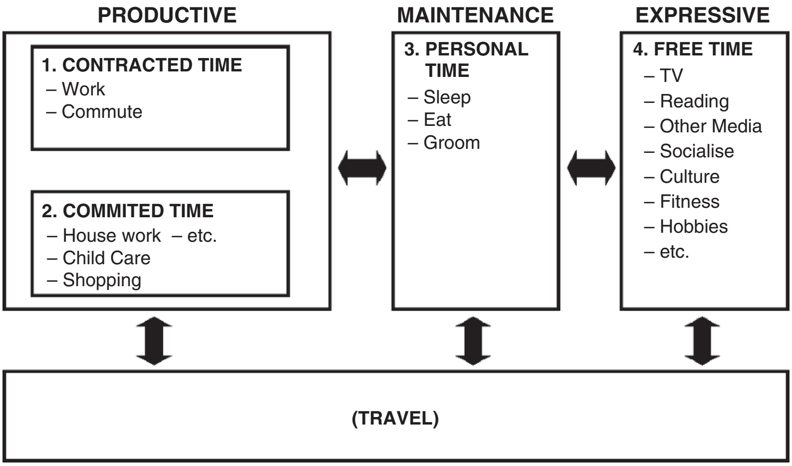

Fig. 37.4 Interrelations Across Four Types of Time (Adapted from Robinson and Godbey [1997])

Table 37.3 Socio-demographic Groups Distinguished in This Study

Abbreviation	Description
av	Average population
<12	Children aged younger than 12
12–65, nw, std	Students between 12 and 65 not enrolled in the labor market
12–65, nw	Citizens between 12 and 65 not enrolled in the labor market
12–65, w, std	Students between 12 and 65 enrolled in the labor 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

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 37.3.

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. These indicators can be readily obtained from the 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 on Integrating Time Use Data, 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, which can be expected to play a key role in the generation of human well-being, still remains unaccounted for.

The total material inputs required to provide for the West-German lifestyle summed up to 63 billion tons. Of these total material flows only about 15% 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 less material-intensive high-tech 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. However, we hope that this provides sufficient indication of the richness of the data set and its potentials.

We have argued earlier that lifestyle analysis is rooted in the basic question of what people actually *do* during the day. Table 37.4 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.

Table 37.4 Socio-Economic and Environmental Key Indicators

Indicator	Unit	Estimate
Population	10^6 persons	63.3
Total time budget	10^9 h	554.1
Productive market activities	10^9 h	128.6
Productive non-market activities	10^9 h	82.3
Unproductive non-market activities	10^9 h	421.4
Residual	10^9 h	4.2
GNP	10^9 DM	2,245.3
GNP^{ext}	10^9 DM	3,230.2
Total material inputs (TMI)	10^9 t	63.0
Monetary trade balance	10^9 DM	118.0
Physical trade balance	10^9 t	−0.2
Employment	10^6 persons	28.5
Material efficiency[11]	%	14.7

A quick glance at Table 37.5 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.[12] 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 37.6 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 Comprehensive Sustainability Research section. Ideally, this matrix should be 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 63% of the total budget,

[11] This indicator divides the total tonnage of goods and service by total material flows.

[12] This again seems to support the claim that traditional monetary input-output tables cannot appropriately reflect the distributional realities as outlined in Section 4.

Table 37.5 What do people do? Activity Patterns across Socio-Economic Groups

		MW	*HPROD*	*DIY*	*COM*	*VW*	*EDU*	*PR*	*SOC*	*LEIS*	*CARE*	*RES*
Total	10^9 hours	46.3	64.2	6.2	12.3	3.1	15.4	265.6	33.6	94.5	8.8	4.2
	%	8.4	11.6	1.1	2.2	0.6	2.8	47.9	6.1	17.1	1.6	0.8
<12	%	0.0	1.0	0.0	0.0	0.0	7.7	60.7	3.2	26.8	0.0	0.7
12–65, nw, std	%	0.0	5.3	0.9	0.0	0.3	17.9	47.0	6.9	19.4	0.7	1.7
12–65, nw	%	0.0	21.1	1.1	0.0	0.9	0.5	47.7	6.9	16.5	3.9	1.3
12–65, w, std	%	16.8	4.7	1.4	5.7	0.8	4.6	43.1	8.9	13.5	0.4	0.4
12–65, w, ls	%	16.3	11.9	1.5	4.5	0.1	0.4	44.5	5.8	13.4	1.3	0.3
12–65, w, ms	%	18.9	9.4	1.7	4.8	0.6	0.4	42.9	6.1	13.4	1.6	0.4
12–65, w, hs	%	20.5	8.1	1.5	5.3	1.0	0.5	42.5	5.9	12.6	1.8	0.5
12–65, w, av	%	18.5	9.2	1.6	4.9	0.6	0.7	43.1	6.2	13.3	1.4	0.4
65<	%	0.0	17.9	0.7	0.0	0.7	0.2	52.7	6.4	20.1	0.8	0.6

Table 37.6 Household Consumption Expenditure by Sector and Activity

Sector		HPRO D	DIY	COM	VW	EDU	PR	SOC	LEIS	CARE	RES	**Sum**	Perc
Agr	10^6 DM	5,899	58	78	10	31	2,144	143	665	59	285	**9,371**	1.0%
En, Wa	10^6 DM	14,070	740	410	80	235	9,662	1,011	6,522	488	1,199	**34,416**	3.8%
Man	10^6 DM	94,799	11,603	7,557	535	1483	83,687	6,530	16,761	2,134	9,123	**234,213**	26.1%
Const	10^6 DM	862	65	69	13	0	1,260	170	817	83	183	**3,522**	0.4%
Serv	10^6 DM	103,915	13,625	20,073	1,950	10,085	223,672	31,324	123,155	8,439	25,290	**561,527**	62.5%
Env	10^6 DM	2,050	198	231	41	123	3,798	529	2,485	252	429	**10,137**	1.1%
Edu	10^6 DM	0	0	0	0	0	0	0	0	0	0	**0**	0.0%
N-serv	10^6 DM	2,619	74	313	20	2,245	12211	204	6,951	62	19,981	**44,679**	5.0%
Sum	10^6 DM	**224,214**	**26,363**	**28,730**	**2,649**	**14,203**	**336,433**	**39,911**	**157,356**	**11,517**	**56,490**	**897,865**	100 %

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 a society's 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.

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 vector $\boldsymbol{x}$ all human activities require the use of time, goods and materials, that is

$$\mathrm{x}_j = F(z_{1j}, z_{2j}, \ldots, z_{nj}, t_j, r_j) \tag{37.1}$$

where

z_{ij} = *intermediate inputs from i used in production of j*
t_j = *time input to production in j*
r_j = *material inputs to production in j*

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

$$\begin{aligned} x_j &= \min\left(\frac{z_{1j}}{a_{1j}}, \frac{z_{2j}}{a_{2j}}, \ldots, \frac{z_{1n}}{a_{1n}}, \frac{t_j}{\tau_j}, \frac{r_j}{\varepsilon_j}\right) \\ &\textit{with} \\ a_{ij} &= \frac{z_{ij}}{x_j};\ \tau_j = \frac{t_j}{x_j};\ \varepsilon_j = \frac{r_j}{x_j} \end{aligned} \tag{37.2}$$

For estimation we therefore augment the intermediate flow matrix $\mathbf{Z}$ and the partitioned final demand matrix $\mathbf{Y} = (\mathbf{Y^{hh}}|\mathbf{Y^{\neq hh}})$, where $\mathbf{Y^{hh}}$ is a matrix of household expenditure classified by household activities and $\mathbf{Y^{\neq hh}}$ is a matrix comprising the remaining final demand categories, with vectors $(\mathbf{0})$ and scalars (0) of zeros, vectors of time inputs $\mathbf{t}^{\text{prod}}$ and $\mathbf{t}^{\text{con}}$, as well as material input vectors $\mathbf{r}^{\text{prod}}$ and $\mathbf{r}^{\text{con}}$. The superscripts "prod" and "con" distinguish inputs to market and non-market activities of households. Hence

$$\mathbf{Z}^{aug} = \begin{pmatrix} \mathbf{Z} & \mathbf{0} & \mathbf{0} \\ \mathbf{t}^{prod} & 0 & 0 \\ \mathbf{r}^{prod} & 0 & 0 \end{pmatrix} \text{ and } \mathbf{Y}^{aug} = \begin{pmatrix} \mathbf{Y}^{hh} & \mathbf{Y}^{\neq hh} \\ \mathbf{t}^{con} & 0 \\ \mathbf{r}^{con} & 0 \end{pmatrix} \tag{37.3}$$

As indicated in Equation (37.2) we calculate an augmented direct coefficient matrix $\mathbf{A}^{aug}$ by

$$\mathbf{A}^{aug} = [a_{ij}] = \frac{z_{ij}^{aug}}{x_j} \tag{37.4}$$

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

$$\mathbf{X}_{act}^{aug} = \begin{bmatrix} \mathbf{X}_{act}^{tot} \\ \mathbf{r}_{act}^{tot} \\ \mathbf{t}_{act}^{tot} \end{bmatrix} = (\mathbf{I} - \mathbf{A}^{aug})^{-1}\mathbf{Y}^{aug} = \mathbf{L}^{aug}\mathbf{Y}^{aug} \tag{37.5}$$

where $\boldsymbol{X}_{act}^{aug}$ is the augmented total output matrix consisting of the total economic output vector $\boldsymbol{iX}_{act}^{tot} = \boldsymbol{x}_{act}^{tot}$ with $\boldsymbol{i}$ being a vector of ones, $\boldsymbol{r}_{act}^{tot}$ is the total material flow vector and $\boldsymbol{t}_{act}^{tot}$ 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 $\boldsymbol{\varepsilon}^{tot}$, we can calculate households' activity-specific material intensities in monetary and time units respectively by

$$\varepsilon_{\$}^{act} = (\varepsilon^{tot})'\mathbf{Y}^{hh}(\hat{\mathbf{y}}_{act}^{hh})^{-1} \tag{37.6}$$

where $\mathbf{y}_{act}^{hh} = \mathbf{iY}^{hh}$ is total household consumption expenditure by activity, the hat symbol ^ indicates diagonalisation of a vector, and,

$$\varepsilon_{time}^{act} = (\varepsilon^{tot})'\mathbf{Y}^{hh}(\hat{\mathbf{t}}^{con})^{-1} \tag{37.7}$$

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 the Time Use Data section, 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).

Model Estimations

As argued in the Integrating Time Use Data section, 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 37.7. Generally, expenditure ($\mathbf{y}_{act}^{hh}$) and resource flows ($\boldsymbol{r}_{act}^{hh}$), as well as embodied production time ($\boldsymbol{t}_{ind}^{hh}$), show very similar distribution patterns across activities, while non-market time ($\boldsymbol{t}^{con}$) seems to be allocated quite differently. Moreover, for some activities, such as household production and leisure, the direct ($\boldsymbol{r}^{con}$) and total ($\boldsymbol{r}_{act}^{hh}$) 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 "Magic Triangle" section. Fig. 37.5 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 Fig. 37.5. *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

Table 37.7 Money, Time and Resource Flows Triggered by Household Activities.

Flow	Unit	HPROD	DIY	COM	VW	EDU	PR	SOC	LEIS	CARE	RES
$\boldsymbol{y}_{act}^{hh}$	10^9 DM	224.2	26.4	28.7	2.7	14.2	336.4	39.9	157.4	11.5	56.5
	%	25.0	2.9	3.2	0.3	1.6	37.5	4.5	17.5	1.3	6.3
$\boldsymbol{x}_{act}^{hh}$	10^9 DM	401.6	43.6	54.3	4.4	23.9	572.1	60.8	252.1	18.0	91.6
	%	26.4	2.9	3.6	0.3	1.6	37.6	4.0	16.6	1.2	6.0
$\boldsymbol{t}^{con}$	10^9 hours	64.2	6.2	12.3	3.1	15.4	265.6	33.6	94.5	8.8	4.2
	%	12.7	1.2	2.4	0.6	3.0	52.3	6.6	18.6	1.7	0.8
$\boldsymbol{r}^{con}$	10^6 tons	722	75	105	15	42	1,241	190	784	86	140
	%	21.2	2.2	3.1	0.4	1.2	36.5	5.6	23.1	2.5	4.1
$\boldsymbol{r}_{act}^{hh}$	10^6 tons	10,313	919	732	93	367	11,507	1,216	6,026	515	148
	%	33.8	3.1	2.5	0.3	1.2	37.1	4.1	19.7	1.7	4.9
$\boldsymbol{t}_{ind}^{hh}$	10^9 hours	4.02	0.40	0.44	0.03	0.24	5.61	0.47	2.06	0.11	1.13
	%	27.7	2.8	3.0	0.2	1.7	38.6	3.3	14.2	0.8	7.8

Note that the superscript hh denotes the total economic activity and material flows respectively triggered by households' consumption activities.

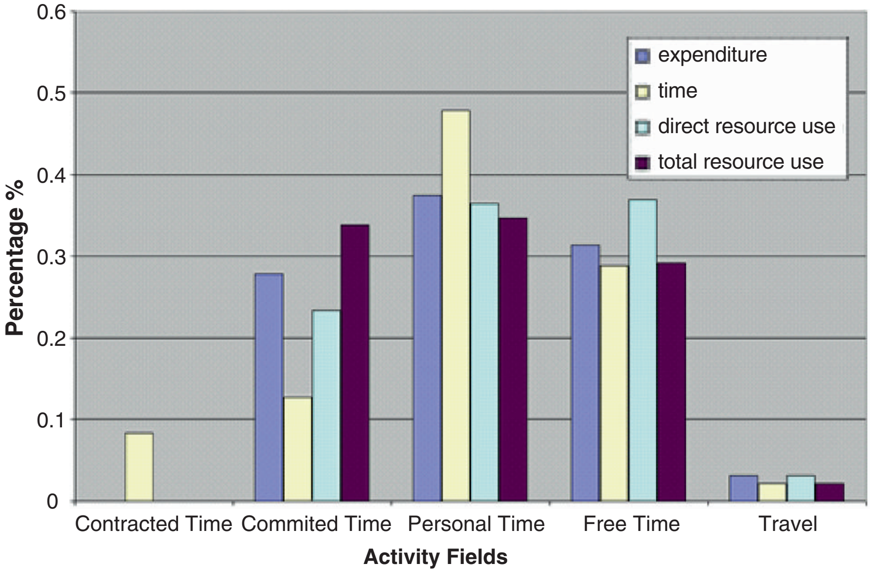

Fig. 37.5 Interrelation Between Expenditure, Time and Resource Use by Activity Field

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 appetizer for more detailed analysis, but 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 many 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.

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 (37.6)). 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 (37.7)).

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 2002; Van der Werf 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

Table 37.8 Resource Intensities by Household Activity

	Units	*HP*	*DIY*	*COM*	*VW*	*EDU*	*PR*	*SOC*	*LEIS*	*CFO*
$\varepsilon_{\$}^{act}$	t/DM	43.0	32.1	22.0	29.8	23.1	30.6	25.9	33.4	37.5
	rk	9	6	1	4	2	5	3	7	8
ε_{time}^{act}	t/h	141.3	129.4	49.8	25.0	20.9	38.0	30.3	54.4	48.4
	rk	9	8	6	2	1	4	3	7	5
ε_{hpi}^{act}	DM/h	3.5	4.3	2.3	0.9	0.9	1.3	1.2	1.7	1.3
	rk	8	9	7	1	2	4	3	6	5

consumption expenditure per unit of time or vice versa. We will henceforth call these coefficients *household production input intensities*, denoted by ε_{hpi}^{act}.

Table 37.8 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 37.7 and Fig. 37.5), 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 that 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 socializing, 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.

Some Further Extensions of the Consumer-Lifestyle Approach

By going back to Fig. 37.5 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 is apply theoretical 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. 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 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. In line with hedonistic explanations of daily life, people do what they say like to do.

This *hedonistic model* can, for example, explain many of the major shifts in activity patterns in the U.S. between 1965 and 1995.[13] Table 37.9 shows such ratings provided on a scale between 0 (dislike) and 10 (like a lot), aggregated into our four main activity fields for the year 1985.

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,[14] this would

Table 37.9 Subjective Enjoyment Ratings for the Four Main Activity Fields

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

[13] 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!

[14] 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).

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 of preparing the meal at home and having to do the washing-up afterwards. 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; Jalas 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 Table 37.4 it was already shown 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 37.10, which again combines data from Germany and the U.S.

It should be clear that our table assumes 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

Table 37.10 Enjoyment Associated with Activity Pattern of Different Socio-economic Groups

	Ø	<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

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 labor 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".

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 representing 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.

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Chapter 38
The Application of Multi-regional Input-Output Analysis to Industrial Ecology
Evaluating Trans-Boundary Environmental Impacts

Glen P. Peters and Edgar G. Hertwich

Introduction

Consumption causes environmental impacts in two different ways. Direct environmental impacts result from consumption when consumers directly burn fossil fuels; for instance, from the petrol used for personal transportation or wood used for space heating. Significant environmental impacts also occur indirectly in the production of consumable goods. When production occurs in the same country as consumption, then government policy can be used to regulate environmental impacts. However, increasing competition from imported products has led to a large share of production occurring in a different country to consumption. Regulating the resulting pollution embodied in trade is becoming critical to stem global pollution levels. Due to increased globalization of production networks, there is increasing interest in the effects of trade on the environment (Jayadevappa and Chhatre 2000; Copeland and Taylor 2003).

With the increased interest in trade and the environment research activity is focusing on methods of accurately calculating the pollution embodied in traded products. Early studies in this area assumed that imports were produced with the same technology as the domestic economy (e.g. Wyckoff and Roop 1994; Lenzen 1998; Kondo et al. 1998; Battjes et al. 1998; Machado et al. 2001), however, using this assumption large errors may result when the countries have diverging technology and energy mixes (Lenzen et al. 2004; Peters and Hertwich 2006a, c).[1] This stimulated research in the use of multi-regional input-output (MRIO) models.

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[1] Similar conclusions are found in the economic literature on factors (labor and capital) embodied in trade (Hakura 2001).

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While MRIO models have been applied to regional economics since the 1950s (Miller and Blair 1985), applications to environmental problems has only recently emerged (Chung and Rhee 2001; Ahmad and Wyckoff 2003; Lenzen et al. 2004; Nijdam et al. 2005; Peters and Hertwich 2006a, b; Guan and Hubacek 2007). These studies are finding large portions of pollution embodied in trade. For instance, Ahmad and Wyckoff, 2003 found that the emissions embodied in trade was on average 14% in OECD countries and over 50% in some OECD countries; they included data covering 80% of global emissions and use "conservative" assumptions to obtain a lower bound. Further, Ahmad and Wyckoff, 2003 found that "emissions embodied in international trade are important, growing, and likely to continue to grow".

In this article we discuss the theory behind MRIO models for applications in industrial ecology (IE; section "Multi-regional Input-Output Analysis [MRIO]") and discuss common modeling assumptions (section "Common Assumptions in MRIO"). Most MRIO models require a considerable amount of data and we discuss many of the practical data issues that are encountered in MRIO modeling (section "Practical Issues"). In section "Applications and Policy Implications for MRIO in IE" we briefly review the main applications of MRIO in the field of IE and finally we discuss the potential for increased use of MRIO models in IE (section "Future Applications of MRIO in IE").

Multi-regional Input-Output Analysis (MRIO)

Using IOA the total output of the domestic economy is given by

$$x = Ax + y \tag{38.1}$$

where A is the total interindustry requirements and y is the total net demand on the economy,

$$y = y^d + y^{ex} - m \tag{38.2}$$

where y^d are the products produced and consumed domestically, y^{ex} are the products produced domestically, but consumed in foreign regions (exports), and m are the products consumed domestically for both final and intermediate consumption, but produced in foreign regions (total imports). In this form, (38.1) is not suitable for applying arbitrary demands since imports are embedded in both A and y (Dietzenbacher et al. 2005).

It is possible to separate the domestic and imported components in A and y to obtain

$$x = (A^d + A^{im})x + y^d + y^{ex} + y^{im} - m \tag{38.3}$$

where A^d is the industry requirements of domestically produced products per unit output, A^{im} is the industry requirements of imported products per unit output, and y^{im} is the final demand of imports (United Nations 1999). A balance must hold for the total imports,

$$m = A^{im}x + y^{im} \tag{38.4}$$

and thus (38.1) can be reduced to domestic activity only,

$$x = A^d x + y^d + y^{ex} = A^d x + y^t \tag{38.5}$$

Using the linearity assumption of IOA, it follows that the output of the domestic economy for an arbitrary demand is

$$x^* = (I - A^d)^{-1} y^* \tag{38.6}$$

where y^* could represent household demand, government demand, a unit demand on a particular sector, and so on. Given the domestic output, the requirement of imports by industry to produce y^* are given by $A^{im} x^*$. This import may instigate a series of feedbacks through trade flows and is discussed further below.

Using the direct multiplier for environmental impacts[2] per unit output, F, the environmental impacts embodied in domestic consumption are,

$$f^* = F(I - A^d)^{-1} y^* \tag{38.7}$$

This equation does not include the environmental impacts that may occur in foreign regions due to imports.

Particularly for environmental impacts with global implications, such as global warming, it is important to calculate the global environmental impacts for production and consumption. Imports are generally produced in countries with different production technologies and energy mixes compared to the domestic economy. This suggests that a multi-regional model is required to correctly evaluate the pollution embodied in traded products. When trade is allowed between two or more countries trade feedbacks may occur so that production in one country, may require some of its own production via feedback loops (see Fig. 38.1a). This type of interaction can be analyzed using MRIO.

An MRIO model extends the standard IO matrix to a larger system where each industry in each country has a separate row and column. If there are m regions then the extended IO matrix becomes[3]

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \dots & A_{1m} \\ A_{21} & A_{22} & A_{23} & \dots & A_{2m} \\ A_{31} & A_{32} & A_{33} & \dots & A_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & A_{m3} & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{m1} \end{pmatrix} \tag{38.8}$$

[2] The same equation applies for the standard economic factors of production such as labor and capital.

[3] Peters and Hertwich (2004) build the MRIO equations from a two-region system and is useful for those that may require a more detailed description of how the equations are derived.

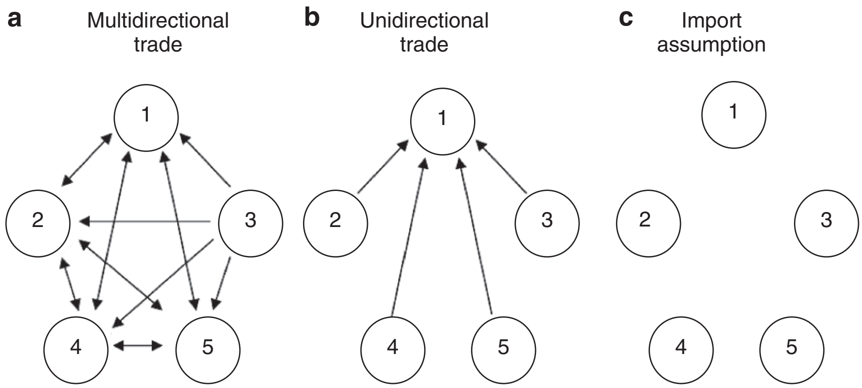

Fig. 38.1 A Schematic Representation of the Three Trade Scenarios for a Five Region Model (Lenzen et al. [2004])

Table 38.1 The Notation Used for the MRIO Model

Name	Description
x_i	Output of region i
y_{ii}	Final demand for goods produced and consumed in i
y_{ij}	Final demand from region i to region j
$y_i^{ex} = \sum_{j=1,j\neq i}^{m} y_{ij}$	Total final demand exports from region i
A_{ii}	Interindustry requirements on domestic production in region i
A_{ij}	Interindustry requirements from region i to j
$A_i = \sum_j A_{ij}$	Total interindustry requirements in region i
$m_{ij} = A_{ij}x_j + y_{ij}$	Total trade from region i to region j
F_i	Direct factor requirements in region i

The notation is described in Table 38.1. We have simplified the system by centering the model on the domestic economy, $i = 1$. Due to symmetry, any region can be considered as the domestic economy by re-labeling it as region 1. The block matrices of the extended IO table represent the global technology. The diagonal block matrices represent domestic interindustry requirements and the off-diagonal elements represent the interindustry requirements of traded products.

For some it may be easier to understand the MRIO model with separate equations. The output in the domestic economy is

$$x_1 = A_{11}x_1 + y_{11} + \underbrace{\sum_{j\neq 1}\left(A_{1j}x_j + y_{1j}\right)}_{\text{exports}} \quad \text{for } i = 1 \tag{38.9}$$

where the export terms are all exports from region 1 to interindustry and final demand in all other regions. The outputs in the other regions are,

$$x_i = A_{ii}x_i + \underbrace{\sum_{j \neq i} A_{ij}x_j + y_{i1}}_{\text{exports}} \quad \text{for all } i \neq 1 \tag{38.10}$$

Since region 1 is treated as the domestic economy, the final demands y_{i1} are imports to region 1.

For a given consumption bundle, y_{i1}, in region 1 the environmental impacts occurring in each region to produce y_{i1} are given by $F_i x_i$ and the global environmental impact are,

$$f = \sum_i F_i x_i \tag{38.11}$$

where F_i are the direct pollution intensities in region i.

Common Assumptions in MRIO

To perform an MRIO study requires a considerable amount of data, much of which is not directly available. Consequently, most current applications of environmental MRIO have applied some approximations to (38.8). In this section we discuss various approximations and simplifications that have been used in environmental MRIO. The following is largely based on Ahmad and Wyckoff (2003), Lenzen et al. (2004), Peters and Hertwich (2004), Nijdam et al. (2005), and Peters and Hertwich (2006a, b). Practical issues associated with data availability and handling are discussed in section "Practical Issues".

Uni-directional Trade

If it is assumed that the domestic economy trades with all regions, but the other regions do not trade amongst each other (see Fig. 38.1b), then the data requirements are greatly reduced without introducing large errors. Lenzen et al. (2004) found these effects to be around 1–4% (see their Table 7) and these terms are often assumed to be negligible in other regional models (Round 2001).

Mathematically, the uni-directional trade assumption reduces (38.8) to,

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & 0 & 0 & \dots & 0 \\ A_{21} & A_{22} & 0 & \dots & 0 \\ A_{31} & 0 & A_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{m1} & 0 & 0 & \dots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + y_1^{ex} \\ y_{21} \\ y_{31} \\ \vdots \\ y_{m1} \end{pmatrix} \tag{38.12}$$

Since this assumption reduces many of the feedback loops, the equation can be solved directly to obtain,

$$x_1 = (I - A_{11})^{-1} \left(y_{11} + y_1^{ex} \right) \tag{38.13}$$

for the domestic economy and the output in the other regions are

$$x_i = (I - A_{ii})^{-1} M_i \qquad \text{for} \quad i > 1 \tag{38.14}$$

where

$$M_i = A_{i1} x_1 + y_{i1} \tag{38.15}$$

The exports term y_1^{ex} now includes both exports to final demand and exports to industry. This approach has been applied by Nijdam et al. (2005), and Peters and Hertwich (2006a, b).

If only analyzing the total final demand on an economy, the uni-directional trade assumption does not require A_{ij}. If the total final demand is used, then (38.15) gives the total imports into the domestic economy and so M_i can be obtained directly from IO or trade data.

The assumption of uni-directional trade gives two options for the diagonal terms of the foreign regions. If $A_{ii}, i > 1$ is placed on the diagonal, then multi-directional trade is totally neglected. Alternatively, if $A_i, i > 1$ is placed on the diagonal, then multi-directional trade is included, but with the assumption that imports are produced with domestic technology (see section "Import Assumption"). However, the country that is allocated the emissions for the production of the imports will be incorrect. Due to data availability, countries may only supply A_i in which case it is implicitly assumed that multi-directional trade is included using domestic technology.

Import Assumption

A common assumption is that imports are produced with domestic production technology (Fig. 38.1c). The import assumption has also been called "autonomous regions" by Lenzen et al. (2004) and "mirrored economy" by Strømman and Gauteplass (2004). The assumption greatly reduces data requirements, but may lead to large errors. Lenzen et al. (2004) found the error between the import assumption and multi-directional trade for Danish CO_2 emissions to be 20–50% depending on the final demand. Peters and Hertwich (2006a) found the difference between the import assumption and uni-directional trade for Norwegian household consumption to be a factor of 2.7 for CO_2, 9.7 for SO_2, and 1.5 for NO_x. Most IO studies of environmental issues apply the import assumption and so it is likely that many of these studies incorrectly calculate the emissions associated with the production of imports.

One way to apply the import assumption is to assume $A_{ii} = A_{11}$, $A_{ij} = A_{i1}$, and $F_i = F_1$ and then substitute into (38.8). Simplification then results in,

$$x_i = (I - A_1)^{-1} y_i \tag{38.16}$$

where y_i is the final demand placed on each region (Peters and Hertwich, 2004). This equation gives the emissions in each region, including imports to industry, but it assumes they have the same production technology as the domestic economy and allocates the embodied emissions to the domestic economy. The correct allocation can be obtained by using (38.8), but with substitution of $A_{ii} = A_{11}$ and $A_{ij} = A_{i1}$.

Others

Some approaches have been slightly different to what is outlined above. Ahmad and Wyckoff (2003) do not use the matrix based approach we have described above, but use an iterative procedure which approximates the matrix solution. Lenzen et al. (2004) replace each of the block matrices with a make and use block which displays additional structure, but applies an industry-technology assumption on solution. Methods not using IOA to estimate pollution embodied in trade often neglect indirect emissions in the production chain and are consequently not considered in this article.

Practical Issues

A significant amount of data from a variety of sources is required to perform an MRIO study. As a consequence several practical issues arise in the data manipulation phase. This section briefly discusses the main areas of concern. Lenzen et al. (2004) also give a detailed discussion of some of these issues.

General Data Availability

To perform a detailed MRIO study IO data is essentially required for every country. This data is generally available for most OECD countries, but for relatively few non-OECD countries. Most EU countries submit data to Eurostat in a consistent format. The USA, Canada, and Australia regularly compile IO data but using different classifications. The data availability in non-OECD countries is sparse and often for major non-OECD countries only. Some data projects have attempted to build large IO databases for global models. The Global Trade, Assistance, and Production project (GTAP; version 6) provides data for 87 world regions in 57 sector detail (Dimaranan and McDougall 2006).[4]

Emissions data is often available for countries that supply IO data, but in many cases the data needs separate construction. Energy data can be used to construct some air emissions data (e.g., Ahmad and Wyckoff 2003; Dimaranan and McDougall 2006) alternatively, additional data work may be required (e.g., Suh 2005; Guan and Hubacek 2007). Care needs to be taken with energy and environmental data from some sources as they may have a different system boundary to the IO data (Gravgård Pedersen and de Haan 2006; Peters and Hertwich 2006c). Energy and emissions data are often constructed according to "national territory", while IO data are constructed according to "resident institutional units". Resident institutional units may operate and pollute outside national territory, but are still a part of the domestic economy. The main differences between the two definitions are for international transportation and tourist activities. For Denmark in 2001 the differences between the two definitions were 23% for CO_2, 93% for SO_2 and 72% for NO_x (Gravgård Pedersen and de Haan 2006). For Norway in 2000 the difference was 25% for CO_2 (Peters and Hertwich 2006c).

Trade data is available from several sources, but generally trade data has missing data and mismatches. This requires addition processing and cross-checking for consistency (e.g., Dimaranan and McDougall 2006). Import and export data often do not match due to different pricing conventions and errors in reporting. If traded goods between two countries go through a third country then allocation problems often arise.

Grouping of Like Regions

Two approaches have been used in the past to fill in for missing IO data. A first approach is to allocate the countries without IO data the IO data of a "representative" country. Ahmad and Wyckoff (2003) used the United States of America and Lenzen et al. (2004) used Australia as the representative country. Another approach is to collect IO data for the most significant trading partners and then allocate the minor trading partners to one of the major trading partners to make larger aggregated regions with fixed technology. This approach was applied by Peters and Hertwich (2006a, b) and the allocation was performed based on energy use per capita, CO_2 emissions per capita, and gross domestic product per capita. If the major trading partners represent a diverse range of economies, then the second approach is likely to give a better approximation. In both approaches, it is also possible to adjust emission coefficients if the data is available; for example, when allocating

[4] While the GTAP database is extensive, it must be noted that it is not always the most up to date and accurate data available. The data for individual regions is usually submitted by users of the data and consequently data is sometimes not updated with new versions of the database. The database also has a strong emphasis on food and agriculture.

emissions data between countries Ahmad and Wyckoff (2003) adjusted the emission coefficient for electricity production based on other reliable data sources (also see Battjes et al. 1998).

Using Trade Shares to Estimate A_{ij}

Data on A_{ij} and y_{ij} is generally not directly available; however, many countries construct $A_i^{im} = \sum_{j \neq i} A_{ij}$ and $y_i^{im} = \sum_{j \neq i} y_{ij}$. Using A_i^{im} together with trade flow data it is possible to estimate the share of trade flows to final demand and industry in each region using

$$A_{ij} = \hat{s}_{ij} A_i^{im} \tag{38.17}$$

and

$$y_{ij} = \hat{s}_{ij} y_i^{im} \tag{38.18}$$

where

$$\{s_{ij}\}_k = \frac{\{m_{ij}\}_k}{\{\sum_i m_{ij}\}_k} \tag{38.19}$$

where $\{m_{ij}\}_k$ is the total imports of product k from region i to j. It is important to consider the trade shares in individual sectors and not the average of all sectors. More details on using trade shares to estimate A_{ij} can be found in Lenzen et al. (2004).

Exchange Rates

In an MRIO model, exchange rates are needed to link the data from different regions to a common currency. There has been considerable debate in the climate change literature about the use of Purchasing Power Parities (PPP) or Market Exchange Rates (MER) in currency conversation (Castles and Henderson 2003; Grübler et al. 2004; Nordhaus 2006). The MER is calculated based on traded products, while the PPP is calculated based on a bundle of consumed products; both traded and non-traded. The PPP rates give a better measure of income levels across different countries. Much of the debate about PPP and MER has been based on the comparison of income levels and not a comparison of traded products. Since MRIO models focus on traded products we suggest the use of MERs to obtain a common currency. It is possible to avoid the exchange rate problems by using physical units for key sectors; however, data in physical units requires additional data issues, particularly availability.

Inflation

The data covering a variety of regions is likely to come from various time periods. Adjustments for inflation are required to make the data consistent for a given base year. The easiest approach is to use the Consumer Price Index (CPI) in each country to adjust for inflation. However, the CPI is likely to introduce other errors. The CPI is an aggregated index, while price changes are likely to be different in each of the IO sectors. Further, the CPI also varies depending on the base year used and the method of indexing applied. These issues are difficult to resolve and the errors will be greater for a large CPI and when there is a big difference in base years.

Product or Industry Classifications

It is possible to perform IOA using a product classification or an industry classification. Through the make and use system it is possible to transfer between the two using the make matrix. The emissions data is usually in an industry classification and the final demand, depending on the application, will be either an industry or product classification. Consequently, for some studies there will be a need to map between the industry and product classifications. Given that the emissions data is always in an industry classification and IO tables are often only supplied in an industry classification we suggest using industry classifications as this requires less data manipulations. This would imply mapping the final demands in a product classification into the industry classification using the make matrix.

Re-classifying Data

The IO data from different regions is often in different classification systems. To perform the analysis requires mapping the data, at some stage, to a consistent classification. For some classifications it is possible to obtain correspondence tables, otherwise, the correspondence tables need to be constructed by referring to the different classification descriptions. Often, the classification systems do not have a direct correspondence between sectors and while the classification definitions can be used as a guide, re-classification will nearly always introduce errors of unknown size.

Another issue is that some data is collected based on entirely different conceptual framework. For example, IO data in an industry classification is based on industries being the smallest unit, while consumer expenditure survey data is collected on the basis of products and functions being the smallest unit (the classification of individual consumption by purpose [COICOP] is a good example). Mapping between products or functions and industries is difficult implying that several assumption and approximations are required. In some cases checks can be applied. For example, when mapping consumer expenditure data to an industry classification, it is possible to ensure that a rough balance is obtained at the sector level between the mapped expenditure data and the household expenditure from the IO tables.

Aggregation

In the MRIO setting, Lenzen et al. (2004) show the importance of aggregation errors with the broad conclusion that the data should be in the highest detail available. Thus, a global MRIO with ten-sector aggregation, for example, may produce unreliable results.

Valuation

IO data is often available in three levels of valuation; basic, producer, or purchaser (retail) prices. The different valuations differ in the trade and transport margins, and taxes and subsidies; producer = basic + taxes – subsidies, purchaser = producer + margins. Typically margins and taxes are applied at different rates in different sectors and on different products. Even across the same product, margins and taxes can differ for a variety of reasons such as, different mark-ups, different modes of transport, different levels of taxation, bulk discounts, different recording principles, and so on (United Nations, 1999). For these reasons it is more homogenous to work in basic prices as they are more representative of the production value of a product compared to the market value.

Unfortunately, not all IO data is available in basic prices. Estimation can be used to adjust the IO data to the required valuation, but without the detailed data in each sector, the possibility for introducing large errors is considerable. Due to data availability, it is likely to be easier to convert the final demand to a new valuation compared to the IO data. In practice, if data is not available in the necessary valuation, it may be best to report the valuation of the data and emphasis that it will either under- or over-estimate the environmental impacts depending on the valuation used.

An addition problem arises in the valuation of trade data. Exports are usually presented as free on board (fob) and imports as cost, insurance, freight (cif). For consistency, the imports need to be converted to basic prices. Lenzen et al. 2004 use economy wide fob/cif ratios and then balance the resulting MRIO table using a RAS technique.

Marginal Technology

It can be argued that the regional technology differences are not relevant in some studies. Instead, any expanded production will occur with marginal technology

(Weidema et al. 1999; Ekvall and Weidema 2004). If modeling past flows, then the technology used in production is required. In the modeling of future scenarios it is important to consider the likely technology mix and emissions coefficients in the future; in this case, marginal technologies may be preferred. A possible alternative is to consider the energy embodied in trade as the energy intensities are less dependent on the fuel mix (Peters and Hertwich 2005a).

Errors

Errors can enter into the calculations in many ways. The IO data and factor use intensities always have an error associated with them (e.g., Rypdal and Zhang 2000; Lenzen 2001). Errors also arise in the adjustments for currency conversions, inflation, different sector classifications, aggregation, and so on. The magnitude of these errors is often difficult to estimate, but the errors still need to be considered (Morgan and Henrion 1990). Ideally, some sort of error analysis should be performed or the potential magnitude of uncertainties discussed.

Applications and Policy Implications for MRIO in IE

Generally, there are three scales of interest in consumption related issues; national, regional, and local (Munksgaard et al. 2005). In the context of this article we will consider two scales; total demand (national and global) and arbitrary demand (regional and local). Most applications of MRIO have been to address global issues of pollution embodied in trade. Only recently have MRIO studies considered arbitrary demands. In this section, we outline the main applications of MRIO in the field of IE. We do not consider studies that have modeled similar questions, but using single region models with the import assumption.

Trans-boundary Pollution

The main motivation for the studies by Chung and Rhee (2001), Ahmad and Wyckoff (2003), Lenzen et al. (2004), and Peters and Hertwich (2006c) was to evaluate pollution embodied in trade at the national level and to determine the different environmental impacts of consumption versus production and its implications to global climate change policy (Kondo et al. 1998; Munksgaard and Pedersen 2001; Bastianoni et al. 2004). These studies generally found a large portion of CO_2 emissions embodied in trade. The most comprehensive study, Ahmad and Wyckoff (2003) found that the CO_2 emissions embodied in imports in some OECD countries was over 50% and on average 14% of OECD CO_2 emissions were embodied in imports. However, the authors used conservative assumption such as not including services trade, excluding process emissions, and intentionally making assumptions that led to a lower bound. It is likely that these numbers are larger in reality. Lenzen et al. (2004) found that 66% of Danish domestic CO_2 emissions in 1997 were embodied in imports which is considerably greater than the value of 36% found by Ahmad and Wyckoff (2003). Peters and Hertwich (2006c) found that 67% of Norwegian domestic CO_2 emissions in 2000 were embodied in imports which is similar to the value of 54% found by Ahmad and Wyckoff (2003) for 1997. The reason for the differences are unknown, but may be since Ahmad and Wyckoff (2003) used different assumptions and data set. Chung and Rhee (2001) used an MRIO for trade between Japan and Korea, but they did not consider the pollution embodied in imports from outside of Japan and Korea. Their study has a regional focus for trade between Japan and Korea, but not on the global implications.

Guan and Hubacek (2007) consider virtual water flows[5] between south and north China using an MRIO model. They found that the water scarce north exports large quantities of virtual water to the relatively water abundant south. Guan and Hubacek (2007) go on to show that this contradicts the standard theory of comparative advantage; often referred to as the "Leontief paradox". This highlights the wider applications of MRIO models to any factor of production embodied in trade (also see Hakura 2001).

Arbitrary Demands

The studies (Nijdam et al. 2005; Peters and Hertwich, 2005b, 2006a) focus on the implication of imports for household environmental impacts (HEI). Both use MRIO models with uni-directional trade only, Nijdam et al. (2005) consider nine environmental indicators for Dutch household consumption, while Peters and Hertwich (2005b; 2006a) consider CO_2, SO_2, and NO_x emissions for different Norwegian final demands. Both studies found that large fractions of HEI are embodied in imports directly to households and imports to domestic industries as inputs to produce domestic household demand. Except for traffic noise (Dutch study) and NO_x (Norwegian study) over 50% of the measured global HEI were embodied in imports; greenhouse gases were around 50% in both cases. In many cases the environmental impacts from developing countries was most significant, particularly considering the smaller share of imports coming from those regions. Both studies reinforced the overall importance of mobility and food in HEI (cf. Hertwich 2005), but found increased importance of consumable items due to imports. The Norwegian study found that for food, business services, clothing, chemicals, furniture, cars, agriculture, textiles, and most manufactured goods the majority of emissions occurred in foreign regions.

[5] Guan and Hubacek (2007) refer to embedded water content as "virtual water".

The study by Peters and Hertwich (2006b) considered the importance of imports for the global CO_2, SO_2, and NO_x emissions of Norwegian household, government, and exported final demands. The article considered the final demands from a consumption perspective, production perspective, and used structural path analysis to analyze the trade linkages between consumption and production. The main empirical conclusion from this study was that a large portion of CO_2, SO_2, and NO_x emissions of the Norwegian economy can be traced back to electricity production, primarily by coal, and other energy intensive industries in developing countries. Further, the different methods of analysis were found to be relevant for different policy applications. The article highlights, for global pollutants in particular, that policy needs to address the environmental implications of imports.

Future Applications of MRIO in IE

There is significant scope for MRIO models to be applied to many areas in IE.[6] Most recent MRIO studies have focused on global issues or aggregated final demands such as total household consumption. With the current importance of globalization, MRIO models will find application in many other areas in IE. A direct extension of the current MRIO models is to focus on particular products, processes, or consumption. Hybrid Life Cycle Assessment (LCA; Suh et al. 2004) already uses IO data to increase system completeness and it is also possible to extend these models further using MRIO data. Similarly, the MRIO studies of households can be extended to include socioeconomic analysis of import behavior in households. An area that is yet to utilize MRIO models is Material Flow Analysis (MFA) and the study of "hidden flows". An extension in this area is possible given the material use intensity in the relevant economic sectors.

In the future, it is likely that global issues will continually be explored using MRIO analysis. Given the interconnectedness of the global economic system, it is important to analyze environmental problems through the global system. Since MRIO models are based on the IO framework, many IO techniques can be applied to study global production structures (e.g., Lenzen 2003; Peters and Hertwich 2006b). This gives considerable insight into the importance of both domestic and global trade flows for various environmental problems. It is also possible to apply MRIO models to the traditional economic factors of production such as labor and capital (Hakura 2001). Combining these studies allows an analysis of the eco-efficiency along the global production network to compare the environmental impacts to the value added of different products (Clift and Wright 2000). Using these methods it is possible to determine if, for instance, developing countries are faced with high environmental burdens for low value added.

[6] Suh and Kagawa (2005) and Gravgård Pedersen and de Haan (2006) give general overviews of IOA applied in IE.

Currently, the main obstacle to increased use of MRIO models is data availability and consistency. There is potential to use current data sets, such as GTAP or OECD IO data, or to build more refined data for specific regions, such as using the Eurostat IO database for a regional model of the EU. Data on environmental impacts is less wide-spread. However, with a concerted effort, many of the current data obstacles can be negotiated. Given that several international bodies already collect large amounts of the data required for MRIO studies, it makes sense to maintain an MRIO database through one of these agencies. With a maintained database MRIO models can be applied directly by all countries through the interconnectedness of the model, Fig. 38.1a).

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