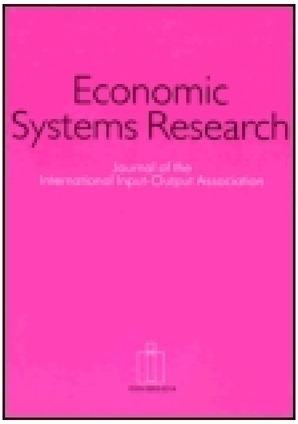

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EDITORIAL: CARBON FOOTPRINT AND INPUT-OUTPUT ANALYSIS - AN INTRODUCTION

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EDITORIAL: CARBON FOOTPRINT AND INPUT–OUTPUT ANALYSIS – AN INTRODUCTION

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This editorial is the introduction to a special issue of *Economic Systems Research* on the topic of carbon footprint and input–output analysis. It provides a brief historical context of the involvement of input–output analysis with applications in environmental research and makes the link to carbon footprint theory and practice. The six papers in this issue are briefly introduced. The aim of the special issue is to bring together the academic world of rigorous economic modelling and the practice of greenhouse gas accounting at various levels.

Keywords: Carbon footprint; Input–output analysis; Greenhouse gas accounting

1 THE AIM OF THIS SPECIAL ISSUE

This special issue of *Economic Systems Research* is devoted to the application of input–output analysis to carbon footprinting. It aims to bring together the academic world of rigorous economic modelling and the practice, sometimes even the politics, of greenhouse gas accounting at various levels. It comes at a time when the world is waiting for global agreement on climate change, when the awareness of the threats of global warming and the complexity and difficulty of tackling it are significant and when there is an increased demand for meaningful and robust quantification models and indicators.

The authors for this special issue have been asked to present their methods and findings in a way that is comprehensible and meaningful to non-input–output specialists, carbon footprint practitioners, or readers generally interested in methods and applications of carbon accounting. The main text of the articles has therefore been kept less technical, although the methodological foundations can still be found in either the appendices or in referenced, peer-reviewed publications.

Carbon footprinting – an attempt to capture the full amount of greenhouse gas emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product – needs economic input–output analysis.[1] Many would question such a statement and, indeed, carbon footprint analysis has been predominantly based on

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[1] The discussion in this special issue is predominantly related to monetary (economic) input–output analysis, although other forms of input–output analysis using hybrid units or pure physical values may just as well contribute to carbon footprinting.

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non-input–output methods and applied on a large scale. The articles in this special issue, however, show that input–output analysis can contribute substantially, if not decisively, to the practice of carbon footprinting at all levels.

This is not new. Countless scientific publications have impressively demonstrated the ability of input–output analysis to support the quantification of environmental impacts of economic activities. A recent and comprehensive example is the *Handbook of Input–Output Economics in Industrial Ecology* (Suh, 2009), which followed a special issue of ESR in 2005 (Suh and Kagawa, 2005). It is this particular focus on input–output assisted carbon footprinting as a subject that is politically and economically relevant, from national greenhouse gas footprints down to product carbon labelling, that makes this issue of *Economic Systems Research* special.

The purpose of the next section is to portray past developments in order to put the present situation into historical context. This is followed by a section that briefly introduces the contributions to this special issue, and by some concluding remarks.

2 AN INTRIGUING COMBINATION WITH HISTORICAL PRECURSORS

The combination of input–output analysis and carbon footprint practice is an intriguing one for various reasons. It is an amalgam of ‘old’ and ‘new’, of ‘economy’ and ‘environment’, of ‘top-down’ and ‘bottom-up’, even of ‘science’ and ‘policy’. On the one hand there is input–output analysis as an economic modelling technique that aims to understand the interactions between economic sectors, producers and consumers. Principally formulated by Wassily Leontief in the 1930s, economic input–output analysis has been used ever since in countless applications addressing questions on economy, labour, social issues, trade, energy, ecology, resource use, industrial ecology and environmental science. The compilation of input–output tables of national and regional economies is now a routine practice governed by a UN standard. Thousands of analysts and researchers use analytical input–output techniques, and Leontief received the Nobel Prize for Economic Science in 1973 for the development of the input–output methodology and its application to important economic issues.

The term carbon footprint, on the other hand, has only emerged into the public domain in the last few years as a rather general description of the total greenhouse gas emissions associated with human activity. An exact origin of the expression cannot be found in the scientific literature but it is reasonable to assume that it was derived from the Ecological Footprint concept formulated in the 1990s (Wackernagel and Rees, 1996). Driven by a widespread use in the media and the public in general, ‘carbon footprint’ has now become a synonym for the climate change impact of individuals, communities, nations, companies, or products. It seems that the academic world has yet to catch up with this rapid deployment of an expression for which it is still debating a precise definition (see, for example, Wiedmann and Minx, 2008; Finkbeiner, 2009).

As a consequence, there is much debate about the methodology for carbon footprint analysis. A ‘footprint’ indicator should, by its nature, encompass all ‘traces’ that an activity leaves behind – in the case of a carbon footprint, all greenhouse gas emissions that can be associated directly and indirectly with this activity. Methodologically, this ‘full life-cycle perspective’ has been addressed from two directions: bottom-up, based on process analysis (PA), and top-down, based on (environmental) input–output analysis

(IOA). PA has been developed to understand the environmental impacts of individual products from 'cradle to grave'. Using specific primary and secondary process data, this approach can achieve results with high precision for defined products, but has to set a system boundary and thus leads to truncation errors of unknown size. Due to the particular data requirements, PA is generally a cost and labour-intensive task.

Environmentally extended input–output analysis provides an alternative, economy-wide approach, making system cut-offs unnecessary. It is appropriate for larger entities such as product groups, companies or countries. Its suitability for assessing the impacts of individual products or processes is limited, however, as it assumes homogeneity of prices, outputs and their carbon emissions at the sector level. Once a suitable input–output model has been set up, a number of analyses can be carried out in a resource-efficient way.

Both methods have been used for carbon footprinting. The importance of employing an all-encompassing approach to avoid the underestimation of carbon emissions for providing products and services has been demonstrated by Matthews et al. (2008). Arguably the best option for a detailed, yet comprehensive and robust carbon footprint analysis is therefore to combine the strengths of both methods by using a hybrid approach where PA and IOA are integrated (Minx et al., 2008b). Such a hybrid life cycle assessment (Hybrid LCA) approach allows the preservation of the detail and accuracy of bottom-up approaches in important processes while the majority of less significant production steps can be covered by the input–output part of the model. The decision on which production pathways are to be seen as significant or important can be aided by an upfront screening of carbon impacts based on pure input–output analysis. Depending on the application, the ratio of process versus input–output analysis will vary in order to achieve an optimum between accuracy, precision and cost efficiency.

These considerations are currently under debate in the ongoing standardisation process for carbon footprinting. The first standard for products, the PAS 2050 developed under the auspices of the Carbon Trust, the UK Department for Environment, Food and Rural Affairs, and the British Standards Institution, was published in 2008 (BSI, 2008, see also Sinden, 2009). It is based on a process life cycle assessment (LCA) method; input–output analysis plays a negligible role, even though a methodological review of the PAS 2050 concluded that 'The method most suited to meet the needs of the PAS various applications [. . .] is a fully integrated [. . .] Hybrid LCA approach' (Minx et al., 2008b, p. 26) and recommended that the 'PAS development should be redirected from a process life cycle assessment approach towards a (matrix-based) Hybrid LCA approach' (Minx et al., 2008b, p 72).

Two other major standardisation efforts are ongoing:[2]

- The World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) are guiding the development of two new standards under their Greenhouse Gas Protocol initiative: A Product Life Cycle Accounting and Reporting Standard and a Corporate (Scope 3/Supply Chain) Accounting and Reporting Standard (WRI and WBCSD, 2009).

[2] More initiatives have been launched by UNEP/SETAC, individual countries and industries (see, for example, Finkbeiner, 2009).

- The International Organisation for Standardisation is developing ISO 14067 on the Carbon Footprint of Products (ISO, 2009) and a further standard on the carbon footprint of organisations is under discussion.

Both draft product standards stipulate the process method as the basic approach, but allow for the use of input–output data as secondary data under certain conditions. The draft corporate standard from WRI/WBSCD explicitly deals with all possible indirect emissions from an organisation, divided into different 'scopes'. Whereas scope 1 refers to direct emissions from sources that are owned or controlled by an organisation, scopes 2 and 3 refer to indirect emissions that occur outside of the organisation. Emissions from electricity generation fall under scope 2, whereas scope 3 is divided into upstream (supplier emissions; indirect emissions from purchased products), downstream (direct and indirect emissions from sold products) and other scope 3 emissions (employee commuting). Input–output analysis seems to play a slightly more prominent role here, as it has been recognised as being useful for estimating higher upstream emissions and filling gaps where primary data from (direct) suppliers is not available. The article by Y. Anny Huang et al. in this issue discusses the role of input–output analysis for the screening of sectoral and corporate carbon footprints by using the WRI/WBCSD draft corporate standard as an example (see below).

Interestingly, we are seeing history repeat itself. The current dispute about carbon footprinting methods, in particular the use of hybrid approaches, mirrors the discussions and developments in energy analysis in the 1970s and life cycle analysis in the 1990s. Leontief (1970) set the scene by proposing a mixed-unit input–output model that deals with the generation and abatement of pollution (under which greenhouse gases can be counted). Suh and Kagawa (2005, p. 352) see this as the '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'. Triggered by the oil price shock in 1973, attention turned to the dependency of the economy on energy resources and soon input–output analysis was used for energy analysis on its own (Herendeen, 1973; Wright, 1974) and increasingly in combination with process-based analysis (e.g. Bullard and Herendeen, 1975, Bullard et al., 1978, see also Chapman, 1974 and van Engelenburg et al., 1994, Wilting, 1996).

A similar development has taken place in life cycle assessment (LCA) where inputs, outputs and the potential environmental impacts of a product system throughout its life cycle are compiled and evaluated (ISO, 2006a, 2006b). Problems with boundary setting and truncation when analysing only selected, distinct processes have led to the introduction of input–output analysis and the application of Hybrid LCA approaches in various forms, beginning in the early 1990s. The study by Moriguchi et al. (1993) is widely seen as the first such approach; some further landmark publications are from Lave et al. (1995), Hendrickson et al. (1998), Joshi (1999), Matthews and Small (2000), Lenzen (2002), Heijungs and Suh (2002), Suh et al. (2004), Suh and Huppes (2005), Heijungs et al. (2006). Nowadays, Hybrid LCA is seen as the state of the art in product life cycle assessments, at least in academia. The *International Journal of Life Cycle Assessment* launched a section on input–output and Hybrid LCA in 2003 (Suh, 2003).

The same journal also introduced a section on carbon footprinting in 2009 (Finkbeiner, 2009), recognising that – whilst (a) the analysis of greenhouse gas emissions and the assessment of global warming impacts of product life cycles has always been part of

LCA and (b) climate change is not the only environmental problem – there is a specific and important case to answer as carbon footprint analysis raises new questions and challenges that have not previously been adequately addressed. Weidema et al. (2008) explain the popularity of carbon footprints by the broad appeal and the simplicity of the concept and the fact that it can easily be communicated. The authors see the potential in carbon footprinting as '. . .a good entry point for increasing consumer awareness and fostering discussions about the environmental impacts of products. This, in turn, facilitates the diffusion of life cycle thinking and LCA' (Weidema et al., 2008, p.6). Finkbeiner (2009) also acknowledges that carbon footprinting 'offers the potential to get life cycle approaches into organisations and decision making contexts which pure LCA did not reach yet. It may offer the opportunity to increase the audience and relevance of [the LCA] community and its journal' (Finkbeiner, 2009, p. 93).

This is where the input–output community is lagging behind. There is one central question to ask: why is input–output analysis not more widely accepted amongst non-IO specialists as a suitable contribution to carbon footprinting/accounting? It is certainly not for the lack of effort and enthusiasm of input–output researchers. Countless publications describe environmental applications, before and after the term 'carbon footprint' was coined, and special sections and topics at IIOA conferences bear witness to the deep involvement of academic input–output research with environmental issues. Two previous special issues of *ESR* were devoted to the subject area (Forssell and Polenske, 1998; Suh and Kagawa, 2005).

One recent and particularly large area of applications for input–output analysis in carbon footprinting is the accounting for greenhouse gas emissions from a consumption perspective on an individual, local, regional, or national level.[3] Several contributions in this special issue are devoted to national and international carbon footprint analyses (see below). In addition to the traditional approach of territorial emissions accounting, a consumption-based perspective (Munksgaard et al., 2009) opens up the possibility of extending the range of policy and research applications considerably. One opportunity, for example, is to assess the extent to which a relocation of production and associated shift of embodied emissions between countries has occurred (according to a wider definition of the term carbon leakage, see Peters, 2008b). For both producers and consumers (as individuals, companies and nations) are responsible for emissions and both have a joint responsibility to address the problem with determination. The burden of this responsibility must be shared; only then can a meaningful and comprehensive deal to cut global emissions be achieved. Again, input–output analysis offers solutions for sharing responsibility between producers and consumers (see, for example, Andrew and Forgie, 2008; Peters, 2008a; Lenzen et al., 2007; Rodrigues et al., 2006; Rodrigues and Domingos, 2008; Serrano and Dietzenbacher, 2008). The wider implications for climate policy that emerge from the possibility of using a consumption-perspective for greenhouse gas emissions, based on input–output analysis, have been well presented in Peters and Hertwich (2008), Hertwich and Peters (2009) and other publications by the same authors.

[3] Most recent examples include Andrew and Forgie (2008); Weber and Matthews (2008); Druckman and Jackson (2009); Minx et al. (2008a); Peters (2008a); Weber et al. (2008); Guan et al. (2009); Hertwich and Peters (2009); Kanemoto and Tonooka (2009); Larsen and Hertwich (2009); Moll and Watson (2009); Wiedmann et al. (2010); Wilting and Ros (2009).

Despite this politically important and wide-ranging field of applications in carbon footprinting there is still not a widespread acknowledgment of the potential for (hybrid) input–output analysis in other areas. Examples are corporate footprinting, which aims at capturing the economy-wide GHG impact of a company and product carbon footprinting, aimed at summarising the life-cycle-wide GHG emissions of a specific commodity. Returning to the question above, there must therefore be other barriers for this lack of recognition. One possible reason might be the relative initial complexity of implementing environmental input–output models. Specialist knowledge in economic *and* environmental theory and frameworks is required, the terminology might be more specialised and the input–output mechanism might be intuitively less accessible than the more practical mapping of process flows. Whether due to actual, practical problems or only perceived complexity, few practitioners have so far acquired the skills to carry out (hybrid) carbon footprint or life cycle assessments. Once established, input–output tools are easy to operate and require relatively little data input compared with bottom-up approaches. Although such tools have been created over the last few years for the purpose of LCA or carbon footprinting, they are not as widely established and used as tools based on process analysis. This might be to do with a lack of integration with the latter type of tools or simply with insufficient marketing.

Possibly an even more important barrier for the acceptance of input–output analysis in (product) carbon footprinting is the perceived uncertainty of input–output calculations. It is often argued by practitioners using process analysis that the aggregation uncertainty in input–output analysis is likely to lead to less accurate (and certainly less precise) results than the uncertainty introduced by truncation in process analysis. In reality, it depends on the product considered and the particular type of data and model used to derive the estimate. Williams et al. (2009) present a very thorough review of all types of uncertainty associated with the compilation of life cycle inventory data. They argue that a holistic approach is needed and propose a hybrid approach to assessing and managing uncertainty and variability, because process-based and input–output approaches have qualitatively different uncertainty profiles. Cut-off or truncation error due to excluded processes cannot be estimated using only a bottom-up model and aggregation uncertainty in input–output frameworks can only be judged by comparing the results with process-based data.

It is possible anyway that a lack of communication to non-academic audiences is the main reason for the lack of a wider appreciation of input–output analysis in carbon footprinting and other environmental analyses. Changing the perception of practitioners and users outside academic circles should therefore be one of the goals of the input–output community. This could be helped by getting environmental applications of input–output analysis into political and corporate decision-making or by disseminating the results of new developments in environmental input–output science to non-academic audiences. It is important that not only high-quality research is promoted but also that its results are made understandable and available to non-specialists. I hope this special issue contributes to this wider goal.

3 CONTRIBUTIONS TO THIS SPECIAL ISSUE

Jan Minx and colleagues set the scene by providing a broad overview of carbon footprinting applications, demonstrating impressively the versatility of input–output analysis.

Referring to evidence from the literature in general, and the United Kingdom in particular, this review paper presents examples of multi-region input–output applications for national emissions inventories and trade, carbon footprint drivers, economic sectors, supply chains, organisations, household consumption and lifestyles as well as sub-national and local carbon footprint inventories. Many of the quoted studies have been used in political discussions, most importantly in the areas of international climate policy and national sustainable consumption and production frameworks, as well as local and regional development issues. The paper considers the further potential of input–output modelling for scenario analysis and other politically relevant questions.

The next paper deals with the issue of carbon footprinting of companies and industry sectors – a topic that has generated intense debate from the desire of businesses to understand the emission patterns of their supply chains, and the call of governments and NGOs for greater transparency of direct and indirect corporate emissions. Anny Huang et al. take the ongoing initiative for updating the GHG Protocol corporate (scope 3/supply chain) accounting and reporting standard (WRI and WBCSD, 2009) as an example and examine how input–output analysis can assist in the screening of sectoral and corporate carbon footprints. By calculating the contributions of distinct supply chain paths to the total carbon footprint of four economic sectors in Australia and the US they show that the introduction of cut-off thresholds for the inclusion of individual production processes leads to severe underestimation of the total, economy-wide impact. Depending on the nature of the sector, the rate of capturing the total upstream carbon footprint can be as low as 60%, even if hundreds of supply chain contributions have been evaluated and the materiality threshold is less than 0.1%. The critical feature of input–output analysis in this context is that it can provide an estimation of the 100% total footprint – an ability that no other method can offer.

A practical application of input–output analysis to national carbon footprint accounting is presented by Richard Wood and Christopher Dey. They calculate Australia's carbon footprint for the year 2005 and break down the results by final consumption category, economic sectors and purchased commodities. Key industries are identified in relation to their carbon footprint and the political implications are discussed in the context of Australia's emissions trading scheme. Wood and Dey also investigate how greenhouse gas multipliers (i.e. the total carbon footprint intensity as calculated by input–output analysis) of sectors in Australia have changed in the time period from 1990 to 2005. This analysis reveals which economic sectors have, or have not, achieved an improvement in greenhouse gas efficiency and it allows the tailoring of environmental policies for industry and business. Of particular interest to the input–output and carbon footprint practitioner will be the Appendix to Wood and Dey's article, where the breakdown of aggregated data sets in order to achieve a final resolution of 344 economic sectors in the model is described in detail.

A method to improve the completeness of product carbon footprint analysis is presented by Keisuke Nansai and colleagues in a methodological as well a political context for Japan. Several policies have been implemented by the Japanese Government aimed at disclosing the CO_2 emissions associated with consumer products. An 'environmental housekeeping book' is currently being tested in some areas of Japan. The aim of this initiative is to make consumers aware of how everyday expenditure on a range of commodities relates to indirect CO_2 emissions. The underlying conversion factors were derived from environmental input–output analysis.

In the present study, Nansai et al. have investigated the global implications of the consumption of food products and consumable items in Japan. For this purpose they have created a global model that links national input–output and CO_2 emissions data, bilateral trade data and specific information on international air and marine transport. A large number of sectors in the Japanese economy (402) and of countries in the model (230) has been used, thus enabling the attribution of emissions in any country of the world to specific product categories of Japanese products. The authors find that indirect emissions outside Japan are an important part of the global carbon footprint and input–output analysis allows them to identify the main contributions along the domestic and international supply chain, both in terms of commodities and countries. This information can be used in Product Category Rules (PCR) for product carbon footprinting, as it helps to prioritise data collection efforts in bottom-up approaches.

Harry Wilting and Kees Vringer use a multi-region input–output model covering the global economy in order to calculate the greenhouse gas emissions and land use associated with consumption in 12 regions of the world. This is broken down further, for the carbon footprint, into 87 countries and smaller world regions. These consumption-based accounts of environmental pressures are then compared with their production-based counterparts, which are defined by territorial boundaries. This allows for an evaluation of international trade, and the authors contemplate the implications for environmental policies, e.g. discussions in global climate policy about responsibility for greenhouse gas emissions.

Constructing a multi-region input–output model in the first place can be a challenge for the practitioner, especially if there is insufficient economic and trade data. Robbie Andrew and colleagues investigate how the accuracy of MRIO analysis for national carbon footprint accounting is affected by using simplifying assumptions and proxy data. They compare ‘best estimate’ national carbon footprints, calculated with a full-scale, multi-directional MRIO model, with results from a number of approximated model designs. Among the simplifications are: assuming domestic production technology for imports, neglecting trade between foreign economies and varying the number and size of trading partners in the model. The authors find that results vary substantially, depending on how imports are treated in the analysis. Accurate estimates for emissions embodied in imports are vital though as, on a global average, imports account for about 40% of a country’s carbon footprint. The authors derive some broad recommendations on obtaining improved estimates of national carbon footprints when using simplified MRIO models.

4 CONCLUDING REMARKS

Over the last decade there has been a tremendous increase in applications of analytical models based on environmentally extended input–output techniques. Besides being scientifically well described and established, the crucial advantage of input–output based analysis is that it is possible to provide a quantitative consumption perspective of virtually any economic activity. The fact that the linear input–output model is inherently scalable serves carbon footprinting well, as it can be applied to many different levels of consumption and production, from individuals and lifestyle types to regions and nations, from products to sectors and multinational consortia. There are clear limitations on the micro-level – input–output analysis on its own cannot replace process analysis – but there are clear advantages too. The consistent combination of standardised environmental and economic accounts, the unambiguous link between production and consumption and its economy-wide character leading to system completeness are the strengths of input–output analysis.

There is also an arsenal of diverse analytical and modelling techniques at the disposal of input–output practitioners, including structural path analysis, structural decomposition analysis, multi-region models at national and global level, simulation techniques, dynamic models, etc. The amount of information that can be drawn from one model alone can be immense and often only a fraction of it is actually used in guiding decisions. Corporate and political decision-makers are only beginning to realise the potential that comes with this information.

Although this Special Issue focuses on the carbon footprint, it is of course not the only environmental problem that can be analysed with input–output analysis. Looking at greenhouse gas emissions from a consumption perspective is politically significant and addresses arguably the most important environmental challenge faced to date. But it cannot provide the full picture of relevant impacts and it will be necessary to monitor other indicators related to consumption alongside the carbon footprint, such as the ecological footprint, water footprint and results from more specialised ecological impact models, informing about biodiversity, ecosystem health and other categories.

Where input–output analysis has been applied to ecological and water footprinting, yet again a repetition of history seems to take place in the methodological discussions of process-based versus input–output based approaches (see, for example, Wiedmann, 2009). A fruitful communication between academics and practitioners across the fields of energy analysis, LCA, IOA, and footprinting can only help us to learn from past lessons and advance the methods, applications and understanding in sustainability science.

The input–output community is faced with the important task of spreading the word about the potential and usefulness of input–output analysis. I hope that this special issue of *Economic Systems Research* contributes to this task and appeals to the traditional (technical) reader and the non-specialist alike.

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