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Thesis for the degree of Philosophiae Doctor

Trondheim, September 2019

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Preface

This thesis has been submitted to the Faculty of Engineering (IV) at the Norwegian University of Science and Technology (NTNU) as a partial fulfilment of the requirements for the degree of Philosophiae Doctor. The work was carried out at the Industrial Ecology Programme (IndEcol), Department of Energy and Process Engineering (EPT), under the supervision of Professor Richard Wood and co-supervision of Professor Edgar G. Hertwich.

Contents

Abstract

Reducing anthropogenic greenhouse gas (GHG) emissions is one of the defining challenges of our time. A prerequisite for designing national or international carbon mitigation policies is the availability of comprehensive methods for GHG emissions accounting. However, in a globalised world where trade volumes keep growing and goods travel long distances from production sites to end consumers, the accounting of GHG emissions is becoming increasingly difficult.

Consumption-based (CB) accounting captures the direct and indirect impacts associated with the production of goods and services and allocates them to the final consumers rather than producers, and the impacts calculated according to CB principles are often referred to as footprints. Environmentally extended (EE) multi-regional input-output (MRIO) analysis has emerged as the tool of choice for calculating footprints as it enables practitioners to calculate a variety of environmental and social impact indicators that take into account the upstream impacts of final products. While current MRIO models effectively account for the upstream impacts associated with intermediate goods, they do not treat capital goods as inputs to production processes but as exogenous components of the inter-industrial system. Capital goods are, per definition, produced in order to be utilised in further production processes, and not treating them as such implies that footprints as they are currently calculated underestimate the impacts of goods and services for final consumption, and thereby also the impacts embodied in international trade. This thesis therefore aims to investigate how capital goods can be better integrated in MRIO models.

A preliminary study was performed to obtain an understanding of how capital contributes to GHG emissions. Using the EE MRIO database EXIOBASE2, we analysed the size, structure and carbon footprint of the gross fixed capital formation (GFCF) for the 48 available countries and regions, and found that in 2007 (the year of study) the GFCF stood for 24% of the global final demand of goods and services but contributed to 30% of the global GHG emissions, with large variations observed across the analysed countries. Furthermore, by comparing the structure of the GFCF in different countries, we concluded that developed countries tended to invest in less carbon-intensive assets than countries at low and intermediate levels of development, and that the overall carbon intensity of GFCF varied substantially. These results pointed to the importance of integrating capital in MRIO models based on detailed and consistent auxiliary data, and models presented in this thesis are therefore constructed using approaches that have substantial data requirements. The flow matrix method described in paper II entails that the capital goods currently in use are disaggregated over assets and industries to create a capital use matrix. This disaggregation was done using capital use proxies from various external sources such as the KLEMS and WORLDKLEMS databases, which were harmonised against the EXIOBASE classification so that capital could be endogenised into the inter-industry system of EXIOBASE, thereby closing the IO system for capital. Using this capital-augmented IO framework, we applied standard Leontief demand-pull calculus to compute footprints that included the upstream impacts associated with both current and capital production requirements.

Our results showed that endogenising capital in MRIO models substantially increased the carbon and material footprints of final consumption, and that this increase varied a lot across countries. We also noted increases in total emissions embodied in trade, and found that current disparities between CB and production-based measures of GHG emissions increased further for most countries. The product-level

results showed important differences between product categories, with the increases in the footprints of service categories being substantially larger than for non-services, indicating that service sectors – which account for an increasingly large share of the global economic output (particularly for wealthier countries) – contribute much more to various environmental problems than previously thought.

While the results confirm that the endogenisation of capital has substantial implications for CB accounting, it must be noted that the models used in this thesis still rely on many assumptions that impinge on the robustness of the model. One of these was analysed in depth in the fourth paper of this thesis, with the conclusion that an explicit temporal resolution is needed to consolidate the capital-augmented IO framework, including detailed age cohort composition of the current capital stock as well as longer time series than currently available. Nevertheless, we hope that the analytical approaches adopted in this thesis as well as the models themselves could help the further development of input-output and industrial ecology methods in answering some of the key sustainability questions of our generation.

Acknowledgments

First and foremost, thanks to my supervisor Professor Richard Wood and co-supervisor Professor Edgar Hertwich. Richard, thanks for your guidance during these five years. You were thrown into the role of main supervisor of several PhDs for the first time, and I believe it has been a learning curve for both of us. Although it remains unclear whether any of us ever actually understood what the other said amidst our respective mumbling, you managed to put me back on track while I was academically adrift on many occasions and, incredibly enough, persuaded me to remove the amazing puns I had squeezed in throughout my papers. Furthermore, thanks for enduring five years of terrible jokes, unconventional emails (to put it mildly) and occasional pranks (including the wallpapering of your office door with deflator series). I will truly miss working with you. Edgar, many thanks for staying on board despite that you left for a new research group at a prestigious institution across the Atlantic at an early stage of my PhD. Our interaction may not have been that frequent, but you stepped in with inspiration and guidance at crucial times, and for that, I am grateful.

Many thanks also to Professor Manfred Lenzen, who agreed to host me for a three-month research stay at the School of Physics at the University of Sydney. You may not realise it, but your contribution, despite that we only managed to squeeze in a handful of talks in person, was of tremendous and invaluable help. Your sharp and precise comments helped me break through several layers of confusion regarding my topic and helped me gain a much deeper understanding of my work. Thanks also to the remainder of the Integrated Sustainability Assessment group who offered me a warm welcome in Sydney.

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Lastly, and most importantly, thanks to Sarah, for, well, everything. We have been at each other's sides (quite literally) for many years, but there has not been a single moment when I have wished to be elsewhere. We are, truly, the best team in the world.

List of publications

Primary publications

I. Södersten, C-J, R. Wood and E. Hertwich. 2018a. Environmental impacts of capital formation. *Journal of Industrial Ecology* 22(1): 55-67.
Author contribution: research co-design, data analysis and visualisation, and writing.

II. Södersten, C-J, R. Wood and E. Hertwich. 2018b. Endogenising capital in MRIO models: the implications for consumption-based accounting. Environmental Science and Technology *52* (22): pp 13250–13259
Author contribution: research co-design, data collection, modelling, analysis and visualisation, writing.
Paper received the ACS Editor's Choice Award and was featured on the front cover of Environmental Science and Technology (see appendix C1)

III. Södersten, C-J, R. Wood and T. Wiedmann. 2019a. The capital-augmented material footprint: the real material footprint of final consumption. *(unsubmitted manuscript)*
Author contribution: research design, data modelling, analysis and visualisation, writing.

IV. Södersten, C-J, M. Lenzen. 2019b. A supply-use approach to capital endogenisation in input-output models. *(under second round of revision at Economic Systems Research)*
Author contribution: research co-design, mathematical derivations, data modelling, analysis and visualisation, writing.

Other publications

V. Wood, R., K. Stadler, M. Simas, C-J. Södersten. DESIRE deliverable D9.2: Report on structural analysis of drivers. 2015.
Author contribution: writing

VI. Stadler, K., R. Wood, T. Bulavskaya, C.J. Södersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernández, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai, J.H. Schmidt, M.C. Theurl, C. Plutzar, T. Kastner, N. Eisenmenger, K.H. Erb, A. de Koning and A. Tukker. 2018. EXIOBASE 3: Developing a time series of detailed Environmentally Extended Multi-Regional Input-Output tables. Journal of Industrial Ecology 22(3): 502-515.
Author contribution: data modelling and analysis, writing

VII. Schmidt, S., C.J. Södersten, K. Wiebe, M. Simas, V. Palm and R. Wood. 2019. Understanding greenhouse gas emissions from Swedish consumption – Current challenges in reaching the generational goal. Journal of Cleaner Production 212: 424-437.
Author contribution: data modelling, analysis and visualisation

VIII. Södersten, C-J. and S. Schmidt. 2019c. Sweden chapter. In A Triple Bottom Line Analysis of Global Consumption, ed. by Joy Murray, Anne Owen, Moana Simas and Arunima Malik. Pan Stanford. *(under preparation).*
Author contribution: data analysis, writing

1 Introduction

1.1 Climate change: the biggest challenge of our generation

A new milestone of unsustainability was recently reached: on the 11th of May 2019, the amount of CO_2 in the atmosphere reached its highest level since the last geological epoch, hundreds of thousands of years before humans walked the Earth[1, 2]. Scientists generally agree that this surge in greenhouse gas (GHG) emissions in the atmosphere observed since the beginning of the industrial revolution and the resulting warming of the planet has been caused by anthropogenic activities[3, 4]. While the exact consequences of rising temperatures are impossible to predict, the consensus is that they are dire[5-8]. A recent report from the International Science-Policy Platform on Biodiversity and Ecosystems Services found that up to one million plant and animal species face extinction due to climate change and other human-induced activities[9]. The United Nations Framework Convention on Climate Change (UNFCCC) has called climate change "the challenge of our generation"[10], and the United Nations (UN) secretary general recently referred to it as the "biggest systemic threat to humankind"[11].

The challenge of reducing GHG emissions to stop global warming is twofold. A drastic decrease in emissions is needed, but as the world population is growing (both in size and affluence), global demand for materials and energy keeps rising[12]. In addition, achieving the objectives described by the UN Sustainable Development Goals (SDGs)[13] will require substantial resource-intensive investments in most parts of the world[14, 15]. Pathways to reach emission reduction targets include a global shift to low-carbon energy technologies and a large-scale restructuring of the global energy infrastructure, as well as changes in the transportation system, efficiency improvements, increase in recycling rates, etc.[16-20]. In fact, the changes needed entail a transformation of the socioeconomic metabolism of such magnitude that it has been compared to what occurred during the shift from agrarian to fossil-fuel based industrialised societies[21].

1.2 The complexity of GHG emissions accounting

What makes global warming a particularly complex issue compared to other environmental problems is its global nature; the negative effects of releasing GHGs are not confined to where the gases are released but affect the entire Earth. As a result, the positive effects of decreasing emissions on one side of the globe may be offset by an increase on the other side of the globe. Global warming can therefore only be stopped if the *total* amount of GHG gases emitted into the atmosphere is curtailed, which entails that climate change mitigation requires international collaboration. Moreover, the globalisation of trade that has occurred in the last few decades has led to a displacement of the environmental impacts associated with production and consumption of goods. By outsourcing emission-intensive manufacturing to distant lands, countries – typically richer ones – can see their territorial emissions stabilise or even decrease while taking limited technological and political emission reduction measures themselves, to the expense of other countries – typically developing countries with less stringent environmental legislation – whose territorial emissions increase due to the production of goods destined for export. This has made GHG emissions accounting increasingly difficult. The rise in emissions that occurs in non-abating countries as a result of other countries introducing domestic carbon abatement measures has been referred to as carbon leakage[22-24]. The phenomenon has received a fair share of attention in the last decades of environmental research and policies related to it, with multiple papers discussing the effectiveness of global territorial policies such as the Kyoto protocol[22, 23, 25-29], as well as how to assign the responsibility for emissions across countries[30-41].

This inherent global nature of emissions makes the design of climate change mitigation policies complex. A prerequisite for designing such policies is therefore the availability of holistic and reliable tools and methods for GHG emissions accounting that achieve a comprehensive description of emissions enabling to address and tackle issues such as carbon leakage[5, 42]. Consumption-based (CB) accounting was introduced as a complement to production-based (PB) accounting to enable the quantification of the upstream impacts of production. The fundamental principle of CB accounting is that consumers, rather than producers, are held responsible for the impacts associated with the production of goods and services for final consumption. This entails that even if carbon-intensive industries are relocated overseas, their environmental impacts can still be allocated to the end consumers. As such, CB accounting aims to capture the life cycle impacts of production processes, and environmental burdens calculated using CB methods are therefore commonly referred to as *footprints*.

CB accounting has been widely applied to quantify the carbon emissions embodied in international trade and to estimate the magnitude of phenomena like carbon leakage[24, 36, 43, 44]. By comparing CB emissions with PB emissions, countries can be categorised as either net exporters or net importers of carbon if their carbon emission balance is negative respectively positive[24, 27, 45-48]. Such information is pivotal in the design of fair and just carbon abatement policies[32, 45, 48, 49], but it also requires that the approaches used for calculating the CB impacts be exhaustive and carefully devised. Today's CB accounting methods may capture the upstream impacts associated with the current production requirements, but as they do not treat capital goods as inputs to production processes, they fail to account for the upstream impacts associated with the capital requirements. This implies not only that footprints of final consumption as they are currently calculated do not capture the full life-cycle impacts of goods and services and are therefore underestimated, but also that capital is treated as an exogenous component of the economy instead of an integral dynamic part of the inter-industrial system.

1.3 The role of capital in climate change mitigation

Manufactured capital plays a central role in the shift towards a less carbon-intensive socioeconomic metabolism, as it encompasses both the infrastructure needed to achieve such a shift as well as the machinery and equipment needed to build up that infrastructure. Understanding this role is therefore a crucial step in developing strategies for climate change mitigation[50]. The IPCC reveals in its fifth Assessment Report[20] that "a number of fundamental questions concerning the link between manufactured capital and climate change mitigation are still insufficiently understood"[19].

Recent studies have highlighted and studied the role of capital in society and sustainability[19, 21, 51]. Pauliuk and Müller[21] note that the role of manufactured capital is manifold. Not only does manufactured capital provide services that are essential to fulfil basic human needs (such as shelter, mobility, protection, sanitation, communication, etc.), but capital stock also plays a role as city shaper and dynamics determiner. Current in-use stocks reflect the development of societies over the last decades, if not centuries. The long lifetimes and slow turnover of capital goods determine the dynamics of stocks and affect the rate of change, and technology lock-in entails that structural changes in e.g. energy and transportation systems take time[52]. This not only impedes the development of alternative technologies but also implies that the design of climate change mitigation strategies must be carefully planned and thought-through. Weisz et al.[19] identify the important linkages between manufactured capital, human capital and natural capital, and stress that manufactured capital should not be considered as a mere conduit between the lithosphere and the anthroposphere, but rather as an engine that enabled the transformation of the natural environment at unprecedented scale.

Meanwhile, capital is a major driver of associated resource use and environmental impact[17, 19, 21, 50, 51] and constitutes a large share of the total output from industries. In monetary terms, the gross fixed capital formation stands for a quarter of the global final demand, but the impacts from producing capital goods are, however, much larger[42]. As current CB methodology does not treat capital as endogenous to the inter-industrial production system, these impacts are not well accounted for in national footprint calculations, and are, in fact, often completely ignored in e.g. footprint assessments of household consumption such as [53-58]. This is the problem addressed in this thesis.

The role of capital in the socioeconomic metabolism and its contribution to global warming cannot be fully understood without a clear insight into what it encompasses and how it is measured and accounted. In the following sections, I will introduce the concept of capital more formally and summarise the past and present capital accounting practices, both in national and international statistics but also in terms of its relation to environmental impacts and climate change.

1.4 Capital – concept and theory

1.4.1 A brief history of capital

The concept of capital is old. In fact, the origins of the word itself are debated[59, 60]. Some argue that *capital* can be traced back to the Medieval Latin adjective *capitalis* (from *caput*, meaning head) which was introduced in the 13th century to replace the word *pars* (meaning part, piece or share), a term used to designate the principal sum of a money loan (that is, the total loan minus the interests[61]). The definition was later expanded to entail the value of all wares sold on credit and was eventually used to describe the total value of a merchant's goods and assets[61] or the total money advanced to establish a business[62]. Meanwhile, Braudel[63] mentions occurrences of the Italian word *capitale* in the 13th century that refer to the capital assets of a trading firm. Whether these definitions are linked or derived independently from Latin is unclear; they become increasingly intermingled in the 17th century[61, 62], during which the word was reportedly used to describe both the value of a trader's merchandise[60], the money that business partners have to advance into a business[60], the principal of a debt[64], as well as a physical store of goods[61]. This latter meaning was consolidated by Adam Smith in his magnum opus the Wealth of Nations[65], and at the beginning of the 19th century, *capital* was for the first time given a definition similar to the one used in today's national accounts, as the "produced means of production used for further production"[61]. Nevertheless, the term *capital* remained used loosely both as a notion of physical stock of goods and financial measure of wealth throughout the 19th century[62, 64, 66, 67], to the confusion (and occasional annoyance) of economists. Fisher states that simply enumerating the works discussing the nature of capital would "fill several pages"[67], and illustrates his claim by listing various definitions of capital provided by eminent Economists of the time, including Adam Smith, Karl Marx, David Ricardo, John Stuart Mill, Eugen Böhm-Bawerk and Léon Walras. Fetter talked of a "chaos of terminology"[61] when referring to the different capital concepts that existed at his time of writing, and complained that the equivocal meaning of the word was destined to "plague economics, the law and accountancy from that day till this"[61]. In fact, the disagreements among economists regarding capital – such as its definition and limitations, how to measure it and whether it can be aggregated into a single measure – pertained throughout the 20th century[68, 69] and remains debated to this date[62, 70].

The ambiguity surrounding the term capital has made it vulnerable to misuse. Indeed, in the last few decades, the word has been applied to a range of other fields, including sociology, psychology and ecology, giving rise to a "plethora of capitals"[71]. Hodgson[62] lists dozens of offshoots of the word, and while some of the applications have become established concepts, such as *human capital*, *natural capital* and *social capital*, others could be considered a little far-fetched (e.g. *self-command capital* and *erotic capital*).

1.4.2 Definitions of concepts used in the thesis

What is, then, capital? As mentioned earlier, capital in its economic sense has two modern connotations: money capital, i.e. capital as a store of value, and physical capital, i.e. capital as physical goods used as means of production[62, 70, 72-74]. These two connotations are reflected in the capital account of the System of National Accounts (SNA), in which the gross capital formation is defined as the "total value of the gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables"[75]. *Changes in inventories* is the change, during the accounting period, in the value of the raw materials and goods held in inventory, while the *acquisitions less disposals of valuables* category accounts for the change in the value of precious metals, minerals and works of art (e.g. paintings and sculptures) over the accounting period. As such, these categories can be likened to the first connotation, i.e. capital as a store of value. The gross fixed capital formation (GFCF) is defined as "the total value of a producer's acquisitions, less disposals, of fixed assets during the accounting period plus certain specified expenditure on services that adds to the value of non-produced assets"[75]. Hence, the GFCF constitutes a flow of long-term investments purposed to build up or maintain production capacity and can be compared to the second connotation.

A prerequisite for understanding the GFCF is to have a clear definition of assets and particularly of fixed assets. The SNA defines *assets* as a "store of value representing the benefit […] accruing to the economic owner by holding or using the entity over a period of time. It is a means of carrying forward value from one accounting period to another"[75]. *Fixed assets* are defined as "produced assets that are used repeatedly or continuously in production processes for more than a year"[75], and *produced assets* are in turn defined as "outcomes of production processes"[75] (as opposed to e.g. natural resources or marketing assets).

The definition of fixed assets implies that the GFCF encompasses a variety of different goods, ranging from tangible goods (buildings, machinery, and transport equipment) to intangible goods (databases, software) as well as cultivated and living assets (fruit trees and dairy cattle). A comprehensive overview of different types of fixed assets is therefore provided in appendix A. The definition of fixed assets also entails that it is not only the type (produced assets) and service life (exceeding one accounting period) of goods that determine whether it should be accounted for as part of GFCF, but also its purpose. For instance, a car purchased by a household to be used privately is considered a consumer good, whereas the same car purchased by someone in the household who also owns a company and intends to use the car for associated business trips should be recorded as capital formation. This implies that one particular asset can be converted from capital good to consumer good (e.g. if an enterprise decides to sell some of its cars to private households), and vice-versa. This distinction between capital and consumer goods is known as the *asset boundary*, and it inevitably makes the estimation of GFCF difficult. Certain goods can be allocated to the GFCF just based on their type (e.g. buildings, large machinery, container ships, etc.), but for many others, additional information is needed to correctly categorise them, as they can both be used for production purposes and be destined for final consumption. This includes, for instance, cars, computers, software, electronics, IT equipment, smaller machinery, etc.

To summarise, while there are still ambiguities surrounding the term *capital*, the definitions provided by the SNA help narrow down the scope of the term. Henceforth in this thesis, *capital* and *capital goods* will refer to fixed assets as they are defined by the SNA. Moreover, the term *investment* will be used interchangeably and synonymously with the terms *GFCF* and *capital formation*.

1.4.3 Capital accounting and measurement

The economics of the 19th century may have been marked by disagreement regarding the definition of capital, but these disagreements undeniably led to progress in the field of capital theory, with several of the earliest prominent works on the topic published at the end of the century[76-79]. The interest in producing detailed and regular estimates of national income increased in the early 1900s[80, 81], during which capital remained a central element: "the fundamental purpose of accounting should consist of an attempt to distinguish clearly between capital and income"[82]. The 1930s witnessed substantial progress in methods, with an increase in the frequency and timeliness of national income estimates as well as the birth of commodity-flow accounting[83], which would prove to be pivotal in the future development of national accounts and capital accounts. Originally developed in Sweden[83, 84], the method entailed that the outputs of industries were categorised depending on their intended use, e.g. as inputs to other industries or final consumption. This proved to be particularly useful in the estimation of national income as it allowed to produce the first[a] national expenditure aggregates separated as consumption and capital formation[80]. The commodity flow approach[b] has been referred to as a "statistical counterpart of input-output analysis"[84], as it enabled the construction of the first supply and use tables (SUTs). For instance, Denmark published its first SUTs in the 1930s, i.e. preceding Leontief's framework[83]. The commodity flow approach was later adopted by Kuznets, who used it to retrospectively estimate capital formation measures for the US for the years 1919 to 1933 (although his definition of capital formation included all durable commodities with a useful life exceeding *three* years, regardless if they were used by households or industries)[85, 86]. The need for rigorous measurements of consumption and capital expenditures was further reinforced when John Maynard Keynes[87] laid out his General Theory in 1936[80, 84]. The idea of producing tables of national accounts spread to more and more countries and marked the beginning of a trend towards establishing official frameworks for national accounting, which eventually gave birth to the first national accounting system in 1947[81, 84]. In 1953, the first version of the SNA was published, containing official internationally agreed guidelines and recommendations on how to compile measures of economic activity, differentiating between current and capital accounts. This differentiation has been kept in the five SNA revisions that have been published since then (the last one in 2008)[88] and further refinement has been done, e.g. separating between financial and non-financial capital transactions.

Capital accounting is more complex than e.g. labour or material accounting, mainly due to the lifetime and diversity of capital assets. As opposed to labour and material inputs, the costs for capital inputs purchased for productive use at the beginning of an accounting period cannot simply be accounted to that period, since the services offered by the capital assets extend over several accounting periods. Hence, the investments must be somehow distributed over the life span of the asset (this has been referred to as the *fundamental problem of accounting*[89]). Since the acquisitions of new capital are reported as a final demand category (the GFCF), the assets that remain in use at the end of an accounting period must also

[a] References of capital in national accounting can be traced back to the early estimates of national income produced by William Petty in the second half of the 17th century[80], which feature entries such as "domestic asset formation" and "disbursements on capital account", as well as changes in the stocks of valuables (gold, silver and jewels).
[b] Also called commodity flow method, product flow approach or product flow method

be accounted for since they are expected to provide productive services in subsequent periods and are therefore still valuable to the industries owning them. Consequently, these capital goods still in use are recorded as part of the value added (VA), under the term "consumption of fixed capital" (CFC – referred to as *capital consumption* in some national accounts[75, 90]). The CFC is defined as "the decline, during the course of the accounting period, in the current value of the stock of fixed assets owned and used by a producer as a result of physical deterioration, normal obsolescence or normal accidental damage"[75].

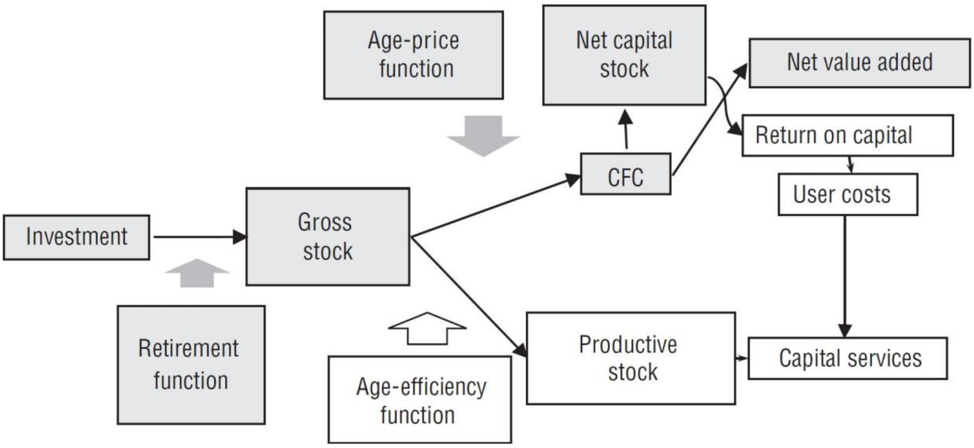

Fig1: Integrated set of capital measures. Source: OECD capital measurement guide[90]

This definition entails several intricacies. Firstly, the terms "normal obsolescence" and "normal accidental damage" are inherently ambiguous in themselves, and therefore need to be clearly defined. Secondly, and most importantly, the current valuation of a producer's stock (and its decline over the accounting period) can be estimated in different ways. The CFC is similar to the concept of depreciation as used in the business accounts, and the terms are often used interchangeably. However, the two concepts are distinct, at least in principle. Depreciation implies that costs of past expenditures on fixed assets are allocated over subsequent accounting periods. It is often calculated mechanically, assuming a fixed yearly depreciation (linear or straight-line depreciation) or a fixed rate of depreciation (geometric depreciation)[90]. The CFC, on the other hand, is a measure of the future benefits that producers expect to derive as a result of utilising the assets in production, i.e. of the discounted future *services* that the asset is assumed to yield in the future[89]. This implies that the CFC of an asset for a certain year depends not only on the actual loss of efficiency over the year, but also by how much the lifetime of the asset has changed (which is affected by several factors, including use rate, physical deterioration, maintenance costs, energy costs, technological advances, structural changes, etc.) and on how much its efficiency declines over its remaining service life. The diversity of capital assets adds an additional level of complexity to the matter: some assets lose value faster than others do; some are more prone to change their rate of loss in value due to external factors. In addition, while some assets have the same efficiency throughout their lifetimes, others' may decrease, which may also affect their value. It has therefore been suggested that in addition to the CFC, a measure of *capital services* should be established[89, 91-98] (illustrated in Figure1). This is further elaborated in the discussion chapter.

To summarise, while the depreciation is a backward-looking, purely economic measure, the CFC is a forward-looking measure that includes both economic and physical aspects. The SNA therefore recommends that the depreciation should not be used in lieu of CFC and that the CFC should be estimated independently using historical GFCF data combined with information on the how the efficiency of different assets decline over their service lives[75]. In practice, however, measuring the CFC according to its definition is rarely done, since asset owners rarely keep record of the asset values, and it is therefore often estimated with the depreciation.

These are complex issues, of which multiple papers and entire books[69, 90, 99] have been written. Hence, discussing them in more details is far beyond the scope of this thesis[c]. What the reader should keep in mind regarding the CFC for this thesis are two main points:

1- The CFC is a measure of the decrease in value of the stock between two consecutive periods and is therefore an economic measure
2- There are different ways to estimate the CFC

These points will be discussed further throughout this thesis as well as in the papers included in it.

1.5 Input-output analysis

Concurrently but unconnected to the work on national income in the 1930s, Leontief developed input-output analysis (IOA), inspired by Quesnay's zigzag tables in his *Tableau Economique*[100, 101] and the mathematics of Walras[81, 102]. The framework was presented in 1936 but first gained attention in the 1940s[80]. The crucial innovation and great strength of IOA was that inputs and outputs were connected in a way that enabled to calculate direct and indirect inputs of production, leading to many useful applications in the politics and economics of the post-war period[84, 103]. Still, the popularity of IOA remained stochastic; IO tables (IOTs) were not published as often as national accounts (once every five or ten years)[80, 81], and they were first explicitly linked to national accounts and the SUTs that they are constructed upon in the 1968 version of the SNA[81]. Today, national statistical offices that publish SUTs often publish IOTs along with them.

1.5.1 Environmentally extended multi-regional input-output analysis

While the first examples of multi-regional input-output models (MRIO) date back to the 1950s[104], it wasn't until 1973 that IOA would be used to assess environmental impacts, when Walter[105] associated environmental stressors to industries in IO tables to quantify "the pollution content" of American imports. The analysis was performed without matrix inversion and as such only included the first production layer[104]. Two years later, Fieleke[106] published the first study that made use of the Leontief inverse to estimate factors (energy) embodied in trade. In 1994, Tiwaree and Imura[107] combined MRIO with environmentally extended (EE) IO to produce a ten-region MRIO with environmental extensions, but it did not take into account trade with other regions. As such, the first EE MRIOTs with global coverage were compiled in the early 2000s[104]. At the time, issues related to pollution and environmental degradation were gaining interest, with e.g. the adoption of the Kyoto protocol in 1997, the first international treaty committing countries to stabilise their GHG emissions. These global MRIO databases enabled researchers to perform quantitative assessments of the upstream (indirect) impacts associated with consumption and thereby to assess the magnitude of the carbon leakage phenomenon discussed in the introduction. This

[c] The OECD guide *Measuring Capital*[90] is a good starting point for readers wanting to gain a more in-depth insight on modern capital measurement

led to the introduction of CB accounting, which, as opposed to PB accounting, assigns the impacts associated with the production of goods and services to the consumers rather than the producers[24, 37]. By comparing CB and PB emission accounts, the effectiveness of global climate policies and territorial emission reduction strategies such as the Kyoto protocol could be quantitatively appraised[25, 36, 108]. Furthermore, CB accounting provided new insights on economic and environmental linkages between countries and could be used to identify hotspots and unsustainable consumption patterns, as well as to inform final consumers on the environmental impacts associated with their lifestyles and consumption choices[109].

The MRIO development flourished in subsequent years, with several global MRIO databases being developed by different institutions on several continents: Eora by the university of Sydney[110], the Global Analysis Trade Project (GTAP)[111], WIOD by the university of Groningen[112] and the EU-funded EXIOPOL/EXIOBASE project[113-115]. This led to a surge in studies using CB accounting as well as the formalisation, standardisation and diversification of the footprint methodology[116-118]. The versatility of EE MRIO enabled practitioners to introduce a variety of environmental and social extensions that had vast application areas. While the concept of *ecological footprint* had already been coined by Wackernagel and Rees in 1996[119], a range of subsets thereof suddenly emerged[120], such as carbon footprint[116, 118], land footprint[121, 122], material footprint[123], water footprint[124], energy footprint[125], biodiversity footprint[126], employment footprint[127], etc. As such, EE MRIO became one of the most important tools in environmental impact assessment and industrial ecology alike[109, 116, 117], with hundreds of studies applying IO methods to estimate CB impacts associated with final consumption[128].

1.5.2 Capital accounting in IOA

The accounting of capital in IOA concurs with the practices prevailing in national accounts and in the SUTs derived from them, in which the capital account is compiled independently and capital transactions differentiated from intermediate transactions and final consumption. These practices entail shortcomings of the current footprint methodology. One of the defining and fundamental characteristics of capital goods is their purpose: as opposed to consumer goods, capital goods are assumed to be utilised in production processes. This assumption is not taken into account in current MRIO models (as explained in the methods chapter). Furthermore, when calculating CB impacts of countries, current CB accounting assigns all impacts from capital to the countries investing in it, i.e. implicitly assuming that the capital built in a country is used to satisfy domestic final consumption only[42]. This assumption has been questioned in previous studies. For instance, Minx et al.[44] conclude that 21-31% of Chinese emissions embodied in capital between 2002 and 2007 could be assigned to exports, i.e. are caused by the demand from other countries. This has important implications; China has overtaken the US as the world's largest emitter of GHG emissions and is now responsible for almost a quarter of global GHG emissions, and more than 50% of those emissions are caused by capital formation. It has therefore been argued that capital goods should be treated as intermediate goods rather than final demand goods and that they ought to be endogenised into the inter-industry system of MRIO models[129-133]. This would entail that CB calculations would include not only the direct and indirect requirements of *current* goods to produce a certain final demand, but also the direct and indirect requirements of *capital* goods. Consequently, the CB impacts associated with a specific final demand would also include the impacts associated with the capital goods used to produce that final demand.

1.6 Research questions and thesis structure

While a few studies have been published with results on capital endogenisation on national level[130-132, 134, 135], none (at the time this thesis began) had so far endogenised capital on a global level. This is a clear research gap that I intend to fill with this thesis. In particular, I wish to answer the following research questions:

1- How can capital be better integrated in current IO methods?
2- How does the endogenisation of capital affect CB accounting of environmental impacts?
3- What are the main difficulties and challenges of endogenising capital, and how can they be addressed?

These questions are addressed in the four primary publications appended to this thesis. A prerequisite to determine how capital can be better integrated in IO methods is to obtain an understanding of what capital in the 21st century entails. In paper I, we therefore focussed on analysing the size, composition and environmental impacts associated with capital formation. As explained in the introduction, the rationale behind this thesis as well as many other studies on GHG emissions and policies related to them is to contribute to the research needed to address the problem of global warming caused by anthropogenic carbon emissions. In the first paper, we therefore concentrated the environmental impact study on carbon emissions. We were particularly interested in comparing the carbon intensity of capital across countries, as this would provide valuable information regarding how capital should be better integrated in IO methods. One of the research questions in the paper concerned the hypothesis that countries that are at an early or intermediate stage of development necessitate particularly carbon-intensive investments to build up the infrastructure needed to achieve better standards of living and thereby eventually leave the "developing" phase. Capital goods such as buildings and infrastructure are often used for decades; depending on the approach taken to endogenise capital, this inherent temporal aspect of capital is treated differently, which may significantly alter the results. The findings from paper I were therefore crucial in the choice of method and the design of the endogenisation models implemented in the subsequent papers.

Our first endogenisation model was constructed and applied in paper II. The empirical analysis and results extended the work done in paper I, and paper II therefore also focussed on the impacts of endogenisation on carbon emissions. We performed several calculations to answer the second research question, i.e. how endogenising capital affects CB emissions. We studied the effects on final consumption but also compared the net total impact on countries and on emissions embodied in trade, as well as the impacts on individual product categories. The development of the endogenisation model used in paper II involved certain challenges, both methodological and in terms of data collection and harmonisation. Lack of data entailed that assumptions often had to be made, and several sensitivity analyses were therefore performed (some of which included and discussed in the online supplementary material of the paper) to determine how the different model assumptions affected the model outcome. The results from these were used to refine the model further for paper III (along with the integration of additional auxiliary data) as well as led to the creation of a different endogenisation model in paper IV, in which one of the assumptions that had been shown to affect the results the most was addressed and analysed.

The structure of the subsequent pages is as follows. Chapter 2 presents a concise overview of input-output analysis as well as of the most important mathematical relationships needed to perform basic consumption-based calculations. The main data sources used in the thesis are also described. Chapter 3 offers a summary of the four primary publications included in this work. In chapter 4, I discuss the scientific contribution of the thesis as well as some of the challenges encountered when developing the models, and recommendations for future work are given. Finally, the main results and conclusions are summarised in chapter 5, along with a brief outlook concerning the future of consumption-based accounting.

2 Methods and data

2.1 Multi-regional input-output analysis

2.1.1 Mathematical fundamentals

This section offers a brief overview of the MRIO methodology. The reader interested in reading more about IO and MRIO analysis is referred to one of the many excellent handbooks that are available[136-138].

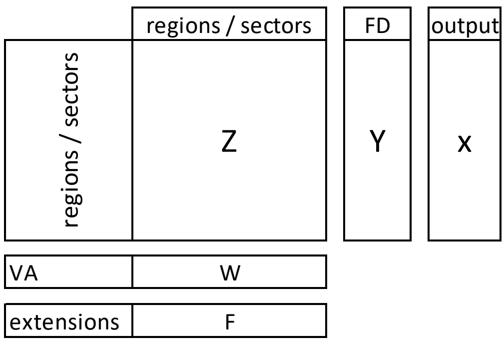

Figure 2: The basic multi-regional input-output framework

Figure 2 illustrates the basic MRIO framework with its main components (bold lowercase font is used for vectors, bold uppercase font for matrices, and italic lower font for scalars and indices):

- $\mathbf{Z}$ *n*-by-*n* inter-industry transaction matrix, where an element $z_{i,j}$ describes the sales from from region and sector combination (RSC) i to RSC j, and with $n =$ (number of regions * number of sectors)
- $\mathbf{Y}$ *n*-by-*f* matrix of final demand, i.e. sales to households, government, GFCF, etc., with $f =$ (number of regions * number of final demand categories)
- $\mathbf{W}$ *w*-by-*n* value added matrix of other financial elements (e.g. compensation of employees, consumption of fixed capital, taxes, dividends, etc.), with $w =$ number of VA elements
- $\mathbf{x}$ *n*-by-*1* vector of total output from industries
- $\mathbf{F}$ *s*-by-*n* extension matrix (also called factor matrix or impact matrix) containing total extensions per RSC (for instance total GHG emissions, water use, land use, number of employees, etc.), with $s =$ number of extensions.

The vector $\mathbf{x}$ is the column sum of both intermediate consumption from the inter-industry matrix $\mathbf{Z}$ and final demand consumption matrix $\mathbf{Y}$, i.e.

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yi} = \mathbf{Zi} + \mathbf{y}, \tag{1}$$

where $\mathbf{i}$ is a summation vector of appropriate length. By normalising the inter-industry transaction matrix $\mathbf{Z}$ we can construct the inter-industry *requirement* matrix $\mathbf{A}$:

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}, \tag{2}$$

where $\hat{\mathbf{x}}$ is a diagonalised version of the vector $\mathbf{x}$, i.e. in which each element x_i is placed on row / column *i*. $\mathbf{A}$ is therefore also an *n*-by-*n* matrix, where an element $a_{i,j}$ describes the requirements from RSC i per unit output of RSC *j*. These requirements are also referred to as *current* requirements. Rewriting equation 2 as

$$\mathbf{Ax} = \mathbf{Z} \tag{3}$$

and combining it with equation 1 yields

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y}, \tag{4}$$

which can be written

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly}, \tag{5}$$

where $\mathbf{I}$ is the identity matrix. The *n*-by-*n* matrix $\mathbf{L}$, known as the Leontief inverse, constitutes a pillar of input-output modelling, as it describes the total (direct and indirect) outputs needed from all industries to produce each unit of *final demand*. That is, an element $l_{i,j}$ describes the requirements from RSC i per unit of final demand from RSC *j*.

Similarly to the inter-industry requirement matrix $\mathbf{A}$, we construct the extension requirement matrix (also called stressor matrix) $\mathbf{S}$ by normalising the extension matrix F:

$$\mathbf{S} = \mathbf{F}\hat{\mathbf{x}}^{-1} \tag{6}$$

$\mathbf{S}$ is an *s*-by-*n* matrix containing extensions per unit output. That is, an element $s_{i,j}$ describes the requirements of extensions i per unit output of RSC *j*. By selecting a single row vector $\mathbf{s}$ from $\mathbf{S}$ containing e.g. emissions of GHGs and normalising it to form a 1-by-*n* stressor vector $\mathbf{s}$, we can calculate the total CB (direct and indirect) GHG emissions d associated with a final demand $\mathbf{y}$ as such:

$$d = \mathbf{sLy}. \tag{7}$$

By diagonalising $\mathbf{y}$ we can keep the final demand resolution and obtain a 1-by-9800 row vector of CB GHG emissions as such:

$$\mathbf{d} = \mathbf{sL}\hat{\mathbf{y}}. \tag{8}$$

Each element of $\mathbf{d}$ describes the CB GHG emissions resulting from the production of a final demand $\mathbf{y}$**,** disaggregated by product and region of *consumption*.

Likewise, we can keep the full resolution of the RSC origin by diagonalising the stressor vector final demand resolution and obtain a 9800-by-1 vector of CB GHG emissions as such:

$$\mathbf{d}^{\mathrm{O}} = \hat{\mathbf{s}}\mathbf{Ly}. \tag{9}$$

Where the O superscript signifies origin. Each element of $\mathbf{d}^{\mathrm{O}}$ describes the CB GHG emissions resulting from the production of a final demand $\mathbf{y}$, disaggregated by product and region of *production*.

By selecting specific rows in the final demand vector and specific columns in the stressor matrix, we can calculate country-specific impacts. For instance, consider a vector $\mathbf{y}_{\mathrm{A}}$ that contains the total final demand of country A from all other countries. By creating a stressor matrix $\mathbf{s}_{\mathrm{B}}$ that contains emission coefficients for country B but with the entries corresponding to other countries set to 0, the GHG emissions that occur in country B due to consumption in country A are given by $\mathbf{s}_{\mathrm{B}}\mathbf{L}\mathbf{y}_{\mathrm{A}}$.

Additional methodological details are provided in the methods chapters of the papers appended to this thesis.

2.1.2 Capital in MRIO analysis

MRIO tables are constructed using the supply-use tables stemming from national accounts (see e.g. method chapter of paper IV or [139] for details), trade-linked with bilateral trade data, and the treatment of capital in MRIO tables conforms with national accounts. The GFCF is reported as a distinct vector as part of the final demand matrix $\mathbf{Y}$. The fundamental difference between the GFCF and other final demand categories is recognised among IO practitioners, and many studies therefore refer to the final demand categories *households*, *government* and *non-profit institutions serving households* (NPISH) jointly as *final consumption*, a term that will be used throughout this thesis. The CFC, on the other hand, is usually embedded in the VA vector. Since many countries do not provide estimates of CFC, most MRIO databases do not explicitly provide the CFC as a distinct row vector but leave it embedded in the VA. As such, capital is treated exogenously in current MRIO databases, which entails that while CB accounting enables to assign the impacts associated with the production of upstream current requirements to the end consumers, the impacts associated with the production of capital goods remain assigned to the producers of that capital.

2.2 Data used

2.2.1 EXIOBASE

EXIOBASE is an EE MRIO database funded by the European Union (EU), containing detailed trade-linked EE SUTs as well as symmetric MRIOTs[d]. In this thesis, several versions of EXIOBASE were used, stemming from two major releases. The results in the first paper are based on EXIOBASE2[114] (v2) while the results in papers II to IV are based on EXIOBASE3 (v3, 4 and 6 respectively). EXIOBASE2 was compiled between 2011 and 2014 under the EU's 7th Framework Programme (FP7) project CREEA[e], and provides high-detailed (200 products by 163 industries) MRIOTs for 43 countries (including the 27 EU countries) and 5 rest-of-the-world (RoW) regions for the year 2007. EXIOBASE3 is an expansion of EXIOBASE2 compiled under the DESIRE[f] project, with the same product and industry resolution but with one additional country (the newest EU member Croatia). The major advancement with EXIOBASE3[113] is the availability of time series from 1995 to 2011 (nowcasted to 2015), as well as a substantial increase in the environmental extensions available. As opposed to other major MRIO databases (e.g. WIOD, EORA, GTAP and OECD), EXIOBASE

[d] Available for download free of charge from exiobase.eu
[e] Compiling and Refining Environmental and Economic Accounts
[f] Development of a System of Indicators for a Resource Efficient Europe

provides the different elements of the VA explicitly, including the CFC. This is discussed further in paper III.

2.2.2 KLEMS and WORLD KLEMS

The EU KLEMS[g] is an industry-level growth and productivity research project financed by the European Commission containing inputs and outputs of capital, labour, energy, materials, and services for all countries of the EU (in the July 2016 release[140]) as well as for the US[141]. The capital accounts are of particular interest for this study as they contained additional information about the GFCF by purchasing industries as well as the asset composition of the CFC. The KLEMS initiative is an ongoing project that releases regular updates and improvements. For instance, the most recent release available when this thesis began (which was used in papers I and II) contained capital data for 13 countries using NACE1 classification of 8 assets and 32 industries, and contained time series until the year 2007 only (2012 for a few countries). For paper III and IV, subsequent releases were used that had been updated to NACE2 classification, which implied that the number of assets was increased to 11 (adding the asset categories *cultivated assets*, *research and development* and *other IPP assets*) and the country coverage to 27 countries, with time series for the period 1995-2014 for most countries.

The WORLD KLEMS initiative[142] is a collaboration between several national statistics bureaus and research institutes, also aimed at facilitating growth and productivity research through a standardised growth accounting framework. Details on the KLEMS and WORLD KLEMS data used in this thesis is available in the main manuscripts and associated supplementary information files of the first two papers of the thesis.

2.2.3 Other sources

Additionally, other sources were used for specific purposes (described in the relevant papers). These include time series of national CFC aggregates from the World Bank[143] and tables of GFCF use by asset and industries from the National Bureau of Statistics of China[144].

[g] Capital (K), Labour, Employment, Material and Service inputs

3 Summary of papers

3.1 Paper I: Environmental impacts of capital formation

The background for this paper lies in the climate change challenge mentioned in the introduction chapter. In order to curb the problem, emissions must be curtailed, including those from capital formation. However, as developing countries are expected to build up and renew their capital stock, emissions from infrastructure development are expected to rise in the future. One of the research questions of this paper was therefore whether this is merely a transitory rise and if investments tend to become less carbon-intensive as countries become more developed (a question related to the Environmental Kuznets Curve hypothesis). We performed several analyses to this aim. Firstly, we calculated the share that the GHG emissions (also referred to as carbon footprint (CF) and GWP in the paper) associated with the GFCF constituted from the total GHG emissions of final demand for all countries in EXIOBASE and compared this share with the monetary share of GFCF and the GDP per capita (in purchasing power parity, or PPP), in other words comparing the relative size of GFCF with its relative impact.

We then investigated if there were any trends regarding the carbon intensity of assets purchased by countries at different stages of development. To enable cross-country comparison, we began by identifying the least and most carbon-intensive assets (that we referred to as "cleanest" and "dirtiest" assets), and determined the global carbon intensity of each asset by calculating the ratio of the GFCF of each asset and the corresponding CF on a global level. Once this was established, we studied how much of these two categories of assets were purchased by each country and compared this to the country' GDP per capita, in order to assess whether we could discern any correlation between the investment composition and level of development of countries.

We also conducted a structural decomposition analysis (SDA – see paper I for detail) of the CF in order to find out how much of the investment composition (reflected by the GFCF vector) respectively the CF multiplier (reflected by the product of the stressor matrix and the Leontief matrix) contributed to the total deviation of the CF against the global average (see paper for details); in other words, to what degree the deviation was due to countries investing in less carbon-intensive assets as opposed to assets being produced with cleaner energy sources.

In order to analyse how the carbon emissions associated with capital production could be allocated across industries, we combined the EXIOBASE database with the detailed capital data available in the KLEMS database. As mentioned in the introduction chapter, one of the difficulties involved when studying capital using MRIO databases is the lack of detailed information about how capital is used across industries. The GFCF vector describes how much of each asset the countries invest in every year, but not which sectors are responsible for the purchase. Likewise, the CFC provides information about the total values of all assets still in use at the end of the accounting period, but not the composition. Using the two-dimensional matrices of capital formation and consumption available in the KLEMS database, we were able to distribute the GFCF across purchasing industries, upon which standard CB calculations were done to calculate the GHG emissions associated with the investment in capital goods of different industries for all the countries covered by the KLEMS databases (see paper I for the country list) with the help of the environmental extensions in EXIOBASE. Full details on the methodological procedure can be found in paper I.

We found that in 2007 (the only year available in EXIOBASE2), GFCF constituted 24% of the global final demand but accounted for 30% of the global GHG emissions[h]. These shares were generally higher for countries with a large share of GFCF. China stood out with a GFCF making up 45% of the final demand and nearly 60% of the CF in 2007. The largest discrepancies between these two shares occurred for China, India, Brazil and Turkey, where the CF share was substantially larger than the GFCF share, indicating that investments were particularly carbon-intensive in these countries (three of which BRIC countries, which are often considered to be at a stage of newly advanced economic development[145]).

We also found that the majority of the global CF of GFCF could be associated to a handful of assets and countries. Out of the 9600[i] asset-country combinations taken into account, the largest 10 accounted for half of the total CF from GFCF (and the following 10 accounted for an additional 10%). Three of these ten assets were Chinese investments (in construction, machinery and equipment, and motor vehicles). Construction work in China alone accounted for 27% of the global CF from GFCF. By disaggregating the investments across purchasing industries using the KLEMS data, we found that service sectors were responsible for two thirds of the global CF from GFCF, with the real estate sector alone being responsible for a quarter of the global emissions.

Furthermore, our study revealed that the monetary value of investments tended to increase faster than the GDP, but that the opposite was true for the CF, indicating that richer countries invested in less carbon-intensive capital. We then analysed the asset composition of the seven countries with the least respectively most carbon-intensive investments and confirmed that the latter group invested in particularly carbon-intensive assets (such as construction goods and various machinery) and was located at the lower end of the GDP per capita scale.

The conclusions we could draw from the SDA were that the multiplier effect was responsible for most of the deviation from the reference value for high-income countries, while for lower to middle-income countries, both multiplier effect and investment structure effect contributed.

Another interesting finding concerned the occurrence of emissions. For the seven countries with the least carbon-intensive investments, only 23% (on average) of the GHG emissions from GFCF were emitted within the country, with the rest being outsourced overseas, particularly China (16%). For the seven countries with the most carbon-intensive investments, the figure was 67% (92% for China).

The results from paper I confirmed the importance of this thesis, namely:

- The GFCF constituted a substantial part of the economy and accounted for an even larger share of the global CF
- The CF of GFCF was particularly carbon-intensive for emerging economies and less so for wealthier countries
- Service sectors were responsible for the majority of the CF from GFCF

[h] In the paper, we state that the figures are 24% for both metrics. However, these figures are non-weighted averages across countries. The weighted (and more meaningful) averages are those plotted in Figure 2 of paper I, which are 24% and 30% respectively. Sadly, despite thorough proofreading, this methodological typo was not spotted until the paper was published.

[i] 49 countries times 200 assets

These results imply that if capital goods were indeed treated as intermediate goods and thereby endogenised into the inter-industry system in IO tables, the consequences for CB accounting would likely be substantial.

3.2 Paper II: Endogenising capital in MRIO models: the implications for consumption-based accounting

Following the results of the first paper, in paper II we constructed a global MRIO model in which capital flows were endogenised into the inter-industry matrix, which, at the time the paper was accepted and to the best of our knowledge, had never been done for a multi-regional model in a published study.

The principle behind capital endogenisation is that capital flows are incorporated into the inter-industry matrix, effectively "closing" the IO model for capital[101]. Previous studies of capital endogenisation on a national scale have applied either the augmentation method or the flow matrix method. The first method entails that the vectors of capital use and formation are simply incorporated as additional "capital" sectors in the inter-industry matric, thereby "augmenting" it. As indicated in a study by Lenzen and Treloar [129], this implies that capital goods are treated as one homogeneous commodity, and the method leads to the overestimation of the low-range multipliers and underestimation of the high-range multipliers. The flow matrix method is therefore preferred, as it entails that a capital flow matrix is constructed, i.e. keeping both asset and industry resolution, yielding more realistic results. The problem with this method is the high data requirements. As mentioned already, IO tables and national accounts typically do not feature detailed tables of capital use, and this paper therefore necessitated a substantial amount of work on data collection, harmonisation and processing, described in the paper as well as the associated supplementary material of the paper.

The principle behind the flow matrix method is, in itself, quite simple. A matrix of capital requirements $\mathbf{K}$ is added to the regular inter-industry matrix $\mathbf{A}$ so that a new Leontief inverse can be calculated:

$$\mathbf{L}^{\mathbf{K}} = \left(\mathbf{I} - (\mathbf{A} + \mathbf{K})\right)^{-\mathbf{1}} \tag{10}$$

This new Leontief matrix describes the direct and indirect current and capital requirements per unit of final demand and can be used to calculate CB impacts that include the impacts associated with the production of both current and capital goods used in the production.

To construct the capital flow tables, we relied on information from the KLEMS and WORLD KLEMS databases as well as additional information from national accounts. For the countries not covered by these sources, we constructed a generic capital use matrix based on an average of the sources available and applied a RAS-based routine to reconcile the generic capital matrix against GFCF and CFC proxies from the respective countries (this is explained in detail in appendix C2, along with additional methodological clarifications).

As discussed in the introduction chapter, measuring the use of capital over a specific period entails several difficulties, since unlike current goods, capital goods are not transformed and transported throughout the supply chain, but rather provide productive services. We chose to use the CFC as a measure of capital use despite the issues raised in the introductory chapter, the main one being the ambiguities regarding the estimation of it. The implications of this choice are further discussed in the penultimate section of this thesis.

The results in paper II are based on EXIOBASE3 (v3.3), which includes time series from 1995 to 2015 (the latter four years nowcasted). The availability of time series entailed an important advantage as opposed to the single year snapshot of EXIOBASE2, as it enabled to analyse trends over time. We found that the CB impacts of final consumption calculated with the new Leontief matrix are larger than those calculated with the regular Leontief matrix for all countries. This was expected; since all entries in the capital requirement matrix were positive, the total production requirements increase, leading to more emissions stemming from them. This increase, however, varied a lot across countries, ranging from an average increase over the entire period of 7% (Poland) and 48% (Brazil), indicating large disparities in the amount and the carbon intensity of the capital used by different countries.

We also studied the net change in CB emissions (that is, comparing the CB emissions of the total final demand). This involved some additional difficulties since it entailed the comparison of models in which capital is treated differently. The CB emissions of final demand calculated using regular CB accounting allocates the emissions of all capital formation occurring during a specific year to that same year (despite that this capital will be used in production processes in subsequent years). Our approach of endogenising the CFC entails that we allocate historical emissions from capital build-up to the final demand of the current year of study. In other words, it involves a comparison of emissions from capital stemming from different age cohorts. Such a reallocation of emissions over time is unconventional in CB accounting, but we argue that it is more consistent with the life-cycle approach that CB accounting implicitly aims to achieve.

Notwithstanding these issues, the comparison enabled us to compare the net change in CB emissions between the two approaches, and this revealed interesting results. We found that for most countries, the divergence between CB and PB emission observed in many previous studies were reinforced. That is, countries that were net importers of emissions saw their emissions import increase, and vice-versa for the countries that were net exporters of emissions. Out of the 49 countries and regions analysed, only four saw their status as emissions importer respectively exporter change. This was confirmed by comparing the patters of bilaterally traded emissions; for instance, using the conventional CB accounting approach, the EU was a net importer of emissions from its five largest trade partners, and this was increased further when capital was endogenised. The same was true for the USA. On the other hand, for China and Russia, the reverse was true.

We also analysed the changes in product level to identify the products that saw their footprint increase the most when capital was endogenised. This was done by studying the change in multipliers between the two approaches, differentiating between services and non-services as well as OECD and non-OECD countries. The study revealed that services, which are typically much less carbon-intensive than non-services, saw their multipliers increase substantially (up to 200% increase for real estate services and post and telecommunication services). We also found that multipliers were generally higher for non-OECD countries than OECD countries, indicating that the capital used was more carbon-intensive. Furthermore, we found that the change in multipliers was larger towards the end of the time series, indicating that the carbon emissions from capital used in production processes increased over time.

3.3 Paper III: The capital-augmented material footprint: the real material footprint of final consumption

In paper III, we continued the study of the implications of endogenising capital but focussing on material use rather than GHG emissions. These two impact categories are fundamentally different. GHG emissions are a flow from the anthroposphere to the natural environment (the atmosphere), while material use are a flow from the natural environment (the lithosphere) to the anthroposphere. Moreover, the release of GHG emissions is an unwanted side effect of production and consumption activities and therefore purely a nuisance, whereas the extraction of materials is a deliberate transfer for human use and a necessity to provide services essential to fulfilling human needs.

The research questions we wished to answer were the following: how much and which types of materials are embodied in the capital used to produce goods and services for final consumption? For which product categories does the material footprint increase the most when the material embodied in capital is assigned to the final products? Are there any differences in the current decoupling trends of material use against economic growth? To this purpose, we introduce a new indicator of material use, the Capital-Augmented Material Footprint (CAMF), which is calculated with a Leontief demand-pull model in which capital flows have been endogenised using the flow matrix method described in paper II.

In paper III, we also made significant improvements to our model. Firstly, the availability of new KLEMS releases entailed that we had access to capital use matrices for an additional 14 countries, bringing the total number of countries with detailed capital data to 31 (out of the 44 covered individually in EXIOBASE). Furthermore, the KLEMS data had been updated to NACE2 classification, which facilitated the harmonisation of data across the varied sources as well as entailed a more detailed differentiation of assets (as mentioned in the data chapter). Additionally, the publication of CFC aggregates for each country by the World Bank provided us with a benchmark value against which we could compare the CFC values available in EXIOBASE. Since EXIOBASE was the only MRIO that featured explicit estimates of CFC (the other MRIOs kept the CFC embedded in the VA), an obvious limitation of our first model was the credibility of those CFC estimates. The comparison with the WB values showed that the EXIOBASE estimates lied within a few percent of the WB estimates for the majority of EU countries, but diverged substantially for a few other countries, notably for Brazil, Russia, South Africa and Mexico. The WB CFC data was deemed more reliable than the EXIOBASE data, and we therefore decided to rescale the EXIOBASE CFC against the WB estimates (more details in method chapter of the paper).

The results presented in the paper focussed on the effects of endogenisation on the material use associated with final consumption. We compared the MF with the CAMF for four main groups of materials (biomass, fossil fuels, minerals and metals) and grouped the countries into OECD and non-OECD countries. We also studied the effects on individual product categories as well as analysed the differences between the CAMF and the MF of countries regarding the decoupling from economic growth. Our main findings were that the effects of endogenisation varied substantially between different materials, with mineral use and metal use seeing a much larger increase than fossil fuels and biomass. We also noted that the footprints of service sectors (particularly real estate services) increased substantially with the CAMF, indicating that the real material footprint of services was substantially larger when accounting for capital goods. Furthermore, we found that although the material use of final consumption was larger in absolute terms for all countries, the relative change over time was smaller for most countries, implying that more countries achieved relative and absolute decoupling of material use from economic growth when calculating it with the CAMF. Nevertheless, these trends were offset by opposite effects in a few large countries such as China, USA and India, and on a global scale, including the materials embodied in capital led to faster increase of the material footprints of final consumption and less decoupling.

While our endogenisation model was significantly improved in paper III, it was still based on certain assumptions that made it imperfect. In the supplementary material of paper II, we discuss these assumptions and present some results from the sensitivity analyses that we ran. One of the assumptions that substantially affected the results was that capital goods and current goods were assumed to have the same stressor intensities. This, of course, is unlikely, since capital goods currently in use were built in previous years, i.e. with different industry structures and different technologies. For the assets that have lifetimes of several decades (such as buildings and infrastructure), these differences could be substantial. For instance, in 1990, China's energy mix was constituted of almost 80% coal. In 2017, this share had decreased to 60% to make way for less carbon-intensive sources such as natural gas and renewables, and it is expected to decrease to 40% by 2040[146]. As such, the carbon intensity of Chinese production is likely to substantially decline over time. However, the flow matrix method entails that the current and capital requirements can no longer be differentiated once the inversion involved in the Leontief calculus has been performed, and the model therefore does not allow to assign different stressor intensities to the two types of requirements. This was the problem that we aimed to solve in paper IV.

3.4 Paper IV: A supply-use approach to capital endogenisation in input-output analysis

As the flow matrix method does not enable the differentiation of the different production requirements in CB calculations, we had to resort to a different type of model to solve the problem. Following an idea suggested by Rueda-Cantuche[147] and formalised by Lenzen and Rueda-Cantuche[148], we resorted to using supply-use table formalism. By developing an integrated supply-use framework that differentiates between current and capital flows (that we called the KSUT), we derived the Leontief inverses and multipliers analytically, which enabled us to perform CB calculations that allow the differentiation between upstream current and capital requirements, thereby enabling to assign different stressors to them. The framework is illustrated in Figure 3, while the full details are described in the paper.

As demonstrated in the paper, the KSUT framework did solve the problem that we set out to solve. However, one major component was still missing, namely the actual capital stressor matrices. These should reflect the technology mix of the capital used in the production processes, and to compile them, knowledge about the age cohort composition of the in-use capital stocks is required[149, 150]. Such information is rarely available, and compiling it requires the application of advanced dynamic stock models as well as substantial data collection. Furthermore, the combination of cross-temporal stressor intensities (which are normalised per monetary unit) also necessitates that these be expressed in constant prices. Although time series in constant prices are featured in recent versions of MRIOs (including EXIOBASE), our own experience with them indicates that they are still somewhat unreliable (details on the compilation process of the EXIOBASE sector-specific time series can be found in the additional publications V and VI). In other words, compiling actual stressor intensities would require tremendous work and lied far beyond the scope of this paper, the primary focus of which was the presentation of the KSUT framework. Therefore, we did not attempt to estimate stressor matrices based on real data, but instead compiled hypothetical stressor matrices that were used to illustrate the effectiveness of the framework (more details on this in the paper). Using these hypothetical stressor matrices, we provided a worked example in which we performed CB calculations on a single-region model (Australia).

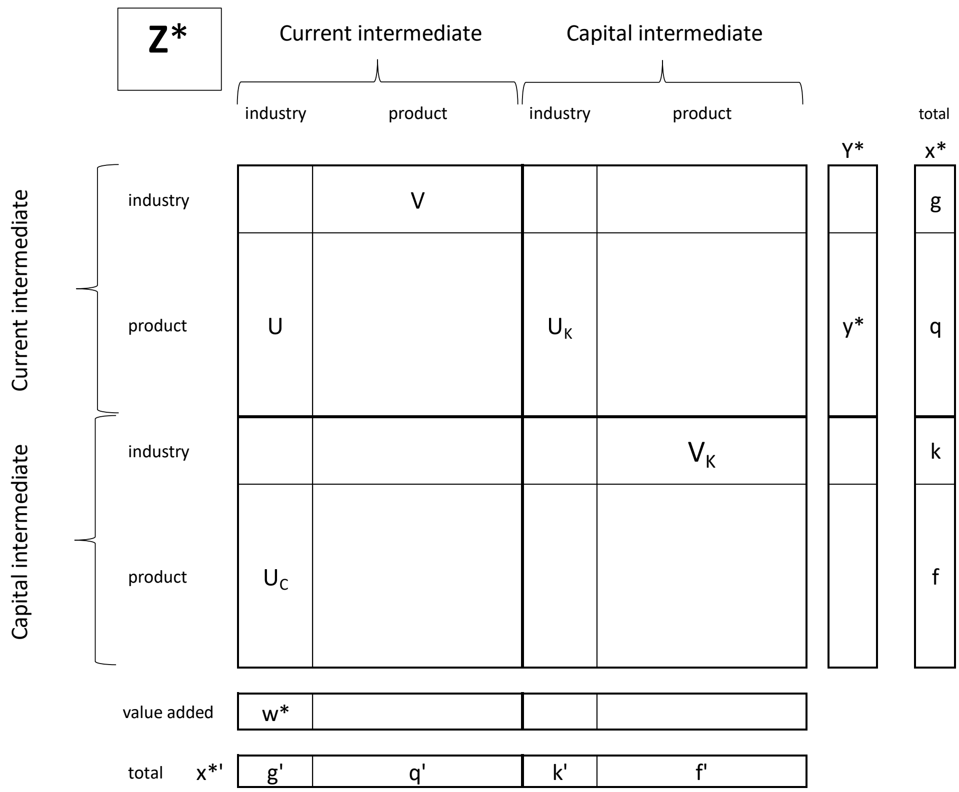

Figure 3: The KSUT framework, with the following main components:
$\mathbf{U}$ – current use matrix
$\mathbf{V}$ – current supply matrix
$\mathbf{U}_\mathrm{C}$ – stock use matrix
$\mathbf{U}_\mathrm{K}$ – investment use matrix
$\mathbf{V}_\mathrm{K}$ – capital supply matrix

The results showed that a change in capital stressor matrices led to a substantial increase in both GHG emissions, material use (domestic extraction) and land use change (LUC). The increase was particularly pronounced for the use of materials: a 100% increase in the stressor intensity of capital led to a 35% increase in total material use. We also studied the effects that our framework had on individual product categories and found that service categories were particularly affected. A 100% change in capital stressor intensities led to an increase of up to 95% in the total material use associated with real estate services, 79% for education services and 64% for public administration and defence services, indicating that these service groups were large consumers of resource-intensive capital. We also noted that the effects varied a lot across indicators. For instance, the material use associated with the generation of electricity by coal increased by up to 90%, while the increase in GHG emissions was negligible (due to the high carbon intensity of coal combustion itself).

While our results may be exaggerated because of the extreme choice of stressor intensity used in our worked example, the results of paper IV confirm that the assumption of constant stressor intensities is indeed problematic, and that an MRIO model with endogenised capital ought to include a dynamic perspective that takes into account the age cohorts of current in-use capital stock.

4 Discussion

4.1 Scientific contribution of this thesis

The treatment of capital in IO and MRIO analysis has been a recurrent theme in IO literature for decades. While several studies have argued that capital ought out to be included in the inter-industry production system, only a few studies that feature capital endogenisation have been published (and to our knowledge, only two that have been done on a global scale, including ours). One of the reasons for this is that detailed data on the use of different assets by industries has, until recently, been scarce and limited to a few countries. The work undertaken by the KLEMS and WORLD KLEMS initiatives therefore constitutes a great resource for the development of models such as those presented in this thesis.

There has been a renewed interest in capital in environmental literature, with three recent papers discussing the importance of capital and infrastructure in the Proceedings of National Academy of Science (PNAS)[17, 19, 51], one study of global capital endogenisation in Nature Communications[42], two articles on the endogenisation of capital in the USEEIO[151], as well as our Environmental Science and Technology paper, which received the ACS Editor's Choice Award and was feature on the front cover of the issue. This is an indication that the importance of capital in CB accounting studies is recognised, and this thesis therefore constitutes an important contribution not only to the field of IO, but also to the fields of Industrial Ecology and environmental science and policy-making in general.

The results presented in this thesis show that the endogenisation of capital leads to important reallocations of CB emissions, which in turn may have important implications for e.g. global climate policies. CB accounting was developed to address the carbon leakage phenomenon and to hold consumers, rather than producers, responsible for emissions. The approach of endogenising capital follows this line of thinking; if new factories in China are constructed to respond to an increasing demand from other countries, the material used and emissions that are associated with them should arguably be assigned to the countries driving their construction, in the same way that CB accounting assigns emissions to end consumers.

Because of the long-term atmospheric effects of carbon dioxide, climate scientists agree that both past and future emissions need to be taken into account when estimating the impacts of anthropogenic GHG emissions on global warming, and that the *cumulative* CO_2 emissions need to remain below a certain level to limit the resulting climate change[152-155]. Hence, climate policies aiming to limit global warming need to set cumulative emission targets, meaning that emission quotas need to be allocated among countries[153, 154, 156, 157]. Achieving a fair allocation of quotas entails not only looking at current and future emissions but also considering countries' responsibility for historical emissions[157-163]. Such intertemporal dynamics are currently ignored in CB accounting, and our approach of endogenising CFC is therefore consistent with this temporal perspective and allocation of emissions, holding well-developed countries accountable for the emissions associated with the capital they are currently using while allowing less developed countries to build up the infrastructure they need to fulfil their basic needs and to reach a level of development that is in accord with the UN Sustainable Development Goals.

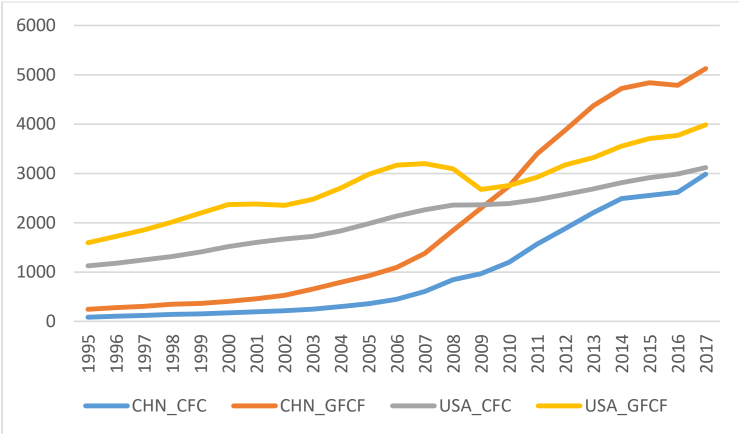

Figure 4: CFC and GFCF (in current billion US$) for the USA and China. Source: World Bank[143, 164]

As can be seen in Figure 4, there is a significant disparity in the evolution of the GFCF and CFC of China, a country that has seen a recent rapid expansion of its infrastructure and capital stock. Since the investment in capital is accounted to the year it occurs and the use of capital to subsequent years, a time lag arises between the two measures. For a developed country that has had a well-established infrastructure in place for a relatively long time (such as the USA), this lag is less pronounced. This leads to a substantial discrepancy between the approach of endogenising the CFC and the traditional CB accounting approach of assigning the environmental impacts of capital formation to the period when they occur, justifying the approaches that have been argued for in this thesis and confirming their importance and relevance for fair and just GHG accounting principles.

4.2 Limitations

4.2.1 Data

4.2.1.1 EXIOBASE

The development of global MRIO databases has provided environmental researchers with a practical and valuable tool to study the impacts associated with consumption activities across the globe. Nevertheless, it is important to keep in mind that they remain models and that both the source input data as well as the processed output data can be uncertain. Furthermore, like all models, MRIO models rely on multiple assumptions that add uncertainty to the results. The limitations associated with MRIO analysis and the discrepancies between different MRIO databases have been studied and discussed in a multitude of papers[109, 117, 165-170] and will therefore not be recited anew here.

4.2.1.2 KLEMS and WORLDKLEMS

The resolution of the KLEMS tables used to disaggregate the EXIOBASE data is much coarser than that of EXIOBASE, particularly regarding assets. Such a low asset resolution may seem like a limitation, but one must remember that this only concerns capital goods, which are typically less diverse than current goods. In fact, for construction-related assets, it was the resolution of EXIOBASE that constituted a bottleneck: while KLEMS differentiates between residential and non-residential structures, EXIOBASE (and other MRIOs) do not. Construction goods (which make up for around half of the global capital formation every year) are all aggregated into one category in EXIOBASE.

As mentioned in the paper summaries, detailed data on capital use by industries was not available for all countries. The generic capital matrix used to construct the capital distribution proxies for the countries not covered by auxiliary databases was compiled as the average of the capital matrices available in NACE1 or NACE2 classification. These stem chiefly from developed countries, and it is therefore likely that the generic matrix does not reflect the actual composition of capital use from countries at a different stage of development. Although the generic distribution matrix was adjusted for each individual country, obtaining additional capital distribution matrices for some of the larger countries not currently covered such as India, Brazil, Russia and Indonesia would be highly desirable.

4.2.2 Model assumptions

Like all models, our model is based on several assumptions. One of these was discussed and analysed extensively in paper IV, namely that the flow matrix approach used in paper II and III assumes that current and past assets are built with the same technologies and stressor intensities, an assumption that was shown to have important implications on the CB impacts.

Other assumptions concern the construction of the capital requirement matrix. As described in the SI of paper II, we use the GFCF to disaggregate the KLEMS assets into the 200 product categories and 49 countries of EXIOBASE, despite that we endogenise the CFC. This entails that the CFC (describing capital stemming from previous years) is distributed according to the current investments, which is arguably not realistic. Furthermore, when no capital use matrices were available, other capital measures were used as distribution proxies to disaggregate the CFC, including matrices of capital stock, capital compensation and GFCF, as these were deemed more appropriate than the alternative of using the generic capital use matrix. Finally, our models endogenise the entire vector of GFCF, as EXIOBASE (as well as all other major MRIO databases) do not provide details on whether GFCF is purchased by industries, government or households. The latter is particularly important for developing countries, where e.g. housing construction is often done by households themselves[171]. This entails that our endogenisation model may overestimate the capital used by industries to produce goods for final consumption.

4.2.3 Estimation of capital use

For the intents and purposes of this thesis, the CFC was considered to be the most appropriate measure of capital use readily available (or at least easily estimated) in today's MRIO databases. The recently released CFC estimates from the World Bank provided an important benchmark value that enabled us to adjust our model so that some of the inconsistencies and unlikely results that we encountered in the first version of our model could be investigated and the data reconciled. Nevertheless, the CFC remains an economic measure that describes a loss in value of past investments, and it is therefore prone to be affected by tumultuous economic events such as economic crises, currency devaluations, introduction of new currencies, etc. Furthermore, it is often estimated through simple depreciation functions, which differ across countries. Economists have therefore argued for the establishment of a formal measure of *capital services*[96, 97, 172].

While the concept of capital services can be traced back to the end of the 19th century[77, 78], the modern capital service theory was developed in the second half of the 1900s[95, 173-175], and has been revived in the last two decades. A large body of literature has been dedicated to capital services, often in connection to the measure of growth and productivity[89, 91-94, 96, 98, 172, 174, 176-178]. Capital services can be seen as the contribution of capital goods to the production processes, i.e. the flow of productive services from capital assets to production. In other words, capital services reflect the physical inputs to production processes, while capital goods act as mere carriers of these services. The terminology has sometimes been criticised, since the services referred to are not services in the classical meaning, i.e. outputs of production such as health services or transportation services.

Problems arise when attempting to estimate capital services since they are not directly observable (i.e. they are not as easily quantifiable as, say, the quantity of fuel needed to drive a truck from A to B). Moreover, there is often no recorded transaction when a capital good delivers a service to a production process[172]. As a result, the estimation of capital services is complex and ambiguous, and capital service estimates remain a rarity in national accounts[90]. The SNA suggests that capital services can be thought of as the way to capture the changes in value of the assets used in production in the balance sheets and production account[75], a definition close to the CFC, which further legitimises our choice of using the CFC as a measure of capital use.

4.2.4 Temporal aspects

A fundamental feature and one of the defining characteristics of capital goods is that they are used for more than a year. In practice, many assets are used for much longer, with lifetimes often exceeding several decades. This temporal aspect complicates not only the accounting of capital but also the endogenisation process, particularly when attempting to assess the net effects of the capital endogenisation by comparing traditional footprints with capital-augmented footprints. As explained in paper II, comparing both approaches entails comparing environmental impacts that account for capital differently; the carbon footprint of a country calculated with the traditional Leontief demand-pull model includes the impacts associated with the GFCF, whereas the footprint calculated with the endogenisation model takes into account historical emissions that occurred when the capital currently in use was produced. This temporal reallocation of emissions, although consistent with a life-cycle perspective, could be seen as less intuitive. For instance, traditional CB accounting can easily be compared to PB accounting on a yearly basis since the global totals are equal. The global capital-augmented CB emissions, however, only match the global PB emissions on a cumulative, retrospective *and* prospective perspective, i.e. when all past, present and future emissions are summed. In paper II, we bypassed the problem by creating a residual vector of capital formation to ensure that the global yearly emissions were comparable, but this was only a workaround. Firstly, this entailed that investments were accounted for during the year of study, which contradicts the fundamental accounting principles advocated for in this thesis. Secondly, for countries where GFCF vastly exceeds the CFC (such as China – see Figure 4), the residual GFCF ends up dwarfing the CFC and the net change observed between the two approaches becomes insignificant. Thirdly, accounting for some of the carbon emissions associated with the GFCF during a specific year implies that the CFC must be adjusted in subsequent years, which further complicates the model (this is discussed in paper II).

4.2.5 Scope of capital

As discussed in the introduction, there are still ambiguities surrounding the concept of capital. Although the publication of capital measurement guides (such as the OECD manual[90]) and the release of official guidelines by the SNA[75] and ESA[179] have contributed to a certain formalisation and standardisation of capital measurement in national accounts, the definition of capital, or at least the recommendations regarding how to measure it, are regularly being changed. For instance, the NACE1 classification standard considered weapon systems as intermediate requirements. In the NACE2 revision (which follows the guidelines set by the ESA[140]), they are to be treated as capital expenditures. Hence, a country's choice of classification standard affects how capital is measured. Other national variations occur; for instance, despite that the SNA dictates that cultivated assets (such as fruit trees, dairy cows, sheep raised for wool production, etc.) are to be treated as capital expenditures, they are still not capitalised in the USA and Canada[180].

4.3 Future development of the model

4.3.1 Incorporating the dynamic aspect of capital

Endogenising capital using methods such as the flow matrix or the augmentation methods entails that capital is modelled statically, which can be warranted when performing ex-post analyses such as those presented in the papers included in this thesis. However, as discussed in paper IV, the dynamics of capital are more complex, and should our model be developed further to allow for ex-ante analyses, capital arguably ought to be treated dynamically. As one anonymous reviewers pointed out, the investments described in the GFCF serve fundamentally different purposes. Capital theorists often differentiate between the *replacement capital*, which constitutes the investments done to maintain and upgrade the existing capital, and the *net capital formation*, which entails new investments. The dynamics of these concepts are evidently different and should therefore be treated accordingly in a prospective model. Substantial work has been done on dynamic IO modelling since Leontief formulated his first dynamic IO model with endogenous capital requirements in 1949[183], from the early works of Morishima[184] and Solow[185] and the models by Duchin[186] and ten Raa[187], to recent work by e.g. Gurgul and Lach[188] and Okuyama[189]. Incorporating the dynamics of capital would hence constitute a potential avenue for future versions of our model.

Using a supply-use framework to perform CB calculations is a recent idea that has so far been applied only in a handful of published studies[148, 190-192]. Whether it has a future along the relatively well-established IO framework remains to be seen. One anonymous reviewer expressed that the advantages that our KSUT offers may be offset by its complexity; or, like the reviewer so eloquently put it, “applied folks will be overwhelmed by the excessive formulas”.

4.3.2 Data refinement and update

The data sources used in this thesis are regularly being updated and refined. During the relatively short period of time that this thesis was performed, major advancements in the data occurred. The time series released along with the third version of EXIOBASE enabled the study of trends over two decades as opposed to the snapshot glimpse of the economy offered in EXIOBASE2. Furthermore, the KLEMS database was updated on several occasions to include a higher asset resolution and a wider country and year coverage. The WORLD KLEMS database has announced future releases covering more countries, and the ongoing development of regional KLEMS initiatives such as ASIAKLEMS[181] and LAKLEMS[182] (Latin America KLEMS) are also promising the release of detailed capital use matrices for a range of countries not covered in KLEMS. Furthermore, other research groups are concurrently working on improving other aspects of capital endogenisation; for instance, a recently accepted paper by Miller et al.[151] has focussed on the disaggregation of the GFCF in the US into private, public and government expenditures by using a variety of auxiliary sources. Such improvements entail that the models developed in this thesis can be further refined. Hence, it is my hope that the model I have constructed in this thesis will not be consigned to oblivion but will live on to be further developed and improved using future data releases and method advancements.

5 Conclusion and outlook

5.1 Summary and conclusion

Capital goods are essential to satisfy most human needs, as they embody the material requirements that provide services such as shelter, mobility and protection, the infrastructure needed to provide clean water, electricity, communication services and consumer products, as well as the means to produce these physical requirements (e.g. machinery, transport equipment, etc.). As we have seen throughout this thesis, capital goods are also responsible for a large share of the global GHG emissions and material extraction from the lithosphere. In monetary terms, the gross fixed capital formation stands for a quarter of the global final demand. The impacts from producing capital goods is, however, much larger. The GFCF contributes to 30% of global GHG emissions and 62% of global mineral use (including 46% of aluminium, bauxite, zinc, and lead ores; 57% of gravel and sand; 62% of iron ores; 63% of clays; 70% of limestone and gypsum; and 74% of building stones).

Current EE MRIO models and CB accounting approaches do not treat capital goods as intermediate production requirements and therefore fail to assign all life-cycle impacts to the end consumer. This important research gap concerning the accounting of capital in MRIO models has been addressed in this thesis. By closing the IO model for capital, capital goods have been incorporated into the inter-industry system, enabling CB calculations that account for the impacts associated with both the current and capital requirements.

I set out this thesis with three main research questions:

1- How can capital be better integrated in current MRIO analysis?
2- How does the endogenisation of capital affect the CB accounting of environmental impacts?
3- What are the main difficulties and challenges of endogenising capital, and how can they be addressed?

These questions have been studied throughout this thesis and in the four appended papers, looking at the environmental impacts of capital, the methods to endogenise capital, and the effect that the endogenisation of capital has on the estimation of carbon and material footprints. Two different models for estimating CB impacts with endogenous capital were presented. The results stemming from them confirmed that the endogenisation of capital leads to significant reallocations of CB emissions not only across countries, but also across product categories. Moreover, it increased the gap between PB and CB emissions observed in many other studies, which is of high relevance for environmental policy-making. The results also revealed that the impacts associated with service sectors (which constitute a growing share of the final demand for OECD countries) increased considerably more than for non-service sectors, implying that services contribute much more to environmental problems than previously thought. The difficulties and future challenges associated with the endogenisation of capital were identified, and these can be aggregated into two main points. Firstly, as opposed to current goods, capital goods cannot be measured in terms of units or kg used, and the input of capital into production processes must therefore be estimated with depreciation models. These vary across countries and are prone to be affected by turbulent economic events. This renders the estimation of capital use complex and ambiguous. Secondly, the lack of available data impinges on the robustness of the endogenisation models, particularly the lack of age cohort composition of the capital stock currently in use. The present thesis has shown that endogenising capital in MRIO analysis has important implications for CB environmental impact assessments and could therefore serve as a useful starting point for future work on the topic. However, I would argue and recommend for the endogenisation models presented here to be further consolidated with e.g. explicit stock-cohort assessments of infrastructure and additional national estimations of capital use disaggregated over assets and utilising sectors.

5.2 The future of consumption-based accounting

It has been nearly two decades since CB accounting was developed, with the aim of assigning impacts associated with production to consumers rather than producers so that fair climate mitigation policies could be instated. The footprint concept is now globally acknowledged and recognised, but global carbon emission policies are still non-existent, let alone based on CB principles. The 2016 Paris agreement may have been the first climate agreement signed by all UN members (at the time)[193], but it entailed emission-reduction *pledges* rather than binding targets. The IPCC recently reported that drastic emission abatement measures are needed in the coming *decade* to avoid lasting and irreversible changes to ecosystems[194]. In light of such adverse developments, some are questioning the political feasibility of CB accounting[40, 195]. While the future of CB arguably lies in politics rather than science, research must continue. As expressed by the American writer and philosopher Elbert Hubbard[j]: "there is no failure except in no longer trying". Hence, databases need to be continuously updated and methods improved, and the work presented in this thesis hopefully constitutes an improvement, or at least a valuable and useful contribution, to the current state-of-the-art of MRIO analysis. Even in the absence of global carbon emission policies, many countries are adopting voluntary measures to reduce both their domestic emissions as well as the indirect emissions occurring overseas as a result of their consumption of imported goods. For such purposes, CB accounting provides the necessary tools to inform consumers about how their lifestyles and consumption choices affect the environment, and it is important that such tools present results that are as trustworthy and exhaustive as possible.

[j] Who, ironically enough, perished aboard RMS *Lisutania* when she was sunk by a German submarine off the coast of Ireland in 1915

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7 List of appendices

7.1 Appendix A: Further notes on the accounting of capital

7.2 Appendix B: Paper I

7.3 Appendix C1: Paper II

7.4 Appendix C2: Supplementary material for paper II

7.5 Appendix D1: Paper III

7.6 Appendix D2: Supplementary material for paper III

7.7 Appendix E: Paper IV

Appendix A: Further notes regarding the accounting of capital

The information featured in this appendix has been gathered mainly from the OECD capital measurement guide[1], the UN Handbook of Input-Output Analysis[2] and the SNA[3]. Further sources are referenced throughout the appendix.

1 The asset boundary

As discussed in the thesis, the GFCF describes the acquisitions less disposals of *fixed assets*, which the SNA defines as "produced assets that are used repeatedly or continuously in production processes for more than a year". This definition contains several elements that are crucial regarding whether or not goods should be recorded as GFCF:

- Assets must be outcomes of production processes
- Assets must be used more than once
- Assets must be used as inputs to production processes
- Assets must be used for more than a year

This section provides additional details on the current guidelines concerning the classification of goods as fixed assets, i.e. whether or not they should be recorded as GFCF. This differentiation is known as the *asset boundary* and is not always clear-cut. While some goods can be classified as capital goods based on their characteristics alone (few people buy combine harvesters for entertainment purposes), other durable goods may be used by final consumers or businesses alike. These includes, for instance, computers, mobile phones, power tools, white goods, cars, trailers, software, etc. Therefore, the classification of such goods as final consumption or GFCF is often done with the help of additional data (such as surveys of household expenditures and business capital formation). The following subsections discuss the characteristics and intricacies of the main asset categories.

1.1 Dwellings

In capital accounting, dwellings used as principal residence are treated as capital goods under the rationale that they produce housing services to unincorporated enterprises (i.e. the owners). What constitutes a dwelling is defined more by the purpose of it (housing) than its appearance. Hence, dwellings include not only "regular" households such as houses and apartments, but also other types of structures as long as their primary use is to provide housing. These include houseboats, caravans, hostels, retirement homes, orphanages, housings for military personnel etc. Also included in the dwelling category are permanent structures associated with residences, such as garages. Incomplete buildings are to be included as well. However, durable products within the household (e.g. machinery, white goods, personal cars, etc.) are categorised as final consumption expenditures, as they do not lie within the production boundary.

1.2 Other buildings and structures, land improvements

Other buildings include all buildings whose primary purpose is not housing, i.e. museums, monuments, prisons, hospitals, schools, warehouses, stores, hotels, restaurants, cinemas, etc. Other structures include all kinds of infrastructure, e.g. roads, tunnels, train tracks, airfield runways, harbours, dams, pipelines, power lines, mining infrastructure, etc. Whether the buildings and structures described above are owned privately or publicly is irrelevant with respect to the asset boundary; they must be classified as GFCF notwithstanding.

According to the SNA, the value of land does not contribute to GFCF. However, land is an important and necessary asset in the production of capital, and therefore, any alteration to land that somehow helps to improve its productivity or quality should be recorded as GFCF. Land improvements include clearance, construction of ditches, local wells, fences, etc. Bigger structures that contribute to the productivity of land, such as dams and larger irrigation systems, fall under the category "other structures", since they are not integral to a specific piece of land.

The value of land can be difficult to distinguish from the value of the structures located on it, but the differentiation is necessary for accounting purposes, since the value of land does not depreciate, whereas the structures on it do[4].

1.3 Machinery and equipment

Machinery and equipment constitute part of GFCF if they are used in production processes. These include transport equipment (for transport of both people and objects – vehicles, aircrafts, trains, etc.), ICT equipment (e.g. computers, phones, etc.), and all kinds of machinery and equipment that are used with the purpose of facilitating production: process machinery, office machinery, medical appliances, furniture, etc. This excludes assets purchased by households for use as final consumption. As exemplified in the introductory chapter of the thesis, a car purchased by a household to be used privately should be treated as consumer good and should therefore be recorded as final consumption, whereas the same car purchased by someone in the household who also owns a company and intends to use the car for associated business trips should be recorded as capital formation. This also implies that one particular asset can be converted from capital good to consumer good (e.g. if an enterprise decides to sell some of its cars to private households), and vice-versa.

Machinery that are integral to buildings (such as solar panels, central heating boilers, etc.) should be accounted for along with the building itself, whether it is a dwelling or a factory building. Moreover, some investments that do fit the criteria for GFCF may be excluded from it for practical purposes if their contribution to the total investments is very small. Examples include small tools or office supplies.

1.4 Military equipment

The guidelines regarding military equipment diverge. In previous versions of the ESA and SNA, all government expenditure on construction and durables used for military purposes was excluded from the capital accounts and was instead treated as intermediate consumption[2]. This was changed in the 1995 release of the ESA[5], and the most recent version (2010) states that GFCF should include "structures and equipment used by the military" as well as "light weapons and armoured vehicles used by non-military units". Also included are "dwellings acquired for military personnel" as well as "military inventories".[6]

Likewise, the 2008 release of the SNA states that expenditures on "large military weapon systems" which includes "vehicles and other equipment such as warships, submarines, military aircraft, tanks, missile carriers and launchers, etc.") should be recorded as GFCF, while "expenditure on durable military goods" (such as ammunition, missiles, rockets and bombs) should be recorded as inventories until used, when they are to be recorded as intermediate consumption. This, however, excludes "certain types of ballistic missile with high destructive capability". The SNA also considers dwellings acquired for military personnel as part of the GFCF, as well as "machinery and equipment other than weapon systems acquired for military purposes"[3].

The most recent release (1999) of the UN Handbook of Input-Output Table Compilation and Analysis, despite being released four years after the 1995 ESA, states that "outlays by government on construction and durable equipment that can only be used for military purposes" should not be included in the GFCF. However, the UN noted in the 2018 Handbook on Supply, Use and Input-Output Tables With Extensions and Applications (released as draft only) that "many countries are already including as GFCF […] government expenditures on military durable goods other than weapons systems"[7]. Meanwhile, the 2009 OECD capital measurement guide considers "weapons systems" as fixed assets and therefore as part of the GFCF[1].

To summarise, while most recent guides agree that buildings and large machinery and equipment purchased for military purposes should irrevocably be treated as GFCF, it is likely that the actual practices vary from country to country.

1.5 Cultivated and living assets

GFCF includes living assets that produce products of agriculture and forestry, under the condition that they are used under longer periods to produce goods repeatedly and that they are under human management. Examples include dairy cattle, sheep raised for wool production, horses raised for breeding, draft animals, animals used for transportation, entertainment, etc. Hence, animals raised for slaughter do not make part of the GFCF. Likewise, cultivated biological resources that yield products repeatedly, such as fruit trees, vines, trees yielding bark, resin, etc., are to be recorded as GFCF, whereas products that are only harvested once (e.g. trees grown for timber), or fruit trees that grow in the wild, are not. The GFCF of cultivated products also includes costs incurred before the assets start to yield output, such as costs of clearing grounds, installing various protections from weather, etc.

1.6 Intangible fixed assets

Intangible fixed assets often take the form of intellectual property and typically entail additional accounting difficulties. Intangible fixed assets can be broken down into several subcategories.

1.6.1 Research and development

Research and development (R&D) expenditures should, according to the SNA, be reported as capital formation, since they contribute to the increase of knowledge and eventually leads to improvements in productivity and hence to economic benefits. R&D expenditures that do not lead to economic benefits should be recorded as intermediate consumption. This distinction is not always clear though, and the valuation of R&D is generally problematic. The SNA recommends that R&D expenditures should be estimated in terms of the economic benefits they are expected to provide; in practice, however, they are often measured as the sum of the costs related to R&D.

1.6.2 Computer software and databases

Many production processes are dependent on computer software and databases, and these should therefore be classified as GFCF. Both the development, purchase and regular extensions and upgrades of the software should be included.

1.6.3 Mineral exploration

Mineral exploration and evaluation expenditures form part of the GFCF, since they contribute to the formation of intellectual capital that affects the productivity and efficiency of future production activities.

All costs incurred in relation to mineral exploration should be included, such as licence costs, pre-exploration assessment costs, costs for drilling, transportation, aerial surveys, etc.

1.6.4 Literary, artistic and entertainment originals

Literary, artistic and entertainment originals may also be considered as fixed assets that contribute to the formation of capital, since they are used to produce copies that will be sold and generate income. The originals include e.g. tapes, models, manuscripts, etc., and they should be valued at the purchaser's cost if they are sold on the market. If not, other valuation methods must be used.

2 Other concerns

2.1 Second-hand goods

Second-hand goods receive a special notion in accounting guides. Only the transfer costs should be added to the GFCF (unless they are purchased from abroad and thus constitute new entries into the domestic economy). The purchase costs must hence be netted out by equivalent sale costs; that is, a sale is reported as a negative expenditure. This implies that final GFCF figures may be negative, although this is rather uncommon[3]. These transfer costs constitute a part of what is referred to as *cost of ownership transfer*, which entails all costs associated with the purchase or disposal of capital assets, including items such as commission charges, extra professional charges involved (lawyers, estate agents, specialists, engineers, etc.), transfer taxes, transport / delivery / end of life costs, etc. All these costs associated with the ownership of capital must be included in the GFCF since they incur as a direct consequence of the capital acquisition / disposal.

2.2 Improvements to existing assets

Another important distinction concerns improvements to existing assets, such as renovation of office buildings, upgrade of software, etc. Such expenditures do not lead to the formation of new assets, but may still need to be recorded as GFCF. However, the SNA dictates that ordinary maintenance should be reported as intermediate consumption, and it may therefore be difficult to decide how to classify the undertaken work. If the improvements lead to an increase in the performance and / or capacity of the asset, it should be reported as GFCF. This is also the case if the improvements are done following a deliberate investment decision and not due to the asset's condition, and / or if they significantly increase the assets' service life. On the other hand, investments that simply keep assets in good condition rather than increase their performance are to be treated as normal operation costs and should be recorded as intermediate consumption.

2.3 Asset ownership

If the owner of a fixed asset is not the same as the unit that uses it in production, the reporting can be problematic. For instance, assets acquired under financial leasing should be recorded in the balance sheet of the lessee rather than the lessor, despite that the lessor is the legal owner. Furthermore, if a fixed asset is built or purchased by several units, e.g. a household committee, it should be assigned either to a separate governing entity that takes over the responsibility or to a NPISH.

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Appendix B – Paper I

Södersten, C-J, R. Wood and E. Hertwich. 2018a. Environmental impacts of capital formation. *Journal of Industrial Ecology* 22(1): 55-67.

Environmental Impacts of Capital Formation

Carl-Johan Södersten, Richard Wood, and Edgar G. Hertwich

Keywords:
carbon footprint
environmentally extended multiregional input output (EE MRIO) analysis
EXIOBASE
gross fixed capital formation
KLEMS
national accounts

Supporting information is linked to this article on the *JIE* website

Summary

The investment in capital goods is a well-known driver of economic activity, associated resource use, and environmental impact. In national accounting, gross fixed capital formation (GFCF) constitutes a substantial share of the total final demand of goods and services, both in terms of monetary turnover and embodied resources. In this article, we study the structure of GFCF and the environmental impacts associated with it on a global scale, and link it to measures of development. We find that the share of GFCF as part of the total carbon footprint (CF) varies more across countries than GFCF as a share of gross domestic product (GDP). Countries in early phases of development generally tend to invest in resource-intensive assets, primarily infrastructure and machinery, whereas wealthier countries invest in less resource-intensive assets, such as computers, software, and services. By performing a structural decomposition analysis, we assess the relative importance of investment structure and input-output multipliers for the difference in carbon intensity of capital assets, and find that the structure of investments plays a larger role for less-developed countries than for developed countries. We find a relative decoupling of the CF of GFCF from GDP, but we can neither confirm nor rule out the possibility of an absolute decoupling.

Introduction

The impacts of infrastructure development are a well-known driver of economic activity and the associated resource use and environmental impacts (Müller et al. 2013; Chen and Graedel 2015). In terms of the carbon footprints (CFs) of nations, capital investments constitute a substantial share of the final demand of goods and services: Hertwich and Peters (2009) assign 18% of global greenhouse gas (GHG) emissions to capital investments. The embodiment of these emissions in the stock of manufactured capital is, however, not necessarily to satisfy the current requirements of a population, but for their future development, and potentially for producing goods for export. Future scenarios of climate-change mitigation will further involve extensive investments in new infrastructure (IPCC 2011).

Understanding the size and composition of the capital is a central objective of industrial ecology (Weisz et al. 2015). Weisz and colleagues (2015) argue that the flow of material and energy from and to the environment generated by the unending process of reproducing manufactured capital defines the whole industrial metabolism, and that reducing its environmental and resource impacts without reducing its function to human well-being is the crucial challenge for long-term sustainability. Pauliuk and Müller (2014) further this line of thinking by identifying different roles of in-use stocks and describe capital stock as not only a means to produce goods and supply services, but also as resource repository, indicator of wealth, and as central part in the social metabolism. Many capital goods are characterized by a long lifetime (several decades/centuries for, e.g., infrastructure, dwellings, power plants, etc.) and static properties (buildings, infrastructure, large machinery, etc.) and, as a result, play important roles as city shapers, consumption couplers, and determiners of the long-term dynamics of the social metabolism.

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Understanding the capital stock is therefore a requirement for understanding the process of economic development, structural change, and the use of resources and could therefore provide valuable insight for further energy and climate research (Pauliuk and Müller 2014).

In the System of National Accounts, infrastructure is treated in a number of ways, one of which is the annual gross fixed capital formation (GFCF)—"the total value of a producer's acquisitions, less disposals, of fixed assets during the accounting period plus certain specified expenditure on services that adds to the value of non-produced assets" (OECD and UN 2009, 198). Fixed assets are assets used repeatedly in production processes for over a year (Eurostat 2008). GFCF accounts for almost 25% of the total global final demand and hence plays a major economic role, but capital stock is also an important constituent in the social metabolism. The GFCF therefore constitutes a flow of long-term investments purposed to build up or maintain production capacity.

While not considering the services that capital provides, the production of capital goods does cause high environmental impacts and is often related to a specific phase of development. In a recent study on the energy use in China, Xie (2014) concluded that energy use associated with GFCF was much larger than for aggregated household consumption, accounting for 49% of the total energy use by final demand category in 2010. Environmental impacts from GFCF are expected to level off as economies mature (Müller et al. 2006; Peters et al. 2007; Pauliuk and Müller 2014; Chen and Graedel 2015), given that building up the capital stock is more energy and resource intensive than maintaining it. Chen and Graedel (2015, 4) talk about goods reaching "saturation levels" in a study estimating historical in-use stocks of various types of capital goods in the United States.

Many countries keep accounts of the total GFCF, but it is seldom specified in which specific industrial sectors the products are invested; conversely, capital inputs are aggregated into one generic entry (the consumption of fixed capital), giving total capital usage, but not by asset type. Economy-wide models are mainly based on national accounts data, and capital accounts are thus structured accordingly. Such data are traditionally reported in the form of supply-use tables (SUTs), but are used in analysis in the form of square input-output (I-O) tables (IOTs). Combining IOTs from different regions yields multiregional (MR) I-O (MRIO) tables (MRIOTs), which can be augmented to include environmental extensions that can be used to calculate environmental impacts from capital.

We wish to assess the environmental impacts associated with global capital formation. Whereas studies on capital goods typically focus on goods and materials associated with construction, we wish to provide a mapping of all types of capital goods produced in the economy as well as of the final use of these goods, in order to obtain an understanding of the functionality of capital investments. We are further interested in linking capital with development by comparing capital investments and the impacts thereof for countries at different levels of development, albeit we do not look at development trajectories of countries over time in relation to the environmental Kuznets curve (Grossman and Krueger 1991), which we discuss in the Supporting Information available on the Journal's website.

In this work, we analyze the CF associated with GFCF. We allocate sectorial specific capital formation to products at the level of detail provided by IOTs, mapping out in which industries and where in the world most GHG emissions are being embodied in the current development of capital stock. By analyzing the structure and calculating the footprints of capital in countries at various levels of development, we are also able to examine whether countries tend to shift away from material- and energy-intensive capital goods as economies develop. We finish by linking our work to potential avenues for future research on the topic.

Methods and Data

Multi-Regional Input-Output

MRIO analysis is a powerful tool for assessing environmental and sustainability impacts of traded commodities and services on a global scale. It is built on a theoretical framework developed by Leontief (1936), which uses previously recorded economic transactions to analyze interdependencies between different sectors of an economy based on records of economic transactions between them. The use of I-O methodology for assessing environmental problems began in the late 1960s and it constitutes the foundations of current MRIO analysis. Environmentally extended (EE) MRIO is widely used today to study global environmental impacts. Wiedmann and colleagues (2011) identify five recently developed projects that have compiled large-scale MRIO databases (AIIOT, Eora, EXIOPOL, GTAP, and WIOD). Tukker and Dietzenbacher (2013) provide a consistent and recent review of the most prominent databases available today, and Moran and Wood (2014) analyze how the choice of database impacts CF calculations. We use I-O analysis to calculate consumption-based environmental impacts, such as CFs, and take the approach of linking capital accounts to the MRIO framework. The basic I-O accounting framework is explained in the Supporting Information on the Web.

Data Used

EXIOBASE

The EXIOBASE database (version 2.2) is based around detailed EE SUTs, trade linked in order to follow global supply chains (Wood et al. 2015). The database consists of detailed MR EE SUTs, as well as symmetric MRIOTs (Eurostat 2008), all for the year 2007. The SUTs have been compiled by gathering information from national and international (e.g., Eurostat, UN) statistical offices, and hence contain detailed accounts from 43 countries, covering 90% of the global gross domestic product (GDP). The remaining countries are accounted for in five rest-of-the-world regions. The EXIOBASE SUT classification contains 163 industries and 200 products, and the symmetric IOTs used here are product-by-product tables

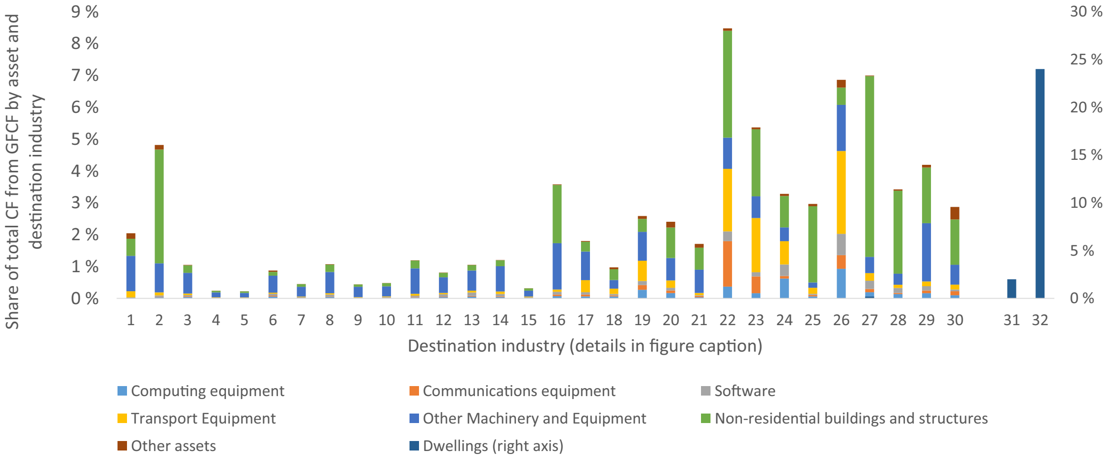

Figure 1 Share of the aggregated CF of the 13 KLEMS countries associated with each asset type and destination industry, 2007. Dwellings are destined almost exclusively to the sectors "real estate" and "other business activities" and are therefore plotted on a separate axis (right axis). All other assets are plotted on the left axis. Industry details: 1, Agriculture, forestry, fishing; 2, Mining & quarrying; 3, Food, etc.; 4, Textiles & leather; 5, Wood & cork; 6, Pulp, paper & publishing; 7, Coke, refined petroleum & nuclear fuel; 8, Chemicals products; 9, Rubber & plastics; 10, Other nonmetallic mineral; 11, Basic & fabricated metals; 12, Machinery not elsewhere classified (nec); 13, Electrical & optical equipment (eq); 14, Transport eq; 15, Manufacturing nec; 16, Electricity, gas & water; 17, Construction; 18, Sale of motor vehicles (mv); 19, Wholesale trade, except mv; 20, Retail trade, except mv; 21, Hotels & restaurants; 22, Transport & storage; 23, Post & telecom; 24, Financial intermediation; 25, Real estate; 26, Renting of machinery and eq; 27, Public admin & defense; 28, Education; 29, Health & social work; 30, Other community & social services; 31, Other business activities (dwellings); 32, Real estate (dwellings). CF = carbon footprint.

according to the industry technology assumption. This, along with the high country resolution, makes it one of the most detailed MRIO database currently available (Tukker et al. 2013). Moreover, one of the objectives of EXIOBASE is that it should be relevant for environmental policy, and one of its benefits for that aim is the availability of interindustry requirement matrices and detailed stressor matrices for agriculture, energy, and resources (Wood et al. 2014).

KLEMS

The EU KLEMS Growth and Productivity Accounts are a set of databases containing inputs and outputs of capital, labor, energy, materials, and services for 25 European countries as well as five non-European (Australia, Canada, Japan, Korea, and United States) (Timmer et al. 2007b; EUKLEMS 2016). Many countries provide highly aggregated capital formation matrices, and the KLEMS database has therefore settled for a low level of industry and asset type detail, including only eight and 32 categories of assets and industries, respectively, which can be seen in figure 1.

Whereas EXIOBASE provides global accounts of GFCF disaggregated over 200 asset types, it only lists the investments as one final demand category. The KLEMS database provides additional information regarding where different types of assets are actually being purchased, which makes it a valuable complement to EXIOBASE. Although it is available only for fewer countries, combining the two databases enables us to assign environmental impacts to different industry sectors.

Methods

Carbon Intensity of Assets

Our research question concerns the structure of capital investments and the hypothesis that countries tend to shift toward less material- and energy-intensive goods as they develop. It is therefore necessary to establish a way to measure the environmental impacts associated with different capital assets. We have chosen the CF as a reference measure for environmental impacts, estimated by the 100-year global warming potential (GWP), calculated according to Intergovernmental Panel on Climate Change (IPCC) guidelines (Pachauri and Reisinger 2007), and expressed in kilograms (kg) of kilograms (CO_2) equivalent (kg CO_2-eq). The procedure to calculate environmental impacts using EE MRIO is explained in the Supporting Information on the Web.

In order to be able to compare assets with one another, we calculate the global GFCF of an asset a, denoted $\overline{GFCF}_a$, as well as the global CF of that GFCF, denoted $\overline{CF}_{GFCF_a}$, and then calculate the share of these measures from the global total GFCF and the CF of the global total GFCF, respectively. In other words, we have:

$$\alpha = \frac{\overline{GFCF}_a}{\overline{GFCF}_{tot}} \tag{1}$$

and

$$\beta = \frac{\overline{CF}_{GFCF_a}}{\overline{CF}_{GFCF_{tot}}} \tag{2}$$

Table 1 Asset types whose GFCF account for more than 1% of the global GFCF and their share of the global GFCF, their respective share of the global CF from GFCF, and the resulting carbon intensity (the ratio of these two shares)

Asset	*GFCF share (%)*	*CF share (%)*	*Carbon intensity (%)*
Construction work	49	59	121
Machinery and equipment n.e.c.	10	12	111
Motor vehicles, trailers, and semitrailers	6	6	99
Computer and related services	6	1	23
Real estate services	3	1	20
Other business services	3	1	29
Other transport equipment	3	3	104
Wholesale trade and commission trade services, except of motor vehicles and motorcycles	2	1	31
Medical, precision, and optical instruments, watches, and clocks	2	2	73
Office machinery and computers	2	2	92
Radio, television, and communication equipment and apparatus	2	2	77
Electrical machinery and apparatus n.e.c.	2	3	148
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts . . .	2	1	43
Furniture; other manufactured goods n.e.c.	2	2	116
Retail trade services, except of motor vehicles and motorcycles; repair services of household goods	1	1	40
Fabricated metal products, except machinery and equipment	1	2	138

Note: GFCF = gross fixed capital formation; CF = carbon footprint; n.e.c. = not elsewhere classified; the darker shading in the carbon intensity column indicates the five most carbon-intensive asset types and the lighter shading indicates the five least carbon-intensive asset types (out of the 16 types analyzed).

To establish a measure of carbon intensity, we calculate the ratio β / α for each asset a and characterize assets as "dirty" if the ratio is above one and "clean" otherwise. We perform these operations for the asset types whose individual GFCF account for more than 1% of the global GFCF, which entails 16 of the 200 assets (summarized in table 1).

Structural Decomposition

In order to determine why a certain country's capital formation has a high or low carbon intensity, we have performed a structural decomposition analysis (SDA). Whereas a typical SDA studies the evolution of a variable over time by separating the changes in the constituent parts (Dietzenbacher and Los 1998), we wish to compare the value of a variable across different countries. Synchronic cross-country decomposition involves certain additional problems that do not occur in chronological decomposition within a single region. Instead of breaking down a continuous time derivative into annual snapshots, the decomposition is a pure counterfactual comparison between two (unrelated) states. This can potentially lead to large residuals because of the large variations in the explanatory factors attributed to inherent differences between countries, such as GDP, energy mix, relative prices, and, to a certain point, structural comparability (Zhang and Ang 2001). For instance, a study by Chung (1998) concludes that 18% of the difference in CO_2 emissions between China and South Korea is attributed to the residual. This residual increases as the variations among countries increase, and the effect on the residual attributed to each variable depends on the variables' specific change patterns, as is explained in detail by Hoekstra and van Den Bergh (2002). In general, Zhang and Ang (2001) describe some of the prevailing methods for tackling the issue of residual, and conclude that perfect decomposition techniques, that is, techniques that leave no residual, are to be favored over conventional techniques when performing cross-country comparisons, but it must be noted that the handling of the residual is performed mathematically, and that the concept of SDA is not uniquely defined. For further details on the performances of various SDAs as well as discussions about nonuniqueness issues, see, for instance, Dietzenbacher and Los (1998); De Haan (2001); Ang and Liu (2007); De Boer (2008); Ang and colleagues (2009); and Wood and Lenzen (2006). In our approach, we avoid many of the uniqueness problems by only decomposing two variables. Reference values have been normalized to reduce the interaction effects caused by the residual, which, in turn, is evenly distributed among the interaction terms, as is done in the refined Laspeyres method (RLM) (Sun 1998; Owen et al. forthcoming).

In this SDA, we wish to decompose the CF $\mathbf{d} = \mathbf{s}_{\mathbf{CF}}\mathbf{LC}$ into two factors: the multiplier $\mathbf{q} = \mathbf{s}_{\mathbf{CF}}\mathbf{L}$ (where $\mathbf{L}$ is the Leontief matrix and $\mathbf{s}_{\mathbf{CF}}$ is the emissions coefficient matrix for CF, both described in detail in the supporting information on the Web); and the capital expenditure factor $\mathbf{C}$, in order to assess which of these factors is the predominant one for each country (analogous to the study by Alcantara and Duarte [2004]). The multiplier $\mathbf{q}$ shows emissions by country of origin of final good (dimension 9600), whereas $\mathbf{C}$ is a matrix of country of origin of final good, by country of consumption (dimension 9600*48).

The CF has been selected as a measure of environmental impacts for the analysis. The CF multiplier q is expressed in kg CO_2-eq per million Euros (MEur), and when multiplied by the capital expenditure $\mathbf{C}$ we obtain total impact in kg CO_2-eq. The goal of our SDA is to calculate how much the CF $\mathbf{d}$ of each country deviates from the average by adding the respective contributions of $\mathbf{q}$ and $\mathbf{C}$ to the deviation (similarly to Alcantara and Duarte [2004]):

$$\Delta \mathbf{d} = \Delta \mathbf{q}\mathbf{c}_{\mathbf{country}} + \mathbf{q}\Delta \mathbf{c} + \Delta \mathbf{q}\Delta \mathbf{c} \tag{3}$$

where $\Delta \mathbf{q} = \mathbf{q}_{\mathbf{country}} - \mathbf{q}_{ref}$, $\Delta \mathbf{c} = \mathbf{c}_{\mathbf{country}} - \mathbf{c}_{ref}$ and $\Delta \mathbf{q}\Delta \mathbf{c}$ is the residual, which is, in turn, allocated to the delta terms (see below, and Sun [1998]). In these terms, the "country" and "ref" attributes refer to the individual country values and reference values, respectively. That is, $\mathbf{q}_{ref}$ describes reference multiplier values and $\mathbf{c}_{ref}$ represents a reference investment structure. This means that a positive $\Delta \mathbf{d}$ implies that a country has a higher CF than the average. Residual values for each country can be found in the Supporting Information on the Web. We are interested in the impact caused by a certain country, and thus defining capital asset j that country k purchases from country i, we wish to recalculate the product-by-region-of-origin multipliers to product-by-region-of-consumption multipliers. We first reshape $\mathbf{q} = Q_{j,k}$ and then calculate product-by-region-of-consumption multipliers as:

$$\overline{Q_{j,k}} = \frac{\sum_i^{48}(Q_{i,j}C_{i,j,k})}{\sum_i^{48} C_{i,j,k}} \tag{4}$$

This calculation provides a weighted average multiplier for product-by-region-of-consumption, weighted according to the level of capital consumption from the region of origin. We further then only consider the expenditure by product-and-region-of-consumption:

$$C^*_{j,k} = \sum_i^{48} C_{i,j,k}. \tag{5}$$

In order to calculate a global reference value of multipliers for the SDA, taking just the average of all 48 countries for each j would result in a skewed reference multiplier $Q_{j,ref}$, given that it would imply an equal distribution of the production of asset j over all 48 countries, which is clearly not realistic. Therefore, in order to obtain reference multipliers that reflect the composition of the global final demand, the multipliers $\overline{Q_{j,k}}$ are weighted over the purchasing countries as well:

$$\overline{Q_{j,ref}} = \frac{\sum_k^{48}(\overline{Q_{j,k}}C^*_{j,k})}{\sum_k^{48} C^*_{j,k}} \tag{6}$$

Investments are summed over origin country and normalized by GDP according to:

$$\overline{C_{j,k}} = \frac{C^*_{j,k}}{GDP_k} \tag{7}$$

The reference value for investments is obtained by taking the average:

$$\overline{C_{j,ref}} = \frac{\sum_k^{48} \overline{C_{j,k}}}{48} \tag{8}$$

The subtraction $\Delta Q_{j,k} = \overline{Q_{j,k}} - \overline{Q_{j,ref}}$ then provides information on how carbon intensive the production of asset j in country k is compared to the norm, that is, the reference value. Likewise, the subtraction, $\Delta C_{j,k} = \overline{C_{j,k}} - \overline{C_{j,ref}}$, provides information on whether country k invests more or less in asset j than the norm, that is, the reference value. Distributing the residual in keeping with the RLM, we obtain, for the GFCF of each country k, the following contribution to CF:

$$\begin{aligned} \Delta d_k = & \sum_j^{200} \left(\Delta Q_{j,k}\overline{C_{j,k}} + \frac{1}{2}\Delta Q_{j,k}\Delta C_{j,k} \right) \\ & + \sum_j^{200} \left(\Delta C_{j,k}\,\overline{Q_{j,k}} + \frac{1}{2}\Delta Q_{j,k}\Delta C_{j,k} \right) \end{aligned} \tag{9}$$

The first term gives the contribution to the global CF that stems from country k's multipliers, weighted by country k's investment in that asset. The second term gives the contribution of country k's investment structure, weighted by the multiplier. The sum hence gives a measure of total environmental contribution of GFCF for country k.

Combining KLEMS with EXIOBASE

In order to combine the capital specifications in KLEMS together with the detailed economic and emissions data of EXIOBASE, we need to make the KLEMS capital accounts compatible with EXIOBASE. First, we convert the KLEMS capital data from national currencies to Euros using yearly averages of exchange rates (XE 2015). For the years preceding the introduction of the Euro, the first official exchange rates were used (analogously to Timmer et al. [2007a] for the development of the KLEMS database). Second, we disaggregate the eight asset types in KLEMS into the 200 product categories of EXIOBASE, using a concordance matrix $\mathbf{G}$ that maps the asset types from KLEMS to relevant product categories in EXIOBASE. When KLEMS products map to more than one EXIOBASE product, the values are disaggregated and distributed among the different destinations using a proxy $\mathbf{p}$ is needed. We use total GFCF values from the existing EXIOBASE data as proxy values. We normalize the concordance matrix to avoid double counting; that is, the sum of the shares that each asset assigns to EXIOBASE product categories should amount to one. We obtain a new matrix $\mathbf{G_{new}}$ calculated as such:

$$\mathbf{G_{new}} = (\widehat{\mathbf{G}\mathbf{p} + \delta})^{-1}\mathbf{G}\hat{\mathbf{p}} \tag{10}$$

The circumflex attribute on $\mathbf{p}$ implies a diagonalized vector, and δ is a threshold value that prevents singularities. Multiplying the 8-by-32 matrix of national GFCF values $\mathbf{C_{KLEMS}}$ with $\mathbf{G_{new}}$ gives a new 200-by-32 matrix of national GFCF values for each KLEMS country. To make it compatible with EXIOBASE, we need to distribute the GFCF values over all regions to form a 9600-by-32 matrix $\mathbf{C_{EXIO}}$. KLEMS does not provide information about which country the capital assets are purchased from, and we therefore again use EXIOBASE proxies to distribute the GFCF expenditures of the KLEMS countries across the 48 EXIOBASE regions (the majority of assets are assigned domestically; see table A6 in the supporting information on the Web). To calculate the CF from each asset, each column from $\mathbf{C}_{\text{EXIO}}$ is diagonalized:

$$\mathbf{d}_{\text{m}} = \mathbf{s}_{\text{CF}}\mathbf{L}\widehat{\mathbf{C}_{\text{EXIO}_{\text{m}}}} \qquad (11)$$

where $\mathbf{C}_{\text{EXIO}_{\text{m}}}$ is the 9600-by-1 vector of capital expenditure that is used by industry m. This results in a 1-by-9600 matrix of CF for each KLEMS country and industry, that can then be summed asset-wise to obtain a 1-by-200 matrix corresponding to EXIOBASE products or aggregated further to KLEMS asset classification as is shown in figure 1.

Results

Size of Gross Fixed Capital Formation

In 2007, GFCF accounted for 24% of global final demand, both in terms of value and GHG emissions. Figure 2 shows that the share of GFCF varies across countries, from 17% to 44% in terms of value and from 14% to 57% in terms of CF. In general, the GFCF is more carbon intensive than the average for countries with a high share of GFCF, whereas for countries with a low share of GFCF, the reverse is true. The calculations have been performed for the 43 countries covered by EXIOBASE, but only the 22 most populated countries are displayed in the graph, as well as the world average. The countries are ordered by GDP per capita (at purchasing power parity [PPP]) and the data are for the year 2007. China stood out as a large investor, with nearly 45% of the final demand going toward building up the capital stock, and other countries' shares were below 29%, with no apparent correlation between GDP per capita and share of investments. The countries with the lowest GDP per capita had carbon-intensive investments and the richest countries had less carbon-intensive investments. It is interesting to see that of the seven BRIC (Brazil, Russia, India, and China) and MINT (Mexico, Indonesia, Nigeria, and Turkey) countries present in the analysis, six have higher shares of CF than GFCF (IND, CHN, IDN, BRA, MEX, and TUR), of which four are substantially higher (IND, CHN, BRA, and TUR). This suggests that an accelerated increase in emissions can be expected as less-developed countries reach higher levels of development.

Nature of Gross Fixed Capital Formation

Using the KLEMS database, we are able to identify the use of different capital assets per destination industry. Figure 1 shows the CF of GFCF, distributed across destination industries. It has been calculated based on the average nominal investments over the accounting years 1995–2007, for the 13 KLEMS countries that provide full capital accounts. Residential structures are almost exclusively destined to the real estate industry and are therefore plotted on a separate axis. They account for one quarter of all GHG emissions from capital. Nonresidential construction investments stand for another 27%, which means that assets from the construction sector account for slightly over half of the total CF from capital. Investments of service sectors involve all asset types, with significant contributions from software, communications, and computing equipment. Even though the latter types of equipment have lower carbon intensities, investments of the service sectors are responsible for a large share of the total CF of GFCF. The "transport and storage" sector has the largest share of impacts after "real estate activities," followed by other service sectors such as "public administration," "renting of machinery and equipment and other business activities," and "post and telecommunications." All manufacturing sectors account for small shares of the CF. The KLEMS countries are considered to be developed countries (World Bank 2015a; IMF 2014), and the results would probably differ if the same disaggregation were available for developing countries.

We have broken down the CF of GFCF at the asset and country level, yielding 9,600 asset-country combinations, and found that the 20 largest national assets account for 61% of the global CF of GFCF (see table S2 in the supporting information on the Web). The top ten accounts for over half of the CF, and assets related to construction work constitute eight of these ten assets. China is present in three of the top ten assets per CF (construction work, machinery and equipment, and motor vehicles), with construction work in China accounting for 27% of the global CF from GFCF. The case of China has been studied extensively (e.g., Gregg et al. 2008; Guo and Fu 2010; Wei et al. 2007; Minx et al. 2011; Weber et al. 2008; Xie 2014; Liu et al. 2013; Lin and Sun 2010). The production of cement and steel constitutes the main source for the large share of China's CF originating from capital formation. Chinese energy consumption is the highest in the world (World bank 2015b), and 17% of it comes from the steel industry alone (2008 figure, Lin et al. [2011]). It has been argued, however, that this peak in emissions for countries in similar stages of development as China is expected to recede as the countries reach a certain level of wealth (Pauliuk and Müller 2014), and we will therefore study how capital investments change as economies mature.

Carbon Footprint as a Function of Wealth

In order to answer the research question concerning whether or not increasing wealth leads to investments in cleaner capital assets, we plotted the GFCF and CF of GFCF of EXIOBASE countries as a function of GDP per capita (PPP) (figure 3a and figure 3b, respectively). The increase in investments seems to have an elasticity over one, but the trend is different for the CF of investments. Although the second graph showing CF per capita contains more outliers, the slope is not as steep and decreases with increasing wealth. This was indeed confirmed when fitting the curves; the highest coefficient of determination (or adjusted R^2) was obtained with a power law fit, with power coefficients p of above one for figure 3a and below one for figure 3b.

To relate the trends observed in figure 3a and 3b, figure 3c displays the inverse of carbon intensity, or amount of capital formation per unit emissions, which has a similar trend as GDP per capita. The division between the countries at different levels of GDP per capita is clear.

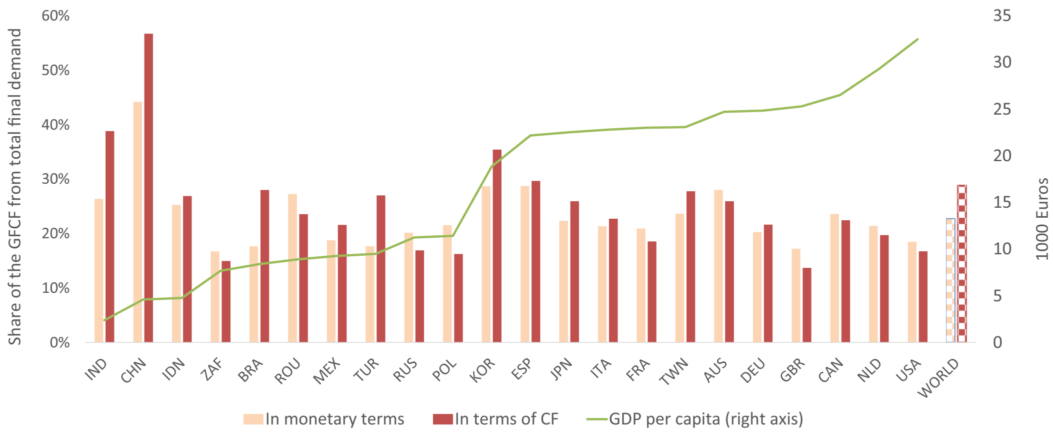

Figure 2 Share of the GFCF from the total final demand, in monetary terms as well as in GWP, for the 22 most populated countries from EXIOBASE2. ISO country codes: IND = India; CHN = China; IDN = Indonesia; ZAF = South Africa; BRA = Brazil; ROU = Romania; MEX = Mexico; TUR = Turkey; RUS = Russia; POL = Poland; KOR = Korea; ESP = Spain; JPN = Japan; ITA = Italy; FRA = France; TWN = Taiwan; AUS = Australia; DEU = Germany; GBR = United Kingdom; CAN = Canada; NLD = Netherlands; USA = United States of America. GFCF = gross fixed capital formation; GWP = global warming potential; ISO = International Organization for Standardization.

Two factors can explain the discrepancies between figures 3a and 3b. The first factor relates to our research question about the structure of capital investments, that is, whether there is a structural shift to less energy-intensive capital goods as countries develop. The second factor is linked to the energy used in the production of the capital assets. The CF of capital goods purchased by a country is directly dependent on the way they are produced, that is, on the electricity mix of the producing country, and for some sectors (e.g., steel and cement production) of process emissions and other energy sources (Guo and Fu 2010; Schneider et al. 2011). These two factors can both amplify each other (e.g., a country that purchases energy-intensive assets that are produced using electricity from coal-fired power plants) or offset each other (e.g., a country that switches from carbon-intensive assets produced with electricity from nuclear power to less carbon-intensive capital assets produced in a country with predominantly coal-based electricity generation). Hence, it is interesting to analyze the outliers from figures 3a and 3b in detail to assess why they deviate. To identify these outliers, we have investigated seven countries each at both ends of the scale in figure 3c—the countries with the least carbon-intensive (green box in figure 3c) and most carbon-intensive capital investments (red box in figure 3c), henceforth referred to as group A countries and group B countries, respectively. Using data from EXIOBASE, we have looked at the nature of capital investments (i.e., asset types) as well as their production country. We then selected the five most (in red) respectively least (in green) carbon-intensive assets (defined according to the method chapter and summarized in table 1) and calculated the shares of these assets that the GFCF (in monetary terms) from the countries in group A and B account for (on a national scale), as well as the average across each country group (figure 4).

The results are clear: The share of dirty assets is substantially higher for the group B countries (between 60% and 90% of the GFCF, with a group average of 77%) than for the group A countries (between 47% and 61%, with an average of 57%). Conversely, the share of clean assets is larger for the group A countries (between 19% and 27%, with an average of 23%) than for group B countries (between 1% and 8%, with an average of 4%). This finding supports the hypothesis regarding the evolution of investments with increasing level of wealth. Plotting the calculated carbon intensity of the countries in group A and group B as a function of their GDP per capita does indeed suggest such an evolution, as can be seen in figure A3 in the supporting information on the Web. It should be noted that this categorization of dirty/clean assets is not entirely candid, in the sense that some dirty investments may occur to ensure a cleaner development. For instance, the construction of wind power plants or hydropower dams require substantial amounts of dirty construction assets. Such an asset disaggregation would be interesting, but lies beyond the scope of this article and the data available in the national accounts.

Investment Structure versus Multiplier

To assess the effect of the multipliers, we performed an SDA (described in the *Methods* section) in which we calculated how much the CF of each country's capital investments deviated against a reference value. The contributions of multipliers and investment structures were calculated separately in order to explain the deviations. The results can be seen in figure 5, where countries are ordered by increasing GDP per capita (PPP). Countries with higher GDP per capita tend to purchase their investments of the same asset type from cleaner suppliers,

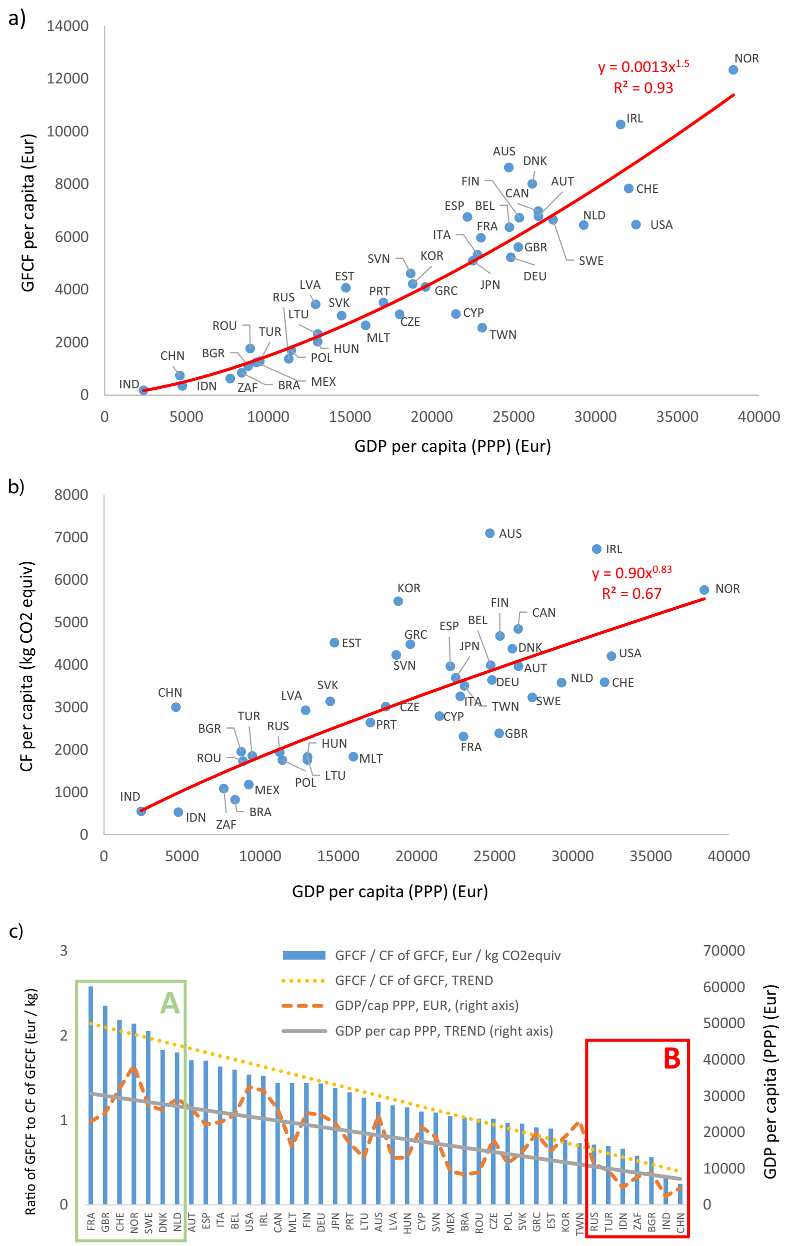

Figure 3 GFCF and CF stemming thereof. The first two graphs display GFCF and CF from GFCF as a function of GDP per capita (PPP), respectively, and the third graph shows the ratio of the two. ISO country codes: FRA = France; GBR = United Kingdom; CHE = Switzerland; NOR = Norway; SWE = Sweden; DNK = Denmark; NLD = Netherlands; AUT = Austria; ESP = Spain; ITA = Italy; BEL = Belgium; USA = United States of America; IRL = Ireland; CAN = Canada; MLT = Malta; FIN = Finland; DEU = Germany; JPN = Japan; POR = Portugal; LTU = Lithuania; AUS = Australia; LVA = Latvia; HUN = Hungary; CYP = Cyprus; SVN = Slovenia; MEX = Mexico; BRA = Brazil; ROU = Romania; CZE = Czech Republic; POL = Poland; SVK = Slovakia; GRC = Greece; EST = Estonia; KOR = Korea; TWN = Taiwan; RUS = Russia; TUR = Turkey; IDN = Indonesia; ZAF = South Africa; BGR = Bulgaria; IND = India; CHN = China. CF = carbon footprint; Eur = Euros; GFCF = gross fixed capital formation; GDP = gross domestic product; ISO = International Organization for Standardization; kg CO_2 equiv = kilograms of carbon dioxide equivalents; MEuro = million Euros; PPP = purchasing power parity.

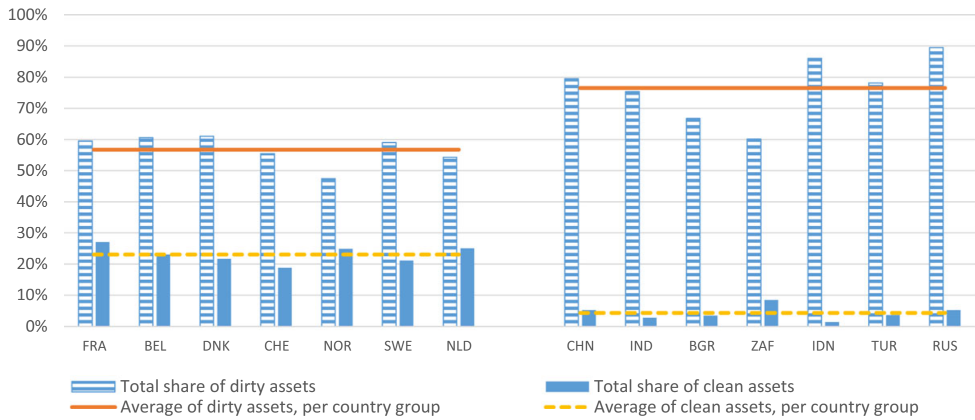

Figure 4 Share that GFCF constitutes of the five cleanest and five dirtiest assets in the countries identified in figure 3c as well as the averages per country group. GFCF = gross fixed capital formation.

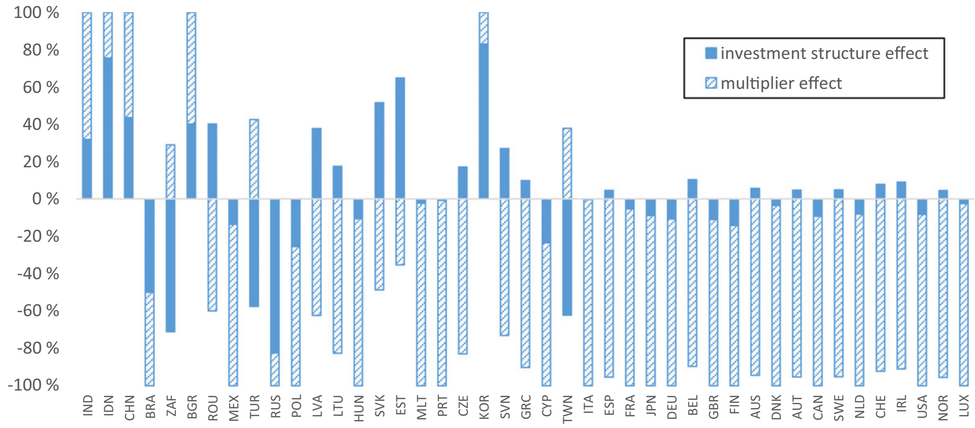

Figure 5 Normalized contributions of multipliers and investment structure to the total deviation of the GWP of GFCF for each country in 2007, ordered by increasing GDP per cap (PPP). The country codes are the same as for figure 3. GFCF = gross fixed capital formation; GDP = gross domestic product; GWP = global warming potential; PPP = purchasing power parity.

which is reflected in the multiplier, and invest in cleaner assets, reflected in the structure of investments. The multipliers explain most of the deviation for high-income countries. For lower-income countries and several middle-income countries, the investment structure has a large effect. For most countries, the aggregated contributions appear smaller than the reference value. This is largely attributed to China's large positive contributions to both investment structure and multiplier.

We also calculated the value added (VA) as well as upstream emissions from capital investments of group A and group B countries, which is summarized in table 2. We see that the VA from GFCF that remains in each country is very similar for both groups, whereas there is a huge difference regarding the upstream emissions. Seventy-seven percent of the CF of investments from group A countries is associated with imports, whereas 67% (on average) of the CF from GFCF from group B countries is associated with domestic production. Table 2 also shows to which countries the CF is outsourced to.

It is well known that one of the loopholes with policies targeting local GHG emissions is the outsourcing of polluting industries from countries with strict emission policies to countries with less-strict policies. This so-called carbon leakage is discussed in several articles (Peters and Hertwich 2008a, 2008b; Babiker 2005; Paltsev 2001). Figure S4 in the supporting information on the Web illustrates the phenomenon for the world's three largest economies; again, the final destination of the VA and CF of the GFCF are plotted, in shares of the respective total (e.g., 52% of the GHG emissions from the total capital investments in the European Union [EU] occur in the EU and the remaining 48% occur outside the EU). In all cases, most of the VA remains in the region, which indicates that a country's capital expenditures tend to profit the country itself. Whereas

Table 2 Occurrence of VA and emissions from GFCF

	VA from GFCF that remains in the country itself (%)	*Average (%)*	*CF from GFCF that remains in the country itself (%)*	*Average (%)*	*Largest receiver of country's CF from GFCF and share thereof (%)*		*Second-largest receiver of country's CF from GFCF and share thereof (%)*	
FRA	76		28		CHN	18	DEU	6
BEL	52		24		CHN	9	RUS	8
DNK	62		25		CHN	18	DEU	9
CHE	67	**64**	22	**23**	DEU	17	CHN	11
NOR	66		27		CHN	16	RUS	8
SWE	61		17		CHN	18	RUS	8
NLD	63		22		CHN	21	RUS	7
CHN	75		92		WWA	2	WWM	1
IND	76		83		WWM	4	CHN	3
BGR	40		48		RUS	14	CHN	8
ZAF	59	**64**	69	**67**	CHN	10	DEU	2
IDN	72		55		CHN	16	WWA	7
TUR	62		56		CHN	12	RUS	9
RUS	67		68		CHN	12	WWE	3

Note: VA = value added; GFCF = gross fixed capital formation; CF = carbon footprint.

the shares of the CF and VA of China's GFCF that remain in China are similar, the EU and United States outsource a relatively large share of their emissions overseas. In fact, our figures show that 17% respectively 13% of the CF from GFCF in the EU and United States end up in China, which concurs with the results from other studies, such as Shui and Harriss (2006), Peters and Hertwich (2008c), and Yunfeng and Laike (2010). When performing the same analysis for the final demand category corresponding to household consumption, figures are much lower: 10% respectively 5% of the GWP stemming from the EU and the United States' household consumption is outsourced to China.

As discussed above, the carbon intensity of the GFCF depends also on how it is produced, that is, the type of energy source. Hence, the small fraction of domestic emissions from group A countries could also be explained by a cleaner energy mix in the production processes. In order to complement our SDA, we have performed additional calculations to identify the source of the emissions from GFCF. More specifically, we have divided the GHG emissions into three categories: combustion emissions from electricity generation; combustion emissions from other sectors; and noncombustion emissions. Combustion emissions are emissions occurring through the burning of fuel, and noncombustion emissions entail emissions occurring elsewise, including process emissions from cement and steel production, agriculture, and so on. The sum of these three emission categories account for all the GHG emissions, and the share that each category accounts for can be directly applied as an explanatory factor for the multiplier effect described in the SDA. These shares are displayed in figure S5 in the supporting information on the Web.

The results do not indicate any clear trends regarding distribution of CF among the three emission categories. Combustion emissions account for 67% of total emissions (electricity related/nonelectricity related 26% respectively 41%). For comparison purposes, the same analysis has been performed for territorial emissions, displayed in figure S6 in the supporting information on the Web, which does show the expected large variations between countries, partly attributed to electricity mix. This finding implies that when calculating consumption-based impacts, the emission intensity is no longer explained by electricity mix. This does, however, explain, to a certain extent, the disparities observed in table 2 above. Indeed, table S4 in the supporting information on the Web provides an overview of the electricity mix of each of the group A and group B countries, and shows similar distribution between the two groups: 69% of the electricity from the group A countries is carbon neutral, that is, made from nuclear power or renewables, and for four countries the share is over 90%. For group B countries, the share of carbon-neutral electricity is only 25%, and nearly half of the electricity production is coal-based—the alternative with the highest CF.

Discussion and Conclusion

Throughout this article, we have performed various calculations with the purpose of gaining an increased understanding of the structure of capital as well as the environmental impacts associated with it. This has been done for 43 countries and five multicountry regions, thereby covering the global economy. We have presented the total size of GFCF per country and compared it with the CF generated by it, and have also disaggregated investments into both products and sectors in order to obtain a more-detailed mapping of GFCF and the CF stemming from it. By linking GFCF and associated CF to the level of development, here expressed as GDP per capita (PPP), we have shown that investments tend to become less carbon intensive as countries develop. An SDA was conducted to analyze whether this effect was attributed to countries investing in less carbon-intensive assets or simply that assets were produced with cleaner energy sources. By performing regional comparisons of the shares of VAS and carbon emissions that are outsourced versus end up locally, we also confirm the occurrence of carbon leakage in the case of GFCF. Finally, to complete our SDA, we studied the sources of the emissions stemming from countries of interest to assess whether the energy mix could explain the deviations in the SDA.

In 2007, GFCF accounted for 24% of global final demand, both in terms of value and GHG emissions. In general, the GFCF was more carbon intensive than the average for countries with a high share of GFCF, whereas for countries with a low share of GFCF, the reverse was true. By comparing GFCF with the CF of GFCF as functions of GDP per capita, we discovered that the increase of investments as countries become wealthier had an elasticity over one, but that the reverse was true for its CF. Similarly to multiple articles preceding this one, China stood out as an extreme case. It had a much larger share of GFCF than other countries, and its two largest GFCF asset categories accounted for one third of the world's total CF from GFCF.

Upon studying GFCF at the product and industry level and using the additional dimension provided by the KLEMS database, we saw that service sectors were the largest consumers of GFCF, and that countries with the lowest GDP per capita had carbon-intensive investments whereas the wealthiest countries had less carbon-intensive investments, suggesting a trend that concurs with studies such as Shahbaz and colleagues (2013). By analyzing the composition of investments, we saw that this trend could be attributed, at least partially, to the structure of investments, in other words that more developed countries invest more in cleaner assets and that less-developed countries tend to have larger shares of dirty assets in their GFCF. To assess the extent of the asset composition contribution, we performed an SDA in which we calculated how much the CF of each country's capital investments deviated against a reference value and isolated the multiplier and investment structure effects. The analysis showed that the contribution of investment structure was much larger for less-developed countries, and that the deviation of the wealthier countries depended mostly on multipliers. Such information could be of great importance for global emission scenario development as well as local environmental policy making, the latter particularly for developing countries that are expected to get substantially more developed in a foreseeable future. Indeed, we saw that of the total CF from final demand in the BRIC and MINT countries, the share stemming from capital investments is substantially higher than the share that GFCF constitutes in monetary terms.

In this article, we have focused on quantifying the emissions stemming from GFCF, and we have established that, as countries develop, their investments increase uniformly, whereas the marginal emissions from GFCF decrease as they reach higher levels of development. This effect is attributed to the nature of capital investments discussed in the introduction, that is, the combination of the long lifetime and the high carbon intensity of capital assets. Hence, the timing of emissions stemming from capital formation is another interesting topic for the continuation for this work. For instance, it could be argued that environmental impacts from GFCF should be spread over time, similarly to the consumption of fixed capital in national accounts.

The additional dimension provided by the KLEMS database constitutes a valuable asset for future research on the use of capital, both in terms of understanding the interaction between natural capital and human capital, which is crucial for understanding the IM of societies and thereby the global future energy and material requirements, but also in terms of contributing to further methodological development of EE MRIO.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes an explanation of the basic input-output framework used in the main article as well as a literature review on the environmental Kuznets curve; also included are additional data results regarding gross fixed capital formation.

Appendix C1 – Paper II

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Including Capital in the Carbon Footprint of International Trade

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Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting

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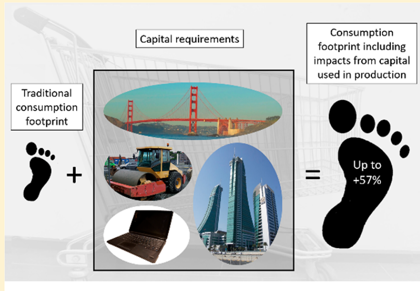
Supporting Information



ABSTRACT: Nearly 30% of global greenhouse gas emissions are associated with the production of capital goods. Consumption-based emission calculations based on multiregional input−output (MRIO) models allocate emissions occurring in the production of intermediate goods to the final goods produced in an economy. Like intermediate goods, capital goods are used in production processes; yet the emissions associated with their production are not allocated to the industries using them. As a result, the carbon footprint of final consumption as well as emissions embodied in trade are currently underestimated. Here, we address this problem by endogenizing capital transactions in the EXIOBASE global MRIO database, thereby allocating emissions from capital goods to final consumption. We find that endogenizing capital substantially increases the carbon footprint of final consumption (by up to 57% for some countries), and that the gap between production-based and consumption-based emissions increases for most countries. We also find that the global emissions embodied in trade increase by up to 11%, and that current patterns of bilaterally traded emissions are amplified. Furthermore, endogenizing capital leads to a 3-fold increase in the carbon footprint of certain product categories. The results suggest that our approach constitutes an important improvement to current input−output methodology.

1. INTRODUCTION

There is a consensus that environmental assessment methods that provide a holistic and systematic approach are needed to account for global pollutants such as greenhouse gases (GHGs). In particular, consumption-based (CB) accounting was proposed as a complement to production-based (PB) accounting to capture the impacts of emissions associated with international trade and the rapid globalization that occurred in the late 1990s and early 2000s.[1−4] A suitable method for distinguishing between the two approaches is multiregional input-output (MRIO) analysis, which combines national accounts with trade statistics to describe the complex network of production and consumption of goods and services that constitute the global interconnected economy. It has been used extensively in the past decade to calculate environmental impacts associated with consumption, and several large-scale projects have been dedicated to creating global environmentally extended (EE) MRIO databases such as EXIOBASE,[5] WIOD,[6] and EORA.[7] The comprehensibility, versatility, and detail richness of MRIO modeling has made it the norm in today's CB accounting for carbon footprint analyses.[8,9]

While CB accounting has proven to be a valuable complement to PB accounting, one of its shortcomings in tracing the impacts of traded commodities concerns the accounting of capital.[10] Today's MRIO tables (MRIOTs) are constructed from supply and use tables (SUTs) stemming from national accounts, in which capital is treated exogenously. As a result, current CB accounting does not assign the emissions from building up and maintaining the capital stock to the products and services that the capital stock is used to produce, but to a distinct final demand category containing all the new additions of capital.[11,12] This implies that not all life-cycle emissions associated with the production of goods and services are included in the final footprints of these products. Studies that assess the environmental impacts of households (e.g., Kerkhof et al.,[13] Baiocchi et al.,[14] Heinonen et al.,[15] Ivanova et al.,[16] Steen-Olsen et al.,[17] and Markaki et al.,[18] to name a few) hence underestimate those impacts.[19]

Previous studies have shown that distributing emissions from capital goods across consuming industries may lead to substantial reallocation of emissions. Södersten et al.[10] showed that a majority of the GHG emissions stemming from the manufacture of capital goods could be assigned to a handful of industries, and that most of these industries produced services (which typically are less carbon-intensive than nonservice industries—see, e.g., Lenzen and Treloar's multiplier comparison[20]). For the 13 countries analyzed in the study (which

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covers the year 2007), over 70% of the GHG emissions from GFCF were allocated to service industries. The emissions associated with dwellings acquired by the real estate sector stood for a quarter of all GFCF emissions. Nonresidential structures accounted for 31% of all GFCF emissions, and two-thirds of these were allocated to service industries, principally services related to public administration, transport and storage, real estate, and education.

Moreover, capital goods represent a large share of the total economy: in 2007, the gross fixed capital formation (GFCF) accounted for 24% of the total final demand of goods and services, while the carbon footprint (see Wiedmann and Minx[21] for a definition) of GFCF stood for 30% of the global carbon footprint.[10] The figures for 2015 were 25% and 31% respectively. These numbers varied greatly between countries, with China standing out as a major purchaser of capital goods. Investments in China have increased rapidly with the recent infrastructure development boom in the country, constituting 32% of Chinese final demand in 2000 and 46% in 2010, while accounting for nearly 60% of the country's total CO_2 emissions. The Chinese case has been studied extensively, with multiple papers analyzing the drivers behind the sharp increase in CO_2 emissions and energy use. In 2007, China was responsible for two-thirds of the global increase of CO_2 emissions,[22] and three-quarters of the energy consumption changes in China between 2007 and 2010 were due to investments.[23] Concurrently, Chinese exports rose steeply as well. Weber et al.[24] showed that one-third of Chinese emissions in 2005 could be attributed to exports. Shui and Harriss[25] conclude that 14% of China's emissions in 2004 were due to U.S. consumption alone. This raised the relevant question of to what degree investments are driven by the increased production capacity required to fulfill the surging export demand. Minx et al.[26] partially answered that question by closing the IO model for capital formation in the Chinese IO tables, and found that between 21% and 31% of emissions from capital investment are reallocated to exports, while the rest is allocated to other final demand categories (e.g., households and government). Though CO_2 emissions associated with infrastructure development in China are expected to decrease in the future,[27] emissions embedded in the in-use stocks of capital will affect life-cycle type impact assessments for decades. While the Chinese case might be extreme, a similar development occurs in other emerging economies such as India,[28] since economic growth is commonly associated with capital accumulation.[29−32]

1.1. Capital Accounting and Modeling. In most national accounts, capital is reported under two metrics: the GFCF, reported as a distinct final demand category, and the consumption of fixed capital (CFC), which constitutes part of the value added. Although both concepts measure a quantity of fixed assets (i.e., assets that are used repeatedly in production processes for a period of over a year[33]), they represent different measures of capital. The GFCF is the yearly acquisitions, less disposals, of fixed assets during the accounting period, and constitutes a flow of long-term investments purposed to build up or maintain production capacity. The CFC is the expected decline in the current value of the stock of fixed assets during the accounting period as a result of physical deterioration, normal obsolescence and normal accidental damage.[34] It is used interchangeably with the economic concept of depreciation to "account for the loss in capital value owing to the use of capital goods in production",[35] and it is therefore a measure of how much of the in-use stock of capital is being consumed. Although these two measures of capital are readily available in most national accounts, they are aggregated into product or industry totals. The GFCF is partitioned by product type, but not destination sector; likewise, official statistics do not keep track of which sectors are using which capital stock, and capital inputs are therefore estimated with the aggregated CFC by industries.

The lack of two-dimensional GFCF and CFC tables implies the loss of valuable information regarding the linkages between the two. In order to fully understand the dynamics of capital, information on the distribution of capital expenditures by industry as well as a detailed asset composition of the CFC would be necessary. IO models that treat capital exogenously fail to capture the dynamics of in-use stocks and the feedback effects associated with capacity expansion,[36] which is crucial for understanding the role of manufactured capital in reaching sustainability goals.[36−39] Weisz et al.[38] describe it as a "precondition to identifying feasible intervention points for a sustainability transition", and Chen and Graedel[39] argue that the determination of in-use stocks constitutes an important step toward understanding the material linkages between manufactured capital and natural capital.

Furthermore, treating capital exogenously implies that current footprint calculations fail to capture the full life-cycle impacts of production. It has therefore been argued that capital transactions should be endogenized into the interindustry matrices of the IO tables,[10,20,26,40−42] but to our knowledge, this has never been done on a global scale. In this paper, we fill this research gap by endogenizing capital in a global MRIO system, and subsequently analyze the implications for CB GHG emissions. In particular, we wish to answer questions regarding how this affects the distribution of CB emissions across countries. Is the difference between CB and PB emissions increased or decreased? Does it change patterns of bilateral emission trade? For which countries do the largest reallocations of emissions occur? What is the impact on the footprints of final consumers, and which product categories are most affected?

We begin with an overview of the conceptual challenges regarding the endogenization of capital followed by a description of the databases and methods used for compiling and integrating the capital data. The general methodology is laid out briefly in the main paper and full explanations are given in the Supporting Information (SI). The results section offers answers to our research questions, and the last section combines discussion and conclusions of our findings and of some methodological aspects, together with an outlook for future work on the topic.

2. MATERIALS AND METHODS

2.1. Endogenizing Capital in MRIO. The idea of endogenizing capital transactions in IO tables is not a novelty in itself. The conceptual rationale behind it is to obtain a higher degree of closure of the input−output system, thereby capturing all life-cycle emissions associated with the production of goods. Such closure is typically performed in MRIOs by endogenizing imports and exports. Endogenizing capital, however, is not as common. Lack of data on the use of capital by industries has limited attempts of doing so to sporadic efforts at the national scale.

Lenzen and Treloar[20] compare some of the early studies that have endogenized capital on national scales. Among these, two

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

methods have been prominent: the augmentation method and the flow matrix method. The augmentation method consists in incorporating capital as a separate, additional industry in the interindustry matrix, thereby creating an artificial sector with a homogeneous commodity "capital", which is produced using inputs according to the GFCF vector, and consumed according to a row vector of capital inputs (the CFC). The flow matrix method consists in disaggregating capital by assets and sectors and then creating a separate capital flow matrix, which is then added to the regular interindustry flow matrix to form a matrix of total flows (describing flows of capital and noncapital). Lenzen and Treloar[20] test the two methods and conclude that the augmentation method, although being easier to implement, results in systematic distortions in the calculated factor multipliers, mainly due to an unrepresentative allocation of different types of capital, whereas the flow matrix method gives much more sensible results. The main challenge of the latter method is the high data requirements, since it requires product-by-industry resolution on capital flows, which is not available in national accounts.

The GFCF and CFC accounts provided in global MRIO databases do not differentiate between public capital and private capital.[19] Public capital, such as roads and other infrastructure, is utilized both by industries and final consumers, and it is therefore questionable to assign it solely to intermediate consumption. However, due to data availability, we chose to assume that all capital was destined for intermediate consumption, following the approach of other studies that feature capital endogenization.[20,26,43]

2.2. Data Used and Procedure. We use EXIOBASE 3.3 in our calculations, which contains time series of symmetric EE MRIOTs from 1995 to 2015, both in constant and current prices, covering 44 countries and five rest-of-the-world (RoW) regions (see Stadler et al.[5] for further details). The EXIOBASE data are complemented with additional accounts of capital use and expenditures obtained from KLEMS,[44] WORLD-KLEMS,[45] and national accounts (full details on the data and methods available in the SI, including an overview of basic IO analysis). These capital accounts are used to distribute the capital transactions across products and industries in order to obtain a two-dimensional capital flow matrix $\bar{\mathbf{K}}$ of the same size as the interindustry flow matrix $\mathbf{Z}$. To obtain a capital *requirement* matrix $\mathbf{K}$ we proceed similarly as when calculating the regular interindustry requirement matrix $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, i.e., dividing the capital flows by the total output $\mathbf{x}$ as such: $\mathbf{K} = \bar{\mathbf{K}}\hat{\mathbf{x}}^{-1}$. The sum of $\mathbf{A}$ and $\mathbf{K}$ hence determines the total production requirements (of noncapital goods *and* capital goods). Using the flow matrix method, we calculate a new Leontief inverse:

$$\mathbf{L}^{\mathrm{K}} = (\mathbf{I} - (\mathbf{A} + \mathbf{K}))^{-1} \tag{1}$$

The flow matrix method can be applied to endogenize either the GFCF or the CFC. Previous studies (e.g., Lenzen and Treloar,[20] Minx et al.[26]) have chosen to endogenize the GFCF. This approach implies that all emissions from capital formation are attributed to current final consumption (which is defined as the final consumption expenditures by households, nonprofit organizations serving households and government); that is, it disregards the fact that capital goods are (per definition) used for a period of more than a year. For extreme cases such as China, where investments have grown substantially over a relatively short period, this could lead to overestimation of emissions attributed to final demand during that time. This also makes the allocation of emissions more sensitive to extreme events in the economy, both for individual countries and globally. For instance, after the financial crisis of 2008, the share of global final demand constituted by investments decreased from 26% in 2007 to 22% in 2009. Hence, it could be argued that endogenizing CFC would be more sensible for footprint-type calculations, since it implies that footprints would include emissions associated with the production of the capital *currently used* by industries, and that emissions associated with the production of *new* capital would be assigned to goods and services produced in the *future* using that capital.[43] Our research questions focus on carbon footprints and emissions embodied in current trade, and our results are therefore derived from endogenizing CFC.

The new Leontief matrix $\mathbf{L}^{\mathrm{K}}$ differs from the traditional $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ since it also includes capital requirements. Care needs to be taken when interpreting the difference in environmental impacts of final consumption. For instance, the CB GHG emissions of final consumption calculated with the new Leontief matrix, $d_{\mathrm{fc}}^{\mathrm{K}} = \mathbf{s}\mathbf{L}^{\mathrm{K}}\mathbf{y}_{\mathrm{fc}}$, will be substantially higher than when calculated with the old matrix, $d_{\mathrm{fc}} = \mathbf{s}\mathbf{L}\mathbf{y}_{\mathrm{fc}}$, since $d_{\mathrm{fc}}^{\mathrm{K}}$ also contains emissions embedded in the capital goods (where $\mathbf{s}$ is a row vector of emission intensities and $\mathbf{y}_{\mathrm{fc}}$ is a national vector of final consumption—see SI for detailed explanations). Henceforth, we refer to $d_{\mathrm{fc}}^{\mathrm{K}}$ and d_{fc} as measures of consumption-based GHG emissions of final consumption with (CBFC$^{\mathrm{K}}$) respectively without (CBFC) capital endogenized.

By defining $\mathbf{y}_{\mathrm{tot}}$ as a country's vector of *total final demand* (i.e., final consumption, GFCF and changes in stocks), the country's total CB GHG emissions without capital endogenized are given by $d_{\mathrm{tot}} = \mathbf{s}\mathbf{L}\mathbf{y}_{\mathrm{tot}}$, which we refer to as the CB GHG emissions of final demand (CBFD). Since $\mathbf{L}^{\mathrm{K}}$ already contains capital transactions, we define $\mathbf{y}_{\mathrm{tot}}^{\tilde{K}}$ as a country's total final demand excluding the GFCF. The country's total CB emissions with capital treated endogenously are then given by the following:

$$d_{\mathrm{tot}}^{\mathbf{K}} = \mathbf{s}\mathbf{L}^{\mathrm{K}}\mathbf{y}_{\mathrm{tot}}^{\tilde{K}} \tag{2}$$

Summing these two measures of CB emissions for all countries, we obtain the global CB GHG emissions without (D_{tot}) and with ($D_{\mathrm{tot}}^{\mathrm{K}}$) capital endogenized. D_{tot} and $D_{\mathrm{tot}}^{\mathrm{K}}$ will not match, since the two totals account for capital in different ways. While D_{tot} contains all GHG emissions emitted during a year, $D_{\mathrm{tot}}^{\mathrm{K}}$ is a measure of the life-cycle impacts of the goods and services produced during that year (excluding GFCF), comprising emissions occurring during production processes as well as emissions that occurred when the utilized capital was produced. In other words, the share of $D_{\mathrm{tot}}^{\mathrm{K}}$ constituted by capital emissions accounts for emissions from capital built in *previous* years. While the discrepancy between D_{tot} and $D_{\mathrm{tot}}^{\mathrm{K}}$ is inherent to how they are calculated, it complicates the comparison between the two approaches. It could therefore be useful to create an indicator that adjusts for the difference between these two measures so that the "net" effects of endogenizing capital for each country can be assessed. This can be done by calculating a residual GFCF vector of net capital formation $\mathbf{y}_{\mathrm{r}}^{\mathrm{K}}$, consisting of the difference between a country's current GFCF and the endogenized CFC, and adding it to $\mathbf{y}_{\mathrm{tot}}^{\tilde{K}}$ to create $\mathbf{y}_{\mathrm{res}} = \mathbf{y}_{\mathrm{tot}}^{\tilde{K}} + \mathbf{y}_{\mathrm{r}}^{\mathrm{K}}$. The final demand vector $\mathbf{y}_{\mathrm{res}}$ hence contains a country's final consumption, changes in stocks and net capital formation, and is used to calculate the CB GHG

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Figure 1. CB GHG emissions of final consumption, excluding (CBFC—dashed blue lines) and including (CBFC^K—solid blue lines) emissions associated with the production of capital used in the production processes. The thin red lines (right axis) show the share of total final demand constituted by the GFCF (in monetary terms).

emissions of final demand with capital endogenized (CBFD^K) as such:

$$d_{res}^{K} = \mathbf{s}\mathbf{L}^{K}\mathbf{y}_{res} \quad (3)$$

The global CBFD^K (the sum of CBFD^K for all countries), D_{res}^K, now matches the global CBFD D_{tot}. Although this correction facilitates the comparison of the two approaches (using $\mathbf{L}$ respectively $\mathbf{L}^K$), care needs to be taken when comparing footprints of different countries, since it entails that we include varying shares of the current investments when comparing the impacts of each country's final demand. Depending on the amplitude and carbon intensity of the investments contained in $\mathbf{y}_r^K$, these residual investments may substantially increase the total CBFD^K. Alternatively, when the GFCF is lower than the CFC, the obtained residual becomes negative, which results in negative emissions for the net capital formation vector (however, this may occur for the final demand category "changes in stocks" in traditional MRIO analysis as well, and is therefore not inherent to our approach only). Furthermore, adding a residual vector of capital implies that the same capital is accounted for both during the year of construction and the year of consumption (i.e., depreciation), which means that the CFC has to be adjusted in subsequent years to avoid double accounting. The inclusion of the residual capital hence only serves as a means to perform snapshot comparisons between the two approaches. When adopting the suggested approach of endogenizing CFC, all emissions are ultimately accounted for, albeit reallocated over time, and there is therefore no need to introduce the concept of residual capital is (that is, the sum of D_{tot} and D_{tot}^K over all years will match). This is discussed further in the last section as well as in the SI.

3. RESULTS

3.1. Impact on Final Consumption. Endogenizing CFC into the IO system implies that emissions from the consumption of fixed capital are reallocated to the remaining final demand categories. Figure 1a shows the CBFC (dashed blue lines) and CBFC^K (solid blue lines), in Gt CO_2eq, for 12 of the largest single-region economies of EXIOBASE (in terms of GDP). While the CBFC only account for the emissions stemming from the production of goods for final consumption, the CBFC^K also account for the emissions stemming from the production of the capital goods required in the process as well, and therefore describe the total life-cycle impacts of final consumption. The thin red lines (right axis) show the share of the total final demand constituted by the GFCF (in monetary terms).

The difference between the two lines shows the carbon intensity of the capital used to produce the respective country's goods and services for final consumption, and it therefore depends both on the amount of capital used and on the carbon intensity of that capital. We see that the emissions of all countries increased, since all impacts associated with the production of capital goods are distributed among the remaining final demand categories. This increase varied a lot across countries—Brazil and Mexico stood out as having the largest relative increases at respectively 57% in 2015 and 45% in 2013, with average rates of increase of 55% respectively 41% between 2010 and 2015. Comparatively, for Russia, Canada, and the U.K., the largest yearly increase over the entire period was of 11%. The range of average increase over the entire period ranged from 7% (Poland) to 48% (Brazil). For several countries, the relative amount of emissions from capital embedded in final consumption increased over the analyzed period. This was the case for Mexico, whose increase went

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

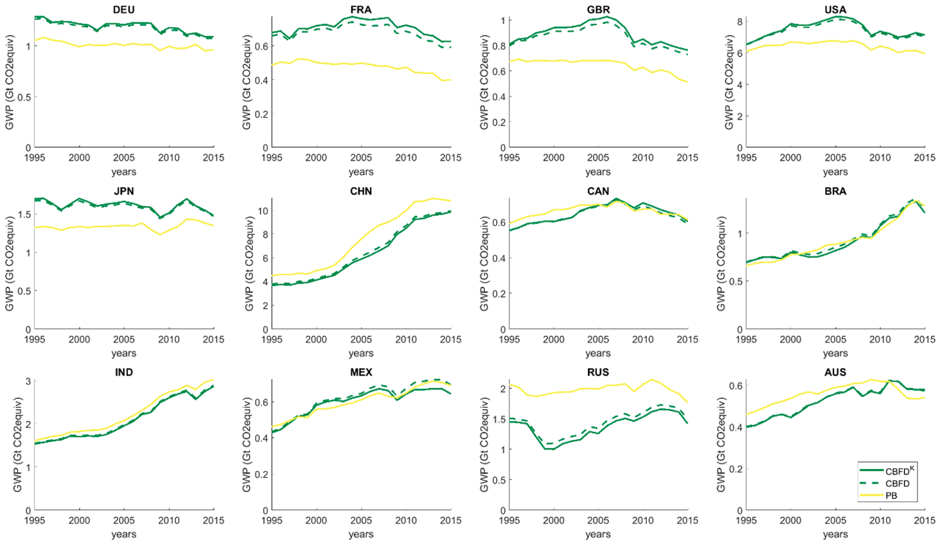

Figure 2. CB GHG emissions of final demand, excluding (CBFD−dashed green lines) and including ($CBFD^K$−solid green lines) emissions associated with the production of capital used in the production processes, as well as PB emissions (yellow line). Global GHG emissions for CBFD and $CBFD^K$ are the same.

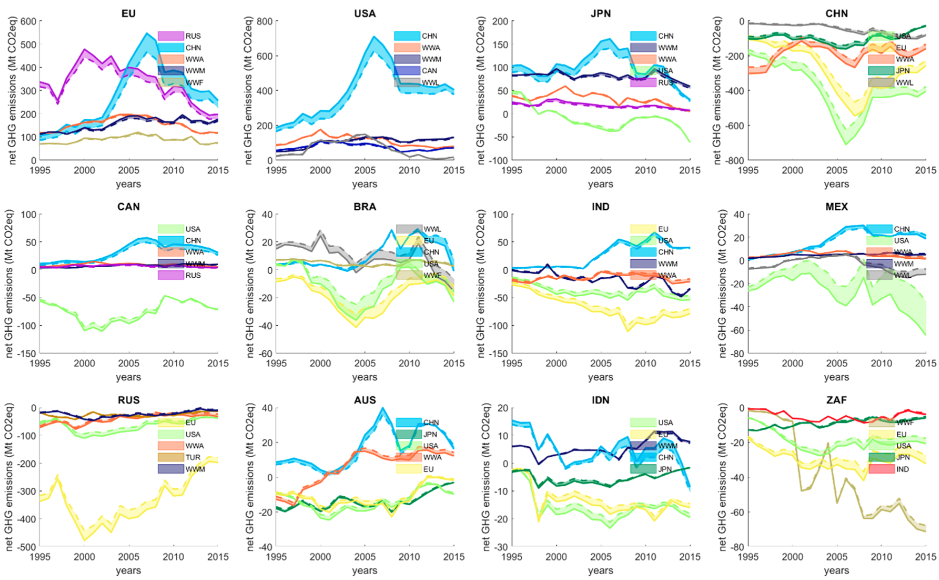

Figure 3. Net traded CB GHG emissions calculated using $CBFD^K$ (solid lines) and CBFD (dashed lines) for the E.U. and the 11 largest countries in EXIOBASE. For each region, the five largest trading partners (in terms of traded emissions over the entire period) are shown.

from 16% (1995) to 43% (2015), Brazil (38% to 57%), and South Africa (8% to 38%).

3.2. Net Impact on Countries. The endogenization of capital leads to a reallocation of CB emissions between countries, as the emissions from capital embedded in the goods and services produced for exports are assigned to final consumption in other countries. To facilitate the assessment of the net impacts of endogenization on individual countries, the CB GHG emissions with capital endogenized ($CBFD^K$), defined in the methods chapter, account for the residual capital of each country (the difference between the endogenized CFC and the GFCF). This implies that the global CB GHG emissions are preserved each year.

Figure 2 shows the CBFD (dashed green lines) and $CBFD^K$ (solid green lines) for the countries displayed in Figure 1. Since emissions are only reallocated among countries, the yearly net global change in GHG emissions is nil. PB emissions are also shown (yellow lines). The net GHG emissions balance

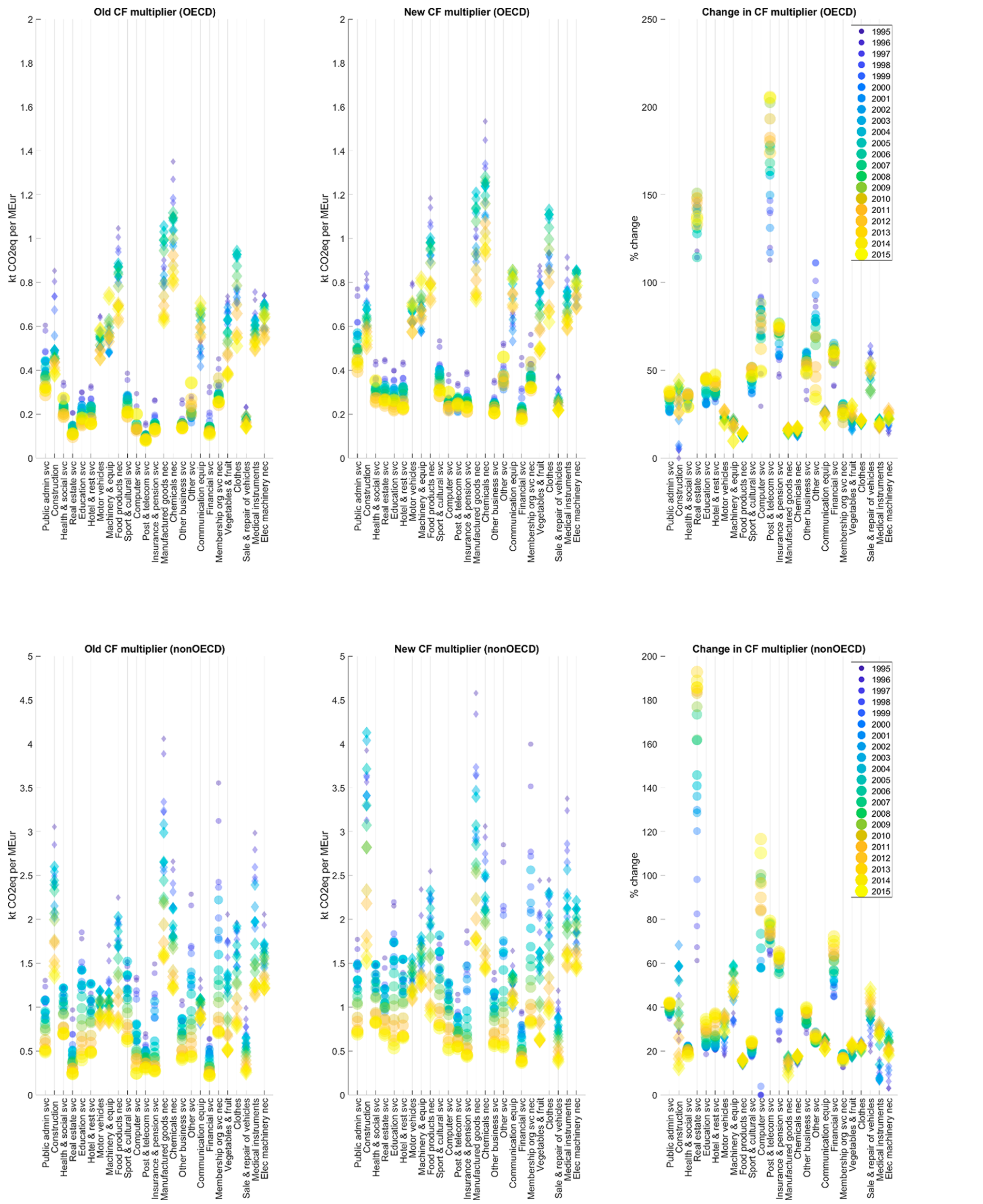

Figure 4. GHG multipliers of the 25 most important (in terms of monetary output during the period 1995−2015) product categories, for OECD (upper graphs) and non-OECD (lower graphs) countries, calculated without (left-hand side graph) and with (middle graph) capital endogenized. The right-hand side graphs show the change in the multipliers. Circle markers indicate service industries and diamond markers indicate nonservice sectors.

(the difference between CB and PB emissions) was increased further for most countries. Due to capital emissions embodied in traded goods, the countries that were net cumulative importers of emissions over the time period before the endogenization of capital (Germany, France, U.K., U.S.A., Japan, Canada, Mexico) were assigned more emissions from the net exporting countries, who in turn saw their cumulative exported emissions increase (China, India, Russia, Australia). The gap between the two emission-accounting approaches (CB and PB) was thereby widened. Out of the 49 countries and regions covered in EXIOBASE, only four countries changed their status from net importer to net exporter of

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

emissions (Brazil and Taiwan) and vice versa (Norway and Estonia). The 45 remaining countries/regions saw their emissions imbalance increase. The largest relative increase was of 6% (occurring for France for the years 2011 to 2015), while the largest relative decrease was for Russia in 2000 (9%). The largest absolute change occurred for China in 2007, when the decrease in allocated emissions amounted to 0.3 Gt of CO_2eq (to put that into perspective, this is more than the total CB emissions of Taiwan for the same year). Detailed tables for all countries are available in the SI.

3.3. Emissions from Capital Embodied in Bilateral Trade. Figure 3 shows the net emissions of capital embodied in bilateral trade (calculated using the MRIO approach, described in the SI), before (dashed lines) and after (solid lines) the endogenization. For each region, the five largest trade partners are displayed. Some regions (e.g., E.U. and U.S.A.) were net importers of emissions from all trading partners shown, while others (e.g., China, Russia and South Africa) were net exporters of emissions to all five trade partners displayed. The effect of including capital emissions increased this emissions trade imbalance further; that is, the E.U. and U.S.A. saw their emissions import increase, while the opposite was true for Russia and China. This increasing effect occurred for the majority of the net bilateral trade trends displayed, with a few exceptions (such as the emissions trade between Australia and China). Overall, most countries saw their CB emissions increase with the new approach; out of the 49 countries or regions, only 15 had a decrease. Out of these, six are among the seven countries singled out in the paper by Södersten et al.[10] as having carbon-intensive investments (Bulgaria, Russia, India, China, South Africa, and Indonesia). The global emissions embodied in trade increased by 11%.

3.4. Impact on Product Multipliers. Closing the IO system for capital implies not only a reallocation of CB emissions across consuming countries, but also across final products. Since we are adding positive requirements of capital to all production processes, all products become more carbon-intensive (since more input is needed per unit output). Goods and services that require a lot of capital during the production phase have a larger increase than less capital-intensive goods, particularly if the added capital requirements are carbon-intensive. This can be quantified by comparing the individual product multipliers, which describe the total CB impacts of production per unit output of final product (explained in the SI). Figure 4 shows the multipliers of the 25 most important (in terms of monetary output during the period 1995−2015) product categories, for OECD and non-OECD countries, calculated without (left-hand side graph) and with (middle graph) capital endogenized. The right-hand side graphs show the change in the multipliers. The figures also distinguish between service sectors (circle markers) and nonservice sectors (diamond markers).

All multipliers increased, since the requirements per unit final demand either remained the same (if no capital goods were used) or increased. While service multipliers were generally much lower than nonservice multipliers (indicating that they were less carbon-intensive), their relative increase between the two approaches was the largest. This implies that the CB emissions of services increased substantially when the capital used in production processes was included. Looking at the changes in individual product multipliers over time, the general trend for all countries was for multipliers to decrease, indicating that production processes were becoming cleaner. This decreasing trend was more distinct for non-OECD countries. Over the accounting period, the largest value for each multiplier (among the product categories displayed) was on average 3.1 times larger than the smallest value for the old multipliers, and 2.7 for the new multipliers. For OECD countries, the average ratios were 1.9 and 1.7, respectively. However, the *changes* in the two approaches over time seemed to be increasing, indicating that the capital endogenization had more impact in recent years.

OECD and non-OECD countries also differed concerning the type of products whose multipliers changed the most. For non-OECD countries, the real estate sector increased the most, which can be explained by the fact that real estate services usually require a lot of carbon-intensive capital goods, such as buildings and infrastructure. Real estate multipliers of OECD countries also increased, but with less amplitude. The real estate sector for non-OECD countries also stood out due to the temporal evolution of the change, going from 60% change in 1995 to almost 200% change in 2015, indicating an increase in capital requirements over time (likely driven to a substantial extent by the massive infrastructure development in China discussed in the introduction). For OECD countries, the corresponding change was much more constant over time. The same occurred for the product category with the largest change for the OECD countries, "post and telecommunication services", in which a similar temporal increase could be seen (from slightly over 100% to over 200%). For computer-related services, the trends for non-OECD and OECD (increasing respectively decreasing) differed, indicating that a certain peak in capital demand can be expected for such services. This is also the trend for the "other services" category, where the OECD change peaked in 1998/1999 at 110% and gradually decreased to 34% in 2015, while for non-OECD countries, the change over the accounting period remained in the range 23% to 29%.

4. DISCUSSION

In this study, we applied the flow matrix method to endogenize capital in a global MRIO database. We analyzed how the endogenization of capital affected the CB GHG emissions on a country level as well as how CB emissions were reallocated among countries. We also compared the impact on product multipliers.

The endogenization of capital had substantial effects on the CB emissions of final consumption, with average increases over the entire period ranging from 7% to 48% for the countries studied, implying a large difference in the amount of capital requirements and carbon intensity of the capital goods used by different countries. We also assessed how the emissions from capital were redistributed across different end products and noted that the product multipliers of service sectors increased considerably more than those of nonservice sectors. As our model reallocates emissions over time, a vector of residual capital was introduced to maintain yearly emission accounts and thereby facilitate the comparison of the net impacts of endogenization on total final demand. This made the effects less pronounced, but a certain reallocation of CB emissions among countries did occur nonetheless (up to 9%), and the gap between PB emissions and CB emissions was widened for the majority of countries. By studying the impacts on emissions embodied in bilateral trade, we could establish that the observed trends of traded emissions were amplified further when taking into account the emissions embedded in capital.

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Environ. Sci. Technol. XXXX, XXX, XXX−XXX

We also found that the approach increased global emissions embodied in trade by 11%.

As opposed to previous studies on capital endogenization, we chose to endogenize the CFC rather than the GFCF. The GFCF contains the new additions to the capital stock that will be used in the production of *future* goods and services, while the CFC describes the depreciation of the capital stock *currently* in use. Therefore, we argue that for footprint-type calculations, the emissions associated with the production of the GFCF should be allocated to goods and services produced in the future, while goods and services produced today should be allocated historical emissions associated with the production of capital, thereby capturing their "true" life-cycle impacts. This also leads to a fairer allocation of emissions, both in terms of historical responsibility and of development opportunity. Complementary to traditional UNFCCC reporting, it is also widely acknowledged that achieving a fair allocation of emission quotas entails not only looking at current emissions but also considers countries' responsibility for historical emissions and the development stage they are at.[46−48]

Nevertheless, the CFC remains an economic concept, which implies that it does not describe the physical use of capital goods in production but their estimated loss in value as a result of their use and obsolescence. It has previously been suggested that a more adequate measure for the inputs of capital to production processes is in the form of capital services, i.e., the flow of productive services from capital assets to production. However, the way to estimate capital services is highly debated[49−53] and tables of capital services remain exception rather than norm in today's macroeconomic accounts (the EUKLEMS tables featured capital services estimates in the 2007 release but not in subsequent ones). This is discussed further in the SI published online.

While endogenizing CFC allows retrospective distribution of historical emissions to currently produced goods, the temporal dimension implies some additional methodological challenges. Capital assets currently in use stem from different age cohorts and were built using different technologies, i.e., with different carbon intensities. While this may not be a major issue for goods that are replaced regularly and/or depreciated rapidly (e.g., computers), it certainly is for assets with longer lifetimes (e.g., buildings, power plants, and roads). Hence, the emissions actually embedded in those goods could potentially be much higher if they were calculated with the technology mix that was used when they were built. This is the approach taken in dynamic stock models used in material flow analysis, where the year of production of capital is considered.[54,55] For instance, Müller et al.[56] suggest that the carbon footprint of a stock can be defined as the historical emissions produced when the stock was build up and refer to it as the CHV (historical value expressed in carbon).

This could be achieved in IO analysis too, through a dynamic framework for the intertemporal assignment of carbon emissions to final demand, such as the ones outlined by Duchin and Szyld[57] and Pauliuk et al.,[37] or by adopting a hybrid LCA form as suggested by Nansai et al.[43] The recent inclusion of time-series in constant prices in some MRIOTs (e.g., WIOD and EXIOBASE) provides the information necessary to enable cross-temporal comparisons of emissions intensities. However, implementing the framework entails other challenges, given that capital stocks are not traced explicitly in any accounts. Furthermore, the flow matrix method applied in this study uses the Leontief model to allocate supply chain impacts to final consumers. The matrix inversion that occurs in the process implies that capital and noncapital requirements can no longer be differentiated once the environmental extensions are added. In this work, we have therefore assumed the steady-state assumption adopted in other studies,[40,43] implying that the capital stock depreciated in a year is replenished in the same year, using that year's technology. This is similar to the concept of carbon replacement value proposed by Müller et al.[56] Future work could consist in improving the current model to allow for differentiation between capital and noncapital goods when applying the environmental extensions, so that the difference in technologies used to produce the capital goods currently in use can be taken into account when calculating footprints. The topic of temporality is explored further in the SI.

The challenge with capital accounting in IO is well acknowledged among input−output practitioners but has remained unsolved for decades, mainly due to the problem of data availability. Today's IO databases only provide capital expenditures as a final demand vector, and the consumption of different types of capital by industries is not available in national accounts. However, recent projects such as the EUKLEMS have developed detailed tables of capital use by assets and sectors. By combining these with MRIO databases, our study has filled a research gap, providing a new, integrated approach to capital accounting in IOA.

CB emissions calculated using currently available MRIO databases do not assign the emissions embedded in the capital goods used in production processes to the goods and services that the capital is used to produce, despite that they constitute a substantial share of the total emissions. Endogenizing capital enables to better capture all life-cycle impacts associated with the production of goods and services, and the method developed in this paper constitutes an important complement and improvement of current IO methodology. The impacts of capital endogenization in MRIO models are substantial and the consequences are wide-ranging. The reallocation of emissions that occurs not only sheds new light on the global impacts associated with the consumption of specific goods and services, but also changes the global CB GHG emission distribution, which could have important implications for climate policy development.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02791.

> Additional explanations about the methodology as well as details about the data sources used to obtain the results, which discusses some of the assumptions of our framework further and provides sensitivity analysis results for some of them (PDF)

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Notes

The authors declare no competing financial interest.

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Appendix C2: Supplementary material for paper II

This appendix describes how the flow matrix approach was applied and how the KLEMS and other auxiliary capital sources were harmonised to the EXIOBASE classification. An extended version of this supplementary material is available along the online version of paper II.

The flow matrix method consists in creating a capital requirement matrix $\mathbf{K}$ with the same dimensions as the inter-industry requirement matrix $\mathbf{A}$. As explained in the main paper, we have chosen to endogenise the CFC rather than the GFCF. A discussion on the implications of this is provided in the main paper as well as in the discussion chapter of the thesis.

Similarly to Södersten et al. [1], we converted the KLEMS accounts (which, in the KLEMS release used in paper II, were provided at an 8 products by 32 industries resolution) to EXIOBASE classification (200-by-163) with the help of binary concordance matrices $\mathbf{G}_{\mathrm{p}}$ (8-by-200) and $\mathbf{G}_{\mathrm{i}}$ (32-by-163) that associate, respectively, products and industries from KLEMS to relevant product and industries in EXIOBASE. We used distribution proxies $\mathbf{p}_{\mathrm{p}}$ (and $\mathbf{p}_{\mathrm{i}}$) when one product (or industry) in KLEMS is assigned to several products (or industries) in EXIOBASE. For instance, if we wanted to distribute product a in KLEMS to products a' and a'' in EXIOBASE, the proxy will determine how much of a is distributed to a' and a'' respectively. These proxies have to be of the same size as the destination target, i.e. 200 respectively 163. We therefore chose the available GFCF and CFC values from EXIOBASE as suitable proxies $\mathbf{p}_{\mathrm{p}}$ and $\mathbf{p}_{\mathrm{i}}$ (the implications of distributing CFC using GFCF are discussed in the discussion part of the thesis). The concordance matrices needed to be normalised to avoid double counting, and we therefore created new normalised concordance matrices $\overline{\mathbf{G}_{\mathrm{p}}}$ and $\overline{\mathbf{G}_{\mathrm{i}}}$ constructed as such:

$$\overline{\mathbf{G}_{\mathrm{p}}} = \left(\widehat{\mathbf{G}_{\mathrm{p}}\mathbf{p}_{\mathrm{p}} + \delta}\right)^{-1}\mathbf{G}_{\mathrm{p}}\widehat{\mathbf{p}_{\mathrm{p}}} \tag{1}$$

and

$$\overline{\mathbf{G}_{\mathrm{i}}} = \left(\widehat{\mathbf{G}_{\mathrm{i}}\mathbf{p}_{\mathrm{i}} + \delta}\right)^{-1}\mathbf{G}_{\mathrm{i}}\widehat{\mathbf{p}_{\mathrm{i}}}. \tag{2}$$

The circumflex attribute implies a diagonalised vector, and δ is a small number that prevents singularities. We obtained a 200-by-163 CFC matrix $\mathbf{K}_{\mathrm{EXIO}}^{cfc}$ from an 8-by-32 start matrix $\mathbf{K}_{\mathrm{KLEMS}}^{cfc}$ as such:

$$\mathbf{K}_{\mathrm{EXIO}}^{cfc} = \overline{\mathbf{G}_{\mathrm{p}}}'\mathbf{K}_{\mathrm{KLEMS}}^{cfc}\overline{\mathbf{G}_{\mathrm{i}}} \tag{3}$$

Where $\overline{\mathbf{G}_{\mathrm{p}}}'$ is the transpose of $\overline{\mathbf{G}_{\mathrm{p}}}$.

The procedure to convert from other classifications is analogous, with appropriate concordance matrices and proxies.

Since KLEMS is constructed using national accounts, it only provides national tables of capital use and expenditure. The MRIOTs from EXIOBASE have been created through partial closure of the input-output system by endogenising imports and exports through trade linking, and the final demand is hence disaggregated by origin country using the same procedure (i.e. the capital flows are traceable globally). We used the disaggregated GFCF vectors as proxies to distribute our $\mathbf{K}_{\mathrm{EXIO}}$ matrices across all 49 regions, assuming, again, that capital inputs have the same origin structure as GFCF.

The type of detailed capital metric available in the sources (KLEMS, World KLEMS, etc.) varied. Ideally, the proxy $\mathbf{K}_{*}^{cfc}$ (where the * is a wildcard denoting the data source) used to distribute the one-dimensional CFC from EXIOBASE should contain CFC data. When detailed CFC data was not available, the proxy was instead based on capital compensation, which is defined as the residual between value added and labour compensation[2]. When neither of those was available, the capital stock or the GFCF were used, since they were deemed more relevant than a generic proxy (described below).

In order to create capital distribution proxies for the EXIOBASE countries that are not covered by KLEMS, we began by creating a generic distribution matrix $\mathbf{K}_{\text{gen}}^{cfc}$ built on an average of all $\mathbf{K}_{*}^{cfc}$ available in either NACE1 or NACE2 classification. Using it directly as a proxy would imply that capital would be used similarly in all remaining regions of the world. This is clearly unrealistic, particularly so because the capital matrices available cover mostly rich, industrialised countries. Countries at different stages of development are likely to have a different capital consumption structure. Therefore, we adjusted the generic capital use matrix so that it reflected the structure of the economy in each country. That is, we reconciled $\mathbf{K}_{\text{KLEMS}}^{cfc}$ with the CFC and GFCF from EXIOBASE, as these are constructed using actual data from national accounts. Such reconciliation can be done using biproportional fitting techniques such as the RAS algorithm (first introduced by Stone[3, 4]). The RAS algorithm (and its many variations – see e.g. Jackson and Murray[5] or Lenzen et al.[6] for an overview) is often used in IO for updating a matrix $\mathbf{A}$ from one year to another with minimum loss of information so that it is consistent with new output and input vectors $\mathbf{u}$ and $\mathbf{v}$. In other words, the new matrix $\mathbf{M}$ should satisfy $\mathbf{Mi} = \mathbf{u}$ and $\mathbf{i}'\mathbf{M} = \mathbf{v}$, where $\mathbf{i}$ is a summation vector of appropriate length, while deviating least from the original matrix. The issue of deviating least has been shown[7] to be equivalent to the problem of minimising the total information gain defined as

$$\sum_i \sum_j |x_{ij}| \ln\left(\frac{m_{ij}}{a_{ij}}\right) \tag{4}$$

Together with the aforementioned constraints, this forms a programming model that can be solved iteratively with RAS-like algorithms, on the condition that the constraints are mutually consistent, i.e. $\sum_i u_i = \sum_j v_j$ (total input = total output).

The problem at hand was slightly different, since the goal was to adjust the matrix $\mathbf{K}_{\text{KLEMS}}^{cfc}$ to a row total (GFCF) and a column total (CFC) whose sums were not equal. That is, $\sum GFCF \neq \sum CFC$. The optimisation problem was therefore only solvable for one constraint at a time, and since traditional RAS variants operate iteratively on the constraints, the algorithm would oscillate between optima and never converge towards one solution. Lenzen et al.[6] tackle the issue of matrix balancing under conflicting information by introducing the KRAS algorithm, a variant of Junius and Oosterhaven's GRAS[7], which iteratively adjusts the constraints while balancing the matrix so that convergence is reached. The KRAS may be suited for cases where it is crucial to preserve the values of the constraints, such as when updating IO flow matrices against new product and industry outputs. Since we were only interested in the distribution of the values across the matrix (i.e. of the relative importance of the constraints elements), we took a shortcut in Lenzen at al.'s approach by skipping the iterative procedure and instead scaled the constraint proxies against each other. That is, we scaled up the CFC row vector with a factor ξ defined by

$$\xi = \frac{\sum GFCF}{\sum CFC} \tag{5}$$

Likewise, we scaled up the distribution matrix $\mathbf{K}_{\text{gen}}^{cfc}$ with a factor χ defined by

$$\chi = \frac{\sum GFCF}{\sum\sum \mathbf{K}_{\text{gen}}^{cfc}} \tag{6}$$

This generic matrix was then disaggregated across products and industries using, respectively, CFC and GFCF from EXIOBASE as individual country proxies, as explained above. To convert from our 9800-by-7987[1] capital transaction matrix to a symmetric 9800-by-9800 capital flow matrix $\mathbf{K}$, we applied the industry technology construct (described in e.g. Miller and Blair[8]) to conform with the way the $\mathbf{A}$ matrix is constructed in EXIOBASE, and refer to Kop Jansen and ten Raa[9] for a discourse about the implications of the choice of model in the construction of IOTs.

The steps described so far lead to a 9800-by-9800 $\overline{\mathbf{K}}$ matrix of capital transactions. In order to obtain a capital *requirement* matrix $\mathbf{K}$ we proceeded similarly as when calculating the regular inter-industry matrix $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, i.e. by dividing the capital flows by the total output $\mathbf{x}$ as such: $\mathbf{K} = \overline{\mathbf{K}}\hat{\mathbf{x}}^{-1}$. The circumflex attribute implies, again, that the vector is diagonalised. From this we calculated a new Leontief inverse based on a matrix of inter-industry transactions containing both $\mathbf{A}$ and $\mathbf{K}$:

$$\mathbf{L}^{\text{K}} = (\mathbf{I} - (\mathbf{A} + \mathbf{K}))^{-1} \tag{7}$$

The whole procedure was performed for all years, with year-specific proxies, capital transactions matrices and inter-industries requirement matrices. When capital matrices were not available for all years in the time series, the nearest available year was used (details over the data sources are available in the online supplementary material associated with paper II).

We also studied the impacts of endogenisation on multipliers $\mathbf{sL}$, which express the CB impacts per unit final demand (as opposed to unit industry output). The increase in multipliers is given by the ratio of each element in $\mathbf{sL}^{\text{K}}$ and $\mathbf{sL}$. To assess the change in multipliers for each product category, we needed to take into account the relative importance of all individual constituents, that is, how much of each product was produced in each region. This was done by calculating the difference in weighted multipliers. As multipliers are not dependent on purchasing region, we created vectors of global final demand $\mathbf{y}_{tot}^{\text{W}}$ and $\mathbf{y}_{res}^{\text{W}}$, constructed by summing $\mathbf{y}_{tot}$ respectively $\mathbf{y}_{res}$ for all countries (where $\mathbf{y}_{tot}$ is the final demand including the total GFCF and $\mathbf{y}_{res}$ the final demand including only the residual capital; see main paper for details). In order to keep the product resolution in our calculations, we superposed a 200-by-200 identity matrix $\mathbf{I}$ 49 times to account for all regions in EXIOBASE as such

$$\mathbf{\Gamma} = \begin{bmatrix} \mathbf{I} \\ \vdots \\ \mathbf{I} \end{bmatrix} \left.\vphantom{\begin{bmatrix} \mathbf{I} \\ \vdots \\ \mathbf{I} \end{bmatrix}}\right\} 49 \tag{8}$$

This enabled us to aggregate the 9800 country-specific products to 200 global product categories. Hence, while the multipliers $\mathbf{sL}\widehat{\mathbf{y}_{tot}^{\text{W}}}$ and $\mathbf{sL}\widehat{\mathbf{y}_{res}^{\text{W}}}$ return 1-by-9800 row vectors of CB impacts of the respective final demand vectors disaggregated by both products purchased and exporting country, multiplying by the

[1] 200*49 = 9800, and 163*49 = 7987

superposed identity matrix yielded a 1-by-200 vector of CB impacts per products (regardless of exporting country) before and after endogenisation of

$$\mathbf{sL}\widehat{\mathbf{y}_{tot}^{\mathrm{W}}}\boldsymbol{\Gamma}$$

and

$$\mathbf{sL}^{\mathrm{K}}\widehat{\boldsymbol{y}_{res}^{\mathrm{W}}}\boldsymbol{\Gamma}$$

respectively. The weighted multipliers were then obtained by

$$\mathbf{m} = \mathbf{sL}\widehat{\mathbf{y}_{tot}^{\mathrm{W}}}\boldsymbol{\Gamma} \oslash \widehat{\mathbf{y}_{tot}^{\mathrm{W}}}\boldsymbol{\Gamma} \tag{9}$$

and

$$\mathbf{m}^{\mathrm{K}} = \mathbf{sL}^{\mathrm{K}}\widehat{\boldsymbol{y}_{res}^{\mathrm{W}}}\boldsymbol{\Gamma} \oslash \widehat{\boldsymbol{y}_{res}^{\mathrm{W}}}\boldsymbol{\Gamma} \tag{10}$$

where the $\oslash$ indicates element-wise division.

The 1-by-200 vector of changes in product-specific multipliers was subsequently obtained by

$$\boldsymbol{\delta}^{m} = \mathbf{m} \oslash \mathbf{m}^{\mathrm{K}} = (\mathbf{sL}\widehat{\mathbf{y}_{tot}^{\mathrm{W}}}\boldsymbol{\Gamma} \oslash \widehat{\mathbf{y}_{tot}^{\mathrm{W}}}\boldsymbol{\Gamma}) \oslash (\mathbf{sL}^{\mathrm{K}}\widehat{\boldsymbol{y}_{res}^{\mathrm{W}}}\boldsymbol{\Gamma} \oslash \widehat{\boldsymbol{y}_{res}^{\mathrm{W}}}\boldsymbol{\Gamma}) \tag{11}$$

In order to be able to perform temporal comparisons of multipliers, they needed to be converted to constant prices. A discourse about constant and current prices as well as a detailed explanation of how to convert from one pricing approach to another is provided in the extended supplementary material of paper II available online as well as in the supplementary papers V and VI.

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Appendix D1: Paper III

Södersten, C-J, R. Wood and T. Wiedmann. 2019. The capital-augmented material footprint: the real material footprint of final consumption. *(unsubmitted manuscript)*

The capital-augmented material footprint: the real material footprint of final consumption

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Abstract

The global extraction of materials has surged in the last century. As materials are increasingly traded across the globe, both unprocessed and embodied in fabricated goods, different indicators have been developed with the purpose of providing a comprehensive measure of material use. However, none of these indicators include the materials embodied in the capital goods when calculating the resources embodied in goods for final consumption. As roughly 50% of metals and 60% of non-metallic minerals are destined for capital formation, the material footprint of consumption as it is currently calculated greatly underestimates the amount of materials used to produce final consumer products. In this paper, we introduce the capital-augmented material footprint (CAMF), a new indicator of material use that includes all the materials used along the supply chain, including those embedded in capital goods. We calculate the CAMF for 49 countries and regions over the period 1995-2015 using the environmentally extended multi-regional input-output database EXIOBASE3. Our results show that when looking at mineral use, about 50 to 60% of the total footprint of final consumption is embodied in the capital goods used in the production processes, whereas for biomass, the figure is around 10%. The product categories that show the largest increase in material footprints are the service sectors, in particular the real estate sector. When studying the decoupling economic growth from resource use, we found that more countries achieve relative and absolute decoupling when using the CAMF as an indicator of material use. Our results demonstrate that current CB assessment methods do not fully capture all the materials embodied in final consumption. To be able to effectively decrease the impacts of consumption, we need to have a sound understanding of all the impacts associated with it. The indicator we propose here constitutes an important step on the way to develop a comprehensive accounting method for the impacts of consumption.

Introduction

The concept of sustainable development was formally introduced in the 1987 Brundtland Report, as a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs"[1, p41]. Correspondingly, it is widely agreed that long-term sustainability cannot be achieved unless continued global growth in economic output and human well-being is decoupled from the use of resources[2-6]. Although a relative decoupling of resource extraction from economic growth has been observed previously[7], studies suggest that current material extraction rates are unsustainable[8], growing faster than GDP and that an absolute decoupling is necessary, at least for the OECD economies[2]. Arguably, as the Earth's mineral reserves are finite, extraction of resources from the lithosphere cannot continue indefinitely, and a global absolute decoupling will ultimately be required.

Global material extraction for human use is, however, increasing at unprecedented rates. Between 1970 and 2010, raw material extraction more than tripled, from an estimated 22 billion tonnes (bt) to over 70bt[9]. During the same period, global population merely doubled, implying that the per-capita rate of consumption of materials increased by 150% (from 7t/cap to 10.5t/cap), and are at the highest ever recorded[10]. For some materials, including iron ore and bauxite (the main component of aluminium), extraction rates have risen faster than GDP[11]. Globalisation has facilitated this increase in material use, with a corresponding increase in the amount of traded goods and materials. Between 2000 and 2010, world production increased by 2% whereas export volumes increased by 3.5%[12]. Material use embodied in trade grew from 23% to 32% of total global material extraction between 1995 and 2010[13]. This entails that tracing the materials used and embodied in goods has become increasingly difficult.

Several different indicators of material use have been developed in the last two decades with the purpose of providing a more comprehensive measure of material use[9, 14]. The nature of these indicators has evolved over time, going from purely domestic measures of material use to indicators capturing all upstream material requirements. Traditionally, material flow analysis (MFA) has been the tool of choice for assessing the use of materials as well as deriving indicators relating to material extraction and consumption[14, 15]. Although the origins of MFA can be traced back to the studies analysing the metabolism of industrial society of the early 1970s[16], the first tables of material flow data were produced in the 1990s[14]. Since then, MFA has been widely applied by statistical offices around the world[17, 18] to derive a variety of indicators of material use. For instance, the domestic extraction (DE) indicator is defined as the annual amount of raw material extracted from a given territory[7]. When the direct material imports are added, it results in the domestic material input (DMI)[9], and when exports are removed from the DMI, it yields the domestic material consumption (DMC)[9, 11, 19, 20]. As international supply chains became more fragmented, it was argued that such indicators needed to be extended for the upstream material requirements of used extraction, referred to as the raw material equivalents (RME), which can be differentiated as RME of imports (RME_{imp}) respectively exports (RME_{exp})[9, 14, 21, 22]. Consequently, the raw material trade balance (RTB) was defined as the RME_{imp} minus the RME_{exp}. This led to indicators that included all direct and indirect requirements, such as the raw material consumption (RMC). The RMC was introduced as a consumption-based (CB) indicator of material use that allocates the upstream material requirements to the domestic final demand[9, 21], and has therefore also been called the material footprint (MF)[9, 10]. The estimation of such indicators that include the upstream material requirements is more difficult than for the DE and the DMC because of the need to capture material use along multiple stages of a supply chain. In fact, there are still different approaches used to calculate the indirect material flows of traded products[11, 14, 23, 24]. For instance, Wiedmann et al [11] calculate it as the sum of the DE and the RTB.

Other studies use the Leontief demand-pull model based on input-output analysis (IOA) to calculate the total material requirements associated with a final demand. Regardless of approach, the difference with conventional indicators of material consumption has been shown to be substantial[10, 12], and CB measures of material use have been used extensively in the last few years[9, 11, 12, 21, 25-30] to estimate the total upstream material use of nations and regions. This has provided important insights into how globalisation has transformed the way that materials are used and exchanged across the globe, both as raw materials and embodied in fabricated goods. Furthermore, indicators such as the MF bring valuable insight to studies assessing the decoupling of economic stress (such as resource use) from economic growth. When comparing the relative changes in material use and GDP over the period 1990-2008, Wiedmann et al.[10] found that some of the decoupling trends that could be observed when studying material use indicators that only account for the materials directly used (such as DMC) are cancelled out (or even reversed) when the indirect upstream materials used are also taken into account (i.e. with the MF). The study shows, for instance, that the DMC of the US grew at a slower rate than the GDP (PPP) during the analysed period, i.e. that a relative decoupling occurred. However, the MF of the US grew faster than the GDP, which entailed a negative decoupling of economic growth from material use. The UK and Japan even experienced an absolute decoupling when considering the DMC (which implies that material use *decreased* over time despite that the GDP was increasing), but again, when taking a CB perspective, the material use not only increased but did so at a faster rate than the GDP.

Although CB indicators provide an important insight into the emissions and materials that are embodied in the goods and services that we consume, they focus purely on the flow of materials and goods, and do not consider the inter-temporal nature of materials in stocks. IOA and multi-regional IO (MRIO) models have been established as the tool of choice to compute footprint-type CB indicators[31]. As explained in recent studies by Södersten et al.[32] and Chen et al.[33], MRIO databases do not currently treat capital goods (such as infrastructure, machinery, transport equipment, etc.) as inputs to the production system but as final goods. As such, while indicators describing the total upstream material requirements of a nation (such as the MF) do account for both current and capital requirements, they consider the latter as part of the final demand of a country. Capital goods, however, are used to provide further production services and may be used in the production of exports. Hence, when calculating the material footprint of households, capital inputs into the production process are left out, and these footprints are thus currently underestimated. This underestimation is likely to be substantial for material footprints, since construction materials are largely used to produce capital goods: half of the materials extracted annually as well as a quarter of the world's economic output is destined to build up and maintain in-use stocks[6, 34]. From a life cycle perspective it is desirable to incorporate these materials into the material footprints of consumption and it is likely that this leads to a substantial increase in the embodied material content of consumer goods and services, particularly the latter. As economies mature, the structure of final demand changes towards goods with lower material contents and services[35, 36]. As the upstream material contents of services are typically less carbon and material-intensive, it has previously been argued that shifting consumption patterns towards an increased consumption of services would lead to an absolute reduction of material use and impacts on the environment[37, 38]. While CB accounting has already been used to show that including upstream requirements substantially increased the total impacts associated with services[36], no study has yet estimated the material requirements of the capital goods used to produce these services. Furthermore, recent studies have highlighted the limitations of technology in solving environmental problems such as climate change[39]. The gains achieved through technology improvements have almost always been offset by increased household consumption[40] to an extent that future technology change would have to be unrealistic to stay within planetary limits[41]. As such, there is a need to investigate ways that policy can be directed towards facilitating sustainable consumption[42]. Most critically, there is a need for better empirical work on the material basis of consumption as economies develop and move away from large consumption of basic goods towards urban service-based societies. Is it possible for consumption (and hence economies) to grow without leading to increased resource extraction? Or are the significant increase in material footprints of investments[43] pointing to consistent increases in material embodied in infrastructure to service this growing consumption?

In this work we introduce a method for including the materials embodied in capital used to produce the goods and services for final consumption. We introduce a new indicator of material use that allocates these materials to the final consumption and use this indicator to calculate new footprints of final consumption to answer the following questions, central to address the abovementioned challenge of reducing the extraction rates of materials: How much and what type of materials are embedded in the capital used to produce goods and services for final consumption? For which product categories does the material footprint increase the most when material embedded in capital is included in the final footprint? How does the endogenisation of capital affect material decoupling trends?

Materials and Methods

We use MRIO analysis to calculate consumption-based indicators of material use (see e.g. Miller and Blair[44] for an overview of IO basics). The calculations are performed using EXIOBASE v3.6[45], an environmentally extended multi-regional IO database containing time series from 1995 to 2015 and covering 44 countries and five rest-of-the-world regions. One of the strengths of EXIOBASE compared with other available MRIO databases is the high level of environmental stressor detail, particularly regarding the use of resources and materials. The environmental extensions include 227 types of material inputs that form part of the used domestic extraction (among which 12 are metal ores), and 223 types of associated “hidden flows” that constitute the unused domestic extraction. These hidden flows are sometimes included in the measure of material use with the rationale that they also contribute to the ecological rucksack[46]. While the time series in EXIOBASE3.6 are based on existing macroeconomic and trade data until the year 2015, empirical material flow data was only available until the year 2013. The material extensions beyond 2013 have therefore been compiled by extrapolating earlier extensions[45].

In order to include the materials embodied in the capital in our material footprint, we use the model described by Södersten et al.[32], in which the IO system has been closed for capital so that capital flows are endogenised in the inter-industry matrix. The model uses external data on capital use by asset and industries provided by the KLEMS and WORLD KLEMS databases. For this paper, the model has been updated with new KLEMS releases so that detailed capital data was available for 31 of the 44 countries included in EXIOBASE. For the countries not covered, capital tables were constructed based on a generic capital data distribution matrix adjusted for each individual country according to the procedure described by Södersten et al.[32]

The flows of capital differ from the flows described by the inter-industry matrix in traditional IOA. Firstly, capital goods (or fixed assets) are not transferred and transformed throughout the supply chain like other tangible production requirements, but rather provide productive services in the form of e.g. transportation, storage space, computational power, etc. Therefore, they cannot be measured in terms of quantity used (physical or monetary), but have to be estimated by the amount of service they supply.

Secondly, while current goods are assumed to be acquired and utilised within one accounting period (which the System of National Accounts[47] defines as one year), fixed assets are goods that are used in production processes for longer than a year and therefore overlap over several accounting periods. These characteristics make the accounting of capital complex. National accounts (and consequently IO tables that are based on them) have resorted to treating the acquisitions of capital goods as a separate final demand category (the gross fixed capital formation, or GFCF), despite that they are, per definition, used in the production and provision of other goods and services for final consumption. The assets that remain in use at the end of an accounting period are expected to provide productive services in subsequent periods and are therefore still valuable to the industries owning them. Consequently, these capital goods still in use are recorded as part of the value added (VA), under the term "consumption of fixed capital" (CFC).

The rationale behind the endogenisation of capital is to assign the environmental impacts associated with the capital goods to the footprint of goods and services they are used to produce. Hence, the amount of capital that each final product consumes ought to be estimated by the amount of service that the asset provides. We estimate the utilisation of capital across industries with the CFC available in EXIOBASE3 and argue that it constitutes the most adequate estimate of capital use readily available in today's MRIO databases. This choice can be contested; the CFC is an economic measure (expressing the depreciation of existing capital during the current accounting period), which is arguably not optimal for assessing physical usage (see further discussion in Södersten et al.[32]). Furthermore, the CFC is not an unequivocal estimation, and there are several ways to calculate it (of which the OECD capital measurement guide offers a comprehensive overview[48]). Indeed, many IO databases do not provide the CFC as a distinct entry but keep it embedded in the more general vector of gross operating surplus within the VA. This brings additional complexity to our approach, as the methods used to construct the CFC vector in EXIOBASE3 often relied on proxy data[45]. The only statistical global estimates of CFC found were those provided by the World Bank[49], and these were only available as one aggregate figure per country and year. Nevertheless, these yearly estimates were deemed the most reliable and we have chosen to adjust the CFC of EXIOBASE to the World Bank data. In order to keep consistency across capital use and capital formation, we compared the GFCF figures from the World Bank against those available in EXIOBASE as well and rescaled the EXIOBASE CFC so that the total yearly ratio between the GFCF and CFC were the same. That is, for each year y:

$$\frac{\sum GFCF_y^{EXIO}}{\sum CFC_y^{EXIO}} = \frac{\sum GFCF_y^{WB}}{\sum CFC_y^{WB}} \tag{1}$$

Hence, each entry in the EXIOBASE CFC vector was multiplied by a factor β given by

$$\beta = \frac{\sum GFCF_y^{EXIO}}{\sum GFCF_y^{WB}} \sum CFC_y^{WB} \tag{2}$$

The impacts of the rescaling varied a lot across countries. European countries were in general less affected (indicating that the original CFC estimates from EXIOBASE were close to those from the WB), while for certain non-European countries, the rescaling led to substantial changes (particularly for Brazil, Mexico, Russia and South Africa). Details on the effects of the rescaling can be found in the supplementary information. Since Taiwan is not featured independently in the World Bank, we used the $\frac{\sum GFCF_y^{WB}}{\sum CFC_y^{WB}}$ ratio of China to rescale the Taiwanese data. Furthermore, for the rest-of-the-world regions, the GFCF over CFC ratio was compiled by summing the data of all relevant countries. For instance, for the rest-of-the-world Africa region (WWF),

$$\frac{\sum GFCF_y^{WWF}}{\sum CFC_y^{WWF}} = \frac{\sum_{C_i}\left(\sum GFCF_y^{C_i}\right)}{\sum_{C_i}\left(\sum CFC_y^{C_i}\right)}, \forall\, C_i \in \{\text{Africa}\} \tag{3}$$

The endogenisation is done with the flow matrix method[50], which entails that a layer of capital flows is added to the regular, or "current", inter-industry flows. While the traditional Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ accounts for the total requirements of current goods, the new inverse accounts for both the current and capital requirements:

$$\mathbf{L}^{\mathrm{K}} = (\mathbf{I} - (\mathbf{A} + \mathbf{K}))^{-1} \tag{4}$$

where $\mathbf{A}$ is the inter-industry requirement matrix of current goods and $\mathbf{K}$ the inter-industry requirement matrix of capital goods. This new inverse can be used to calculate a new measure of material use. For instance, for a vector of final demand $\mathbf{y}$ and a row vector $\mathbf{s}$ containing total material use per unit output, the total material use associated with the final demand $\mathbf{y}$ is

$$d = \mathbf{s}\mathbf{L}^{\mathrm{K}}\boldsymbol{y} \tag{5}$$

Here, d are the upstream (consumption-based) material requirements of final demand that account not only for the materials embodied in the final products, but also the materials embodied in the capital goods used in the production processes. Therefore, we refer to this measure as the Capital-Augmented Material Footprint (CAMF).

This way of accounting for materials embodied in capital goods is novel and perhaps less intuitive, and care needs to be taken when applying the suggested method to calculate footprints. For instance, one implication of this is that the total CAMF of a country will be difficult to compare with the total MF as it is traditionally estimated, since the CAMF includes the materials embodied in the CFC while the MF includes the materials embodied in the GFCF. The CFC and GFCF are two measures of capital that differ both conceptually and quantitatively; the GFCF is a measure of all new additions to the capital stock, whereas the CFC is a measure of the depreciation of the *current* in-use stock. Therefore, the CAMF and MF account for capital that stem from different age cohorts, and therefore differ as well. To enable the comparison, Södersten et al.[32] resort to the creation of a residual vector of GFCF (containing the net capital formation), but their approach entails other complications and is not without drawbacks. In this study, we wish to obtain a better understanding of what is driving the increase in the materials embodied in capital goods and which products and countries are ultimately responsible for their consumption, and the results therefore focus on the material contents of final consumption only (defined as the consumption of goods and services by households, government and non-profit institutions serving households).

Results

Treating capital goods as intermediate goods rather than final products entails that production processes will consume more inputs, i.e. that the requirements per unit output will increase for all industries and countries. As a result, the associated use of materials will increase as well, as can be seen in figure 1, which shows the footprints of final consumption of the OECD (red curves) and non-OECD (blue curves) economies for four types of materials (biomass, fossil fuels, metal ores and mineral ores). The areas show the increase in material use that occurs when capital is endogenised. Both absolute (upper graphs) and per-capita (middle graphs) values are shown, as well as the relative increase (lower graphs) between the MF and CAMF (the relative increase is the same in absolute and per-capita measures). The lower graphs hence illustrate the effects of endogenising capital on the footprints of final consumption.

The relative increases vary substantially depending on material category. While the increase in biomass remains within 5% and 13%, the increase in metals and minerals is much larger, ranging from 20% to over 160%. This could be explained by the fact that most minerals are extracted for use in the construction sector and will subsequently be transformed into capital goods such as buildings, infrastructure, etc., whereas biomass is mostly consumed by the agriculture sector, i.e. is already accounted for in the traditional MF. The effects of endogenising capital are generally larger for OECD economies than for non-OECD economies, though this difference between the country groups diminishes over time and is even reversed at the end of the time series for biomass, fossil fuels and metals.

The OECD countries are still consuming much more per capita than non-OECD countries, but the gap between them is narrowing for both approaches. Whereas non-OECD countries are steadily increasing their consumption across all material groups, OECD countries have managed to reverse the consumption trends for biomass, fossil fuels and metals. As a result, non-OECD countries have overtaken OECD countries during the analysed period regarding the total use of fossil fuels, metals and materials. Non-OECD consumption of biomass considerably exceeded that of OECD countries across the whole period. Biomass is principally used to produce food, a consumption product that is much less elastic than products containing fossil fuels (e.g. gasoline), metals (e.g. electronics) and minerals (dwellings). Moreover, while increasing wealth may lead to amassing electronics and buying a larger house, there is only so much food one can consume, which could explain why the non-OECD, with its much larger population, is consuming substantially more biomass than the OECD.

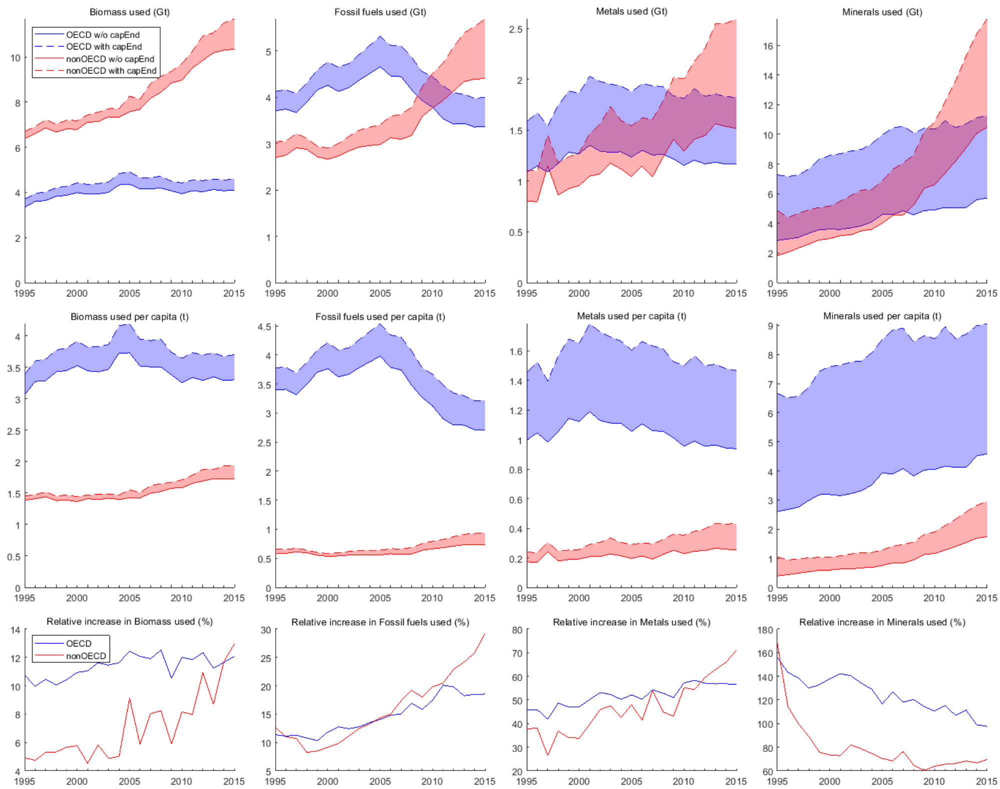

*Fig1: Footprint of final consumption for OECD and non-OECD countries, with (CAMF) and without (MF) capital endogenised. Upper graphs show total footprints, middle graphs show footprints per capita and lower graphs show the increase in footprints as materials embodied in capital are taken into account (calculated as (CAMF/MF)*100).*

Underlying the increases in overall footprints are increases in product level footprints. In figure 2, we have plotted the footprints of the five most important (in terms of total material use of final consumption for each material type and over the analysed period) services and non-service products respectively for biomass and mineral use, aggregated over OECD and non-OECD countries. The shaded areas show the traditional footprints (i.e. the MF) and the dotted lines show the additional impacts that arise when the materials embodied in capital are taken into account in the footprints (i.e. the CAMF). The plotted lines are cumulative, meaning that the upper line in each graph represents the total CAMF of the five product categories shown in the legend. The colours in the legend refer to both metrics.

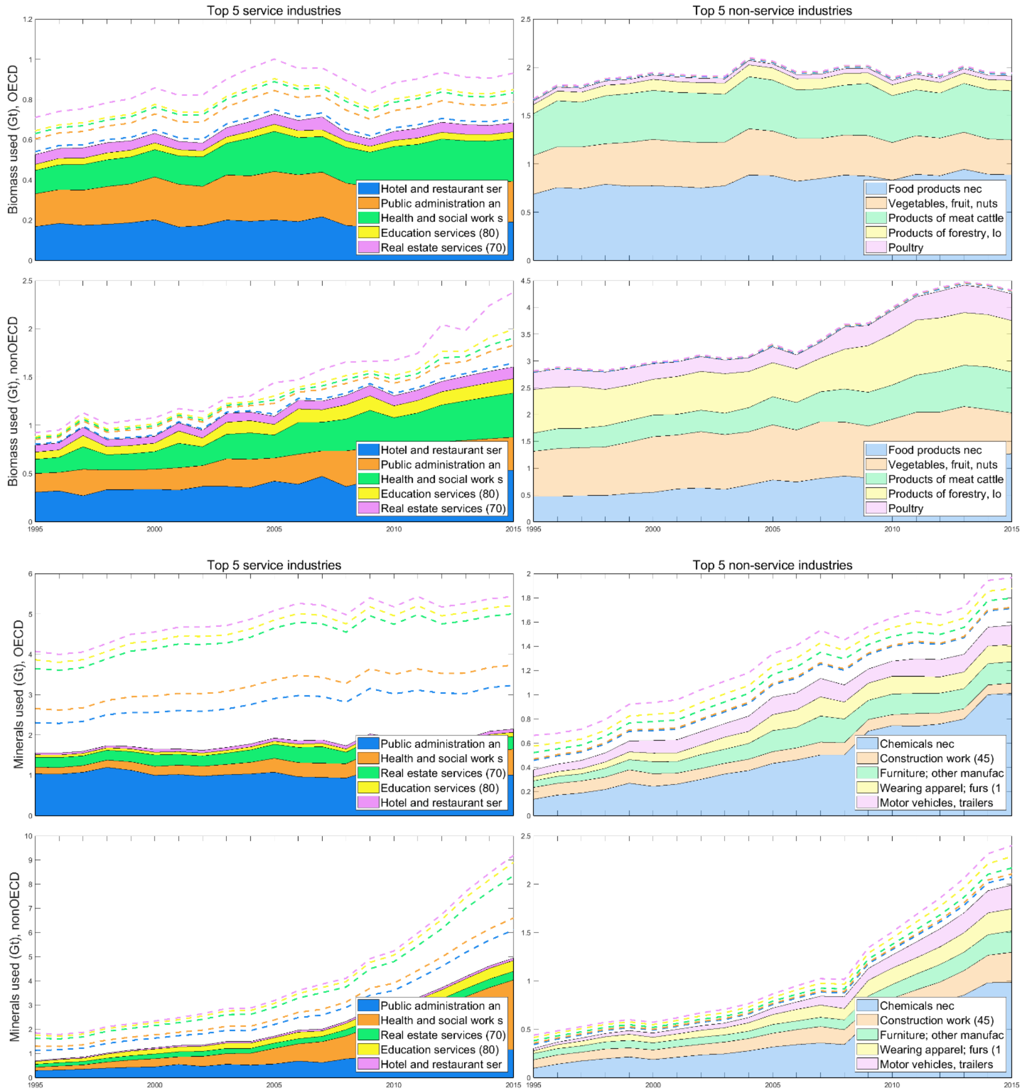

Fig2: Biomass and mineral use of the five most important (in terms of total respective material use by final consumption) service respectively non-service product categories, aggregated over OECD and non-OECD countries. Shaded areas show the MF (without capital endogenised) and dotted lines show the additional impacts that arise when the materials embodied in capital are taken into account in the footprints (CAMF). The colours in the legend refer to both metrics.

Several observations can be made from the figure. One recurrent trend across both material types and country groups is that services see their footprint increase substantially more than non-services when the materials embodied in capital goods are taken into account. The five largest service categories are the same across both material types: health and social work services; education services; hotel and restaurant services; public administration and defence services; and real estate services. The latter two categories increased the most (the average mineral use of real estate services in the OECD over the whole period more than quintupled when taking into account capital goods). There are two reasons for these steep increases. Firstly, services require less material in their production processes than non-services, which entails that the MF is low. Secondly, services (particularly real estate and public administration) are typically capital-intensive – education services require schools, real estate services require dwellings, health services require hospitals and electronic equipment and machinery, public administration and defence services require offices, housing for military personnel, transport and defence equipment, etc. This increase in material use for services is particularly large for mineral use, where it more than doubles for certain years. For OECD countries, the increase appears homogenous for both materials, while for non-OECD countries, it becomes more important towards the end of the time series, indicating an increased dependence on material-intensive capital. The difference between service and non-service categories is particularly striking for biomass: the CAMF is substantially larger than the MF for service categories, but for non-service categories, the increase is negligible, for both country categories.

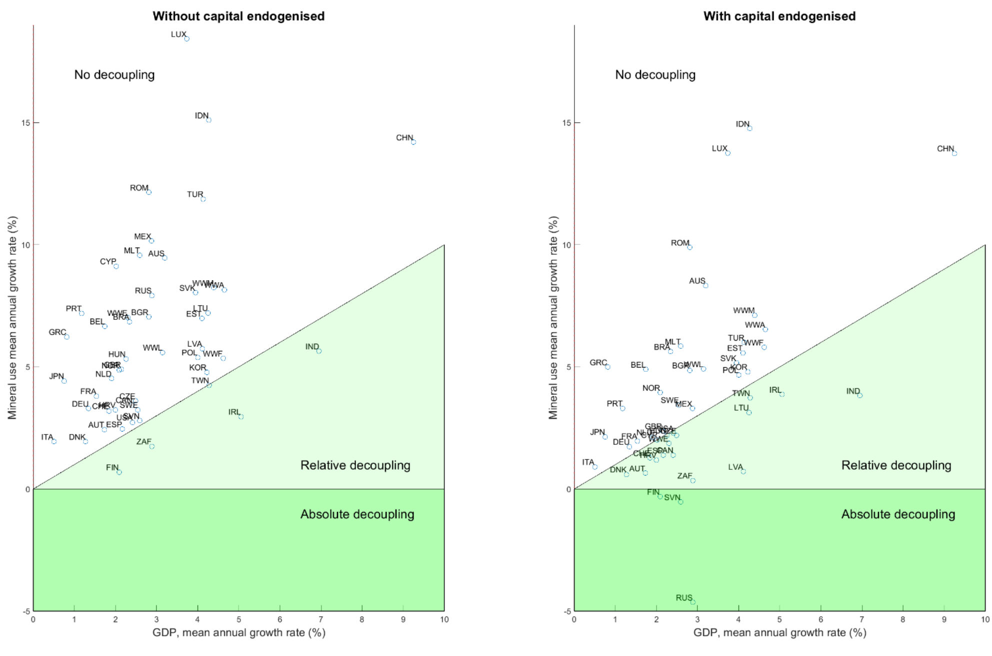

Figure 3: Mean annual growth rate of mineral use of final consumption and mean annual growth rate of GDP (PPP), a) without (MF) and b) with (CAMF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions.

As economies mature, a smaller portion of economic activity is related to resource exploitation. Figure 2 revealed that the use of materials (both for current and capital requirements) increased substantially more for non-OECD countries than for OECD countries, indicating that a certain saturation – or at least a slower growth – of material use can be expected upon reaching a certain development level. In other words, we expect to see a decoupling of material use from GDP. Figure 3 shows the mean annual growth rate of mineral use (the largest of the four material groups addressed in this study) of final consumption against the mean annual growth rate of GDP (PPP), with (CAMF) and without (MF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions (rest of Europe – WWE; rest of Africa – WWF; rest of Asia and Pacific – WWA; rest of Latin America and Caribbean – WWL; rest of Middle East – WWM). On the first graph, only a few countries achieve relative decoupling of material use from economic growth (FIN, ZAF, IRL, IND and TWN) and none sees their absolute MF decrease. When studying the CAMF however, 20 countries achieve relative decoupling and three reach absolute decoupling (FIN, SVN and RUS). These results may seem unintuitive at first since the CAMF is larger than the MF for all countries, but they can be explained by looking at the mineral use trends in Figure 1. While both the MF and CAMF increase over time, the relative difference between them decreases over time. This implies that the relative increase in MF is larger than the relative increase in CAMF; therefore, the mean annual rate of change of the MF is higher than that of the CAMF. This decoupling was also true for the global use of minerals.

We did not, however, find any correlation between the decoupling trends and the level of economic development (measured as GDP/cap in PPP), for neither the MF nor the CAMF. When comparing the decoupling trends for the total use of materials (i.e. the sum of the four material groups), the global decoupling trend was different. Despite that more countries reached relative or absolute decoupling for the CAMF than for the MF, the mean annual *global* growth rate was higher for the CAMF than for the MF, as some of the biggest consumers of materials (China, USA, India, Indonesia, and the rest-of-the-world Asia region) had a larger mean annual growth rate for the CAMF than for the MF. Decoupling figures for the other material groups are available in the supplementary information.

Discussion

The application of EE MRIO to derive CB indicators in the beginning of the 21st century constituted an important step in the indicator development as it enabled to capture the upstream material use associated with countries' final demand. In this study, we have driven this indicator development further by endogenising capital flows into the intermediate inter-industry matrix in the IO system with the rationale that capital goods ought to be considered as production requirements rather than goods for final demand. As a result, the CB requirements of final consumption calculated with the Leontief demand-pull model now account for both the current industry requirements and the capital industry requirements. Using this new model, we presented a new metric for estimating the material use of final consumption, the capital-augmented material footprint (CAMF), which includes not only the upstream materials embodied in the production processes (i.e. the MF) but also the upstream materials embodied in the capital goods used to produce the products for final consumption.

We showed that the CB material use of final consumption increased substantially when comparing the CAMF with the MF. By partitioning materials into four types (biomass, fossil fuels, metals and minerals), we found that the increase was particularly large for metals and minerals, with metal use increasing by around 45% for non-OECD countries and 50% for OECD countries, and mineral use averaging 80% respectively 120% increase over the analysed period. The average increase of fossil fuel use was around 15% for both country categories and the increase in biomass still lower, averaging 7% for non-OECD countries and 11% for OECD countries. The trends over the analysed period were found to be different for the two country groups. The material use of OECD countries stabilised and even decreased for the first three material categories, but the mineral use kept increasing. For non-OECD countries, all four material types showed a steady increase across the time series.

By looking at the material use by product categories, we found that endogenising capital affected service categories much more than non-service categories, particularly real estate and public administration services: the average mineral use associated with real estate services in the OECD more than quintupled over the analysed period when including the minerals embodied in capital. The reason for the substantial increased in the material use by services is twofold. Firstly, the intermediate material requirements of service sectors are relatively small (compared to non-service sectors). Secondly, service sectors rely on a lot of material-intensive capital goods to provide their services: real estate services require dwellings and other buildings, health services require buildings, machinery, etc.

We also analysed the decoupling trends between material use and economic growth and compared those trends for the CAMF and MF. The main results were that while more countries achieved relative or absolute decoupling when looking at the CAMF (indicating that fewer material-intensive capital goods were used in the production of goods and services for final consumption over time), the global trends were reversed. We could not find any correlation between decoupling trends and level of economic development.

The approach of calculating CB impacts with capital treated as intermediate goods brings new insights into the discussion about how to account for environmental impacts, but certain methodological challenges remain to be addressed. Some general comments about the limitations of the flow matrix method and its implementation are listed in Södersten et al. [32], and the drawbacks of MRIO analysis have already been discussed in multiple papers, e.g. [51-54]. Nevertheless, it is worthwhile to stress that estimating material use with monetary models, particularly when the main focus of the study concerns material-intensive capital goods, entails many uncertainties.

Conclusion

In this paper, we have seen that the choice of indicator substantially affects the estimation of material use associated with final products. The introduction of CB indicators in the early 2000's already led to significant changes in the measures of material use. By also including the materials embodied in capital goods, the total material use associated with final goods and services increased again, and this increase varied greatly across product groups and countries. This has important implications. For instance, it is increasingly argued that a change in the final demand composition is needed to meet emission reduction targets that will stop global warming from reaching levels that could have catastrophic ecological consequences. Multiple studies have therefore analysed the environmental impacts associated with household consumption[55-59] or of individual products or technologies[60, 61] to draw conclusions regarding e.g. how to design environmental policies, inform consumers about the environmental impacts associated with their consumption, etc. Furthermore, as countries become more developed, they tend to consume more services, and it has been argued that such a shift towards a more service-based economy is beneficial to reduce the environmental impacts and resource use associated with final consumption. When the materials embodied in the capital used to provide these services are included, however, the material use increases substantially. Furthermore, the results imply that the material use associated with government expenditures increases a lot, since a large share of e.g. public administration, education and health services are purchased by the government sector. While it is generally agreed that policies aiming at reducing and changing household consumption patterns are hard to implement, this may be less the case for government consumption.

The results presented in this paper lay the ground for future work and analysis regarding the use of materials in society. Resource extraction and material use are likely to increase further; the world population is growing in size and affluence, substantial infrastructure expansion is expected in many developing countries, and pathways to reach emission reduction targets involve many resource-intensive investments such as large-scale changes of the energy and transport infrastructure.

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Appendix D2: Supplementary material for paper III

This appendix is intended for online publication as supplementary material for paper III

1 Additional product footprint results

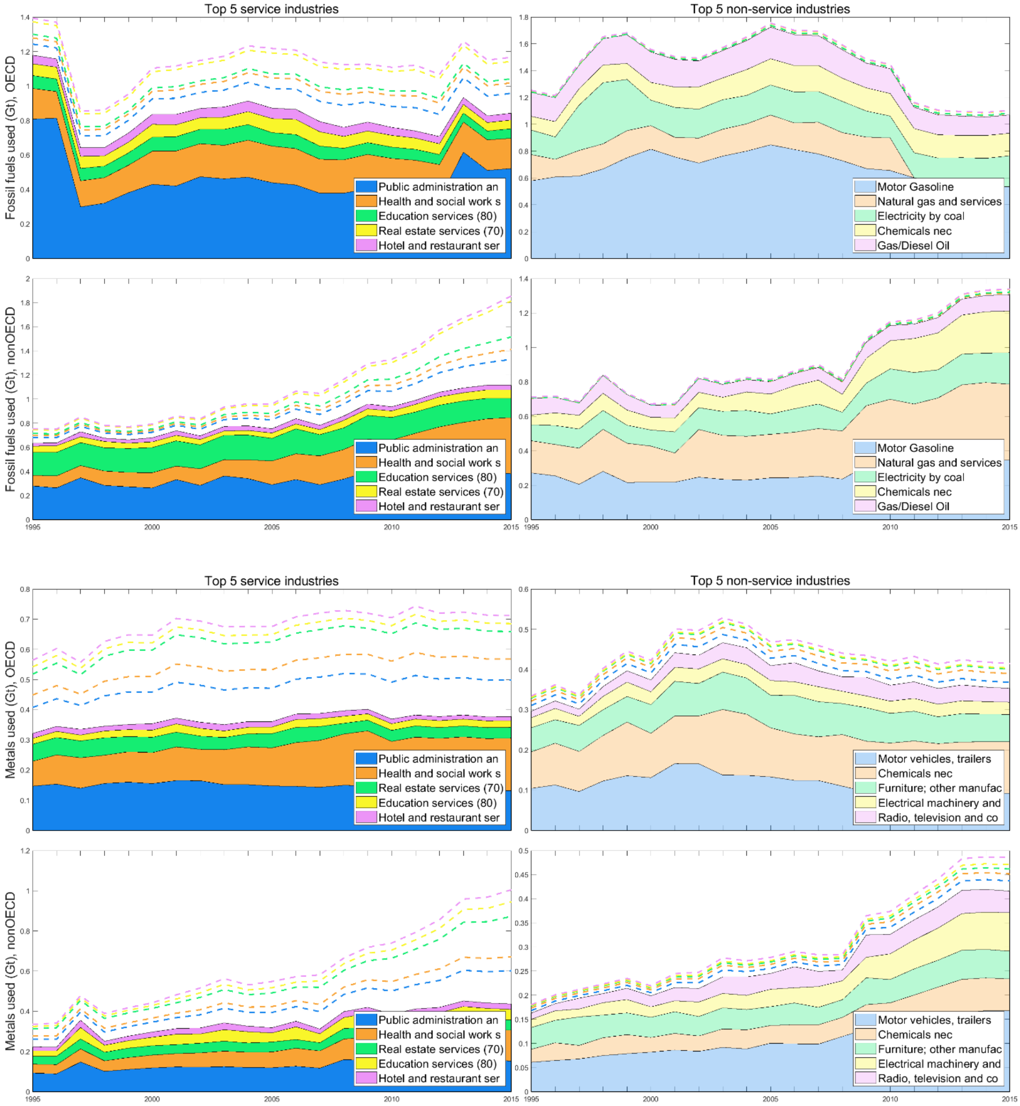


Fig D2.1: Fossil fuel (2a) and metal (2b) use of the five most important (in terms of total respective material use by final consumption) service respectively non-service product categories, aggregated over OECD and non-OECD countries. Shaded areas show the MF (without capital endogenised) and dotted lines show the additional impacts that arise when the materials embodied in capital are taken into account in the footprints (CAMF). The colours in the legend refer to both metrics.

2 Additional decoupling results

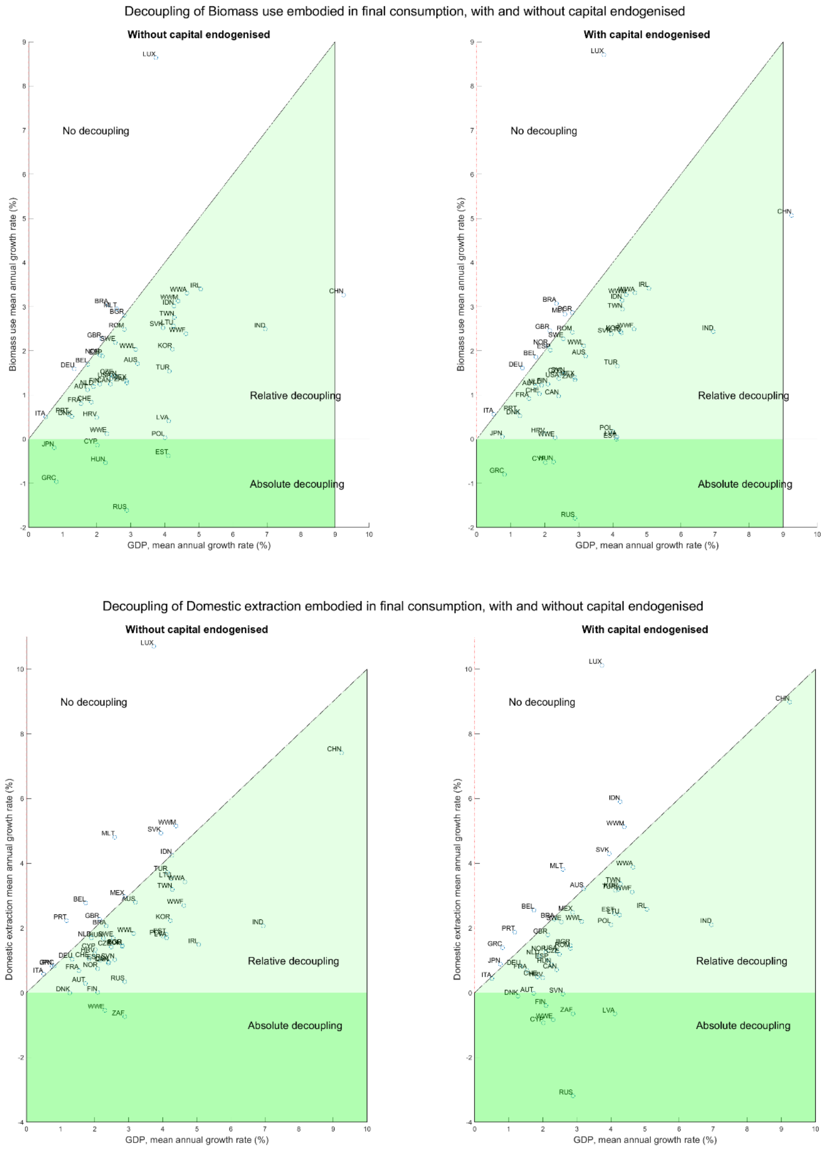
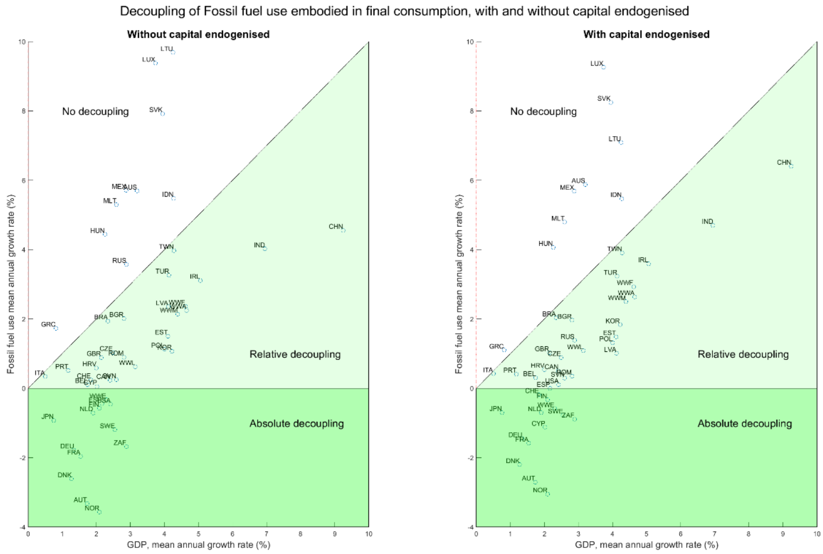


Figure D2.2: Mean annual growth rate of biomass use (upper figure) and total domestic extraction (lower figure) of final consumption and mean annual growth rate of GDP (PPP), with (CAMF) and without (MF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions.



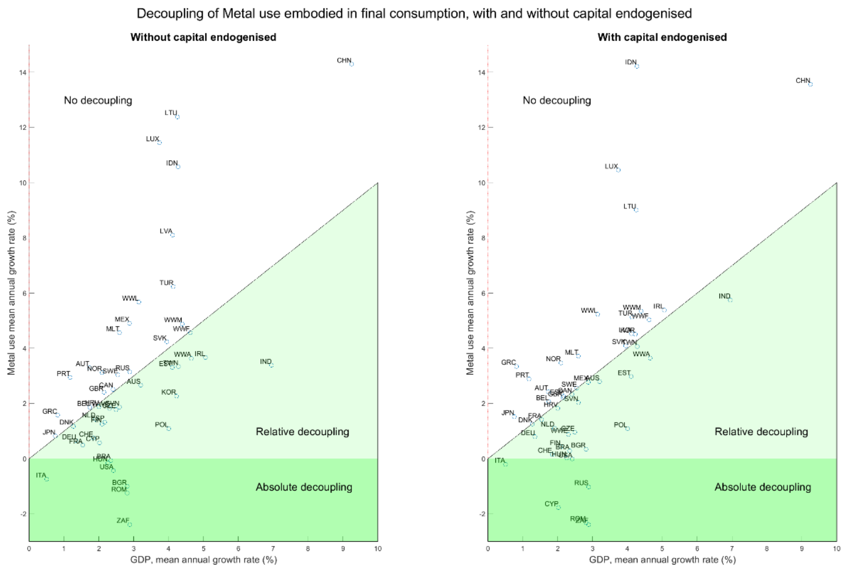


Figure D2.3: Mean annual growth rate of fossil fuel use (upper figure) and metal use (lower figure) of final consumption and mean annual growth rate of GDP (PPP), with (CAMF) and without (MF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions.

Appendix E – Paper IV

Södersten, C-J, M. Lenzen. 2019. A supply-use approach to capital endogenisation in input-output models. *(under second round of revision at Economic Systems Research)*

A supply-use approach to capital endogenization in input-output analysis

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Abstract

Input-output analysis currently treats capital transactions as exogenous components of the inter-industry system despite that capital goods are, per definition, destined for further use in production processes. Previous studies of capital endogenization have applied the Leontief calculus to include impacts of capital in footprint calculations. In Leontief's demand-pull model, the calculation of multipliers requires an inversion of the requirement matrix, which implies that the differentiation between capital and non-capital goods can no longer be made when associating stressor intensities to the multipliers. Here, we adopt a supply-use approach to capital endogenization and construct capital supply-use tables (KSUTs) that enable differentiation between the two types of intermediate goods when performing consumption-based impact calculations. By deriving the resulting inverse analytically, we are able to keep full transparency throughout the process of calculating multipliers. We implement the framework using time-series of the Australian economy along with environmental extensions from the EXIOBASE3 database.

Keywords

Input-output analysis, consumption-based accounting, supply-and-use tables, gross fixed capital formation, consumption of fixed capital, EXIOBASE

1 Introduction

1.1 Capital accounting in input-output analysis (IOA)

Input-output analysis (IOA) has become a popular tool for performing various types of consumption-based impact assessments, ranging from greenhouse gas (GHG) emissions (Hertwich, 2005; Lenzen, Pade, & Munksgaard, 2004) and resource use (Giljum, Lutz, & Jungnitz, 2008) to biodiversity loss (Lenzen et al., 2012) and bad labor (Simas, Golsteijn, Huijbregts, Wood, & Hertwich, 2014), and it is seen as the methodology of choice for footprint-type assessments (Wiedmann, 2009; Wiedmann & Minx, 2008). The basic IO framework developed by Leontief (1936) consists in linking supply and demand from all industries in an economy to form a symmetric input-output table (IOT) describing the inter-industry flows necessary to produce the goods and services for final consumption. By incorporating import and export patterns, several economies can be linked together to form a multi-regional input-output table (MRIOT). The (MR)IOT is then converted into a Leontief matrix that encapsulates effects on outputs from the inter-industry transactions.

Current MRIOTs treat final demand as exogenous, so that the Leontief framework can be used to calculate direct and indirect (i.e. upstream) impacts associated with a specific final demand. This is done by constructing multipliers that describe the amount of impact (such as kg of CO_2 emitted) per unit of final demand. Those multipliers only include the feedback effects occurring within the inter-industrial system, and such IO models are therefore said to be open or open-looped (Pyatt & Round, 1979). The resulting multipliers are referred to as type-I multipliers (Bradley & Gander, 1969; Katz, 1980; Miller, 1980). In contrast, type-II multipliers are derived from a partially closed (semi-closed) IO system where household expenditure and income are endogenized (Bradley & Gander, 1969). While type-I modelling is the norm in most current studies using IOA, treating final demand exogenously implies that these studies fail to capture some of the feedback mechanisms that exist between the different components of the economy, such as the multiplier effects of income on consumption (Q. Chen, Dietzenbacher, Los, & Yang, 2016; Lenzen & Schaeffer, 2004; Miyazawa, 1976; Pyatt & Round, 1979) or the induced effects of household spending due to a change in industrial output (Batey & Rose, 1990). Closing the IO system for households is also done to restrict the number of exogenously determined variable in analyses of structural change; for instance, Gurgul and Lach (2018b) endogenized household flows in their operating surplus optimization model so that the input variable of final demand only included investments and government spending. Pyatt and Round (1979) offer a lengthier explanation on the implications of closing the IO system for households. For additional discourse on open/closed IO models, see Batey and Rose (1990); Bradley and Gander (1969); Cohen (1989); Miller and Blair (2009); Robinson (1989).

Similarly, current MRIO databases treat capital exogenously, with the expenditures on capital (the gross fixed capital formation, or GFCF) reported as a vector of final demand and the depreciation of existing capital as a row vector of consumption of fixed capital (CFC), which for some countries is embedded in the gross operating surplus (GOS; see for example ABS

(2016)). The GFCF and the CFC both measure a quantity of fixed assets; that is, assets that are used repeatedly in production processes for a period of over a year (Eurostat, 2008). This definition implies that capital goods ought to be treated as intermediate goods rather than goods destined for final consumption. The reason for this accounting practice is inherited from the way capital is accounted for in the supply-use tables (SUTs) that are used to construct the IOTs, and stems from the fact that the lifetime of fixed assets exceeds the length of the accounting period used in national accounts (one year). Since capital goods therefore span over multiple accounting periods (several decades for e.g. factory buildings and infrastructure), recording them as intermediate inputs entails additional complexity with regards to valuation, loss of efficiency, etc. (see e.g. Pauliuk, Wood, and Hertwich (2014); Södersten, Wood, and Hertwich (2018a) for further discourse on this topic).

Treating capital transactions as exogenous components implies that footprint-type analyses that make use of the Leontief inverse do not take into account the impacts embodied in the capital goods used in the production processes. Conversely, it also implies that countries that have expanded their production capacity in response to rising export demands are likely to have been assigned impacts that occurred as a result of consumption in other countries (as Minx et al. (2011) investigate for the Chinese case). Several papers have therefore suggested that capital transactions ought to be endogenized into the IO framework (Z.-M. Chen et al. (2018); Hertwich (2011); Lenzen (2001); Lenzen and Treloar (2004); Peters and Hertwich (2006); Södersten, et al. (2018a)), so that the effects of building up and maintaining capital are included in impact assessment calculations. A handful of studies have published empirical results of endogenization on a national level (Wolff (1985) for the US, Lenzen (2001) for Australia, Peters and Hertwich (2006) for Norway, McGregor, Swales, and Turner (2008) for the UK, Minx, et al. (2011) for China), and recent papers by Södersten, et al. (2018a) and Z.-M. Chen, et al. (2018) look at the impacts of endogenization on a global scale and conclude that distributing the emissions associated with capital to the countries effectively consuming it leads to substantial reallocations of emissions across countries. Among these papers, two methods have been used to close the IO system for capital: the augmentation method and the flow matrix method. In the augmentation method, the GFCF and CFC vectors are added to the intermediate demand matrix as artificial one-dimensional fields of capital production and use respectively, which implies that capital commodities are assumed to be homogeneous. The flow matrix method, on the other hand, entails the construction of a detailed capital flow matrix that describes the use of different capital commodities by industries, allowing to discern between different types of capital assets when performing impact assessments.

In a comparison of the effects of both methods on factor multipliers, Lenzen and Treloar (2004) conclude that the flow matrix method is superior for estimating the inter-industry effects of capital expenditures, as the augmentation method systematically overestimates low-range multipliers and underestimates high-range multipliers. In the augmentation method, all capital assets are aggregated into one generic capital commodity. This aggregation involves obvious loss of information, and the implications of this when calculating for instance embodied CO_2 emissions or land use can be substantial. For instance, building a road or grazing cattle clearly leads to more emissions respectively land use than writing computer software, and keeping a detailed capital input structure of industries is therefore preferable.

While the flow matrix method allows for asset and industry differentiation, Södersten, et al. (2018a) identify some of the method's shortcomings when estimating consumption-based impacts of final demand using Leontief's demand-pull model. In traditional IO modelling, the calculation of multipliers entails an inversion of the inter-industry requirement matrix. In the flow matrix method, this requirement matrix contains both direct industry requirements (henceforth referred to as "current" requirements) and capital requirements. Hence, when applying stressor intensities to the multipliers, the differentiation between capital goods and current goods can no longer be made. As pointed out by Pauliuk, et al. (2014), the capital stock currently used in production processes is highly diverse. Capital assets stem from different age cohorts, which implies that the technologies that were used to build up the current in-use stock were different too. Technological progress generates improvements in productivity and resource efficiency (Grübler, 2003), and depending on the lifetime of the assets, the differences in the environmental impact embedded in different cohorts can be substantial (see supplementary information in Södersten, et al. (2018a)).

1.2 Using supply-use tables for impact analyses

The Leontief calculus entails the inversion of IOTs, and these therefore need to be symmetric. SUTs, however, are rarely symmetric, and the conversion from SUTs to IOTs therefore requires the use of a construct that decides upon the resolution of the IOTs (product-by-product or industry-by-industry) as well as the method used to handle by-products (see Kop Jansen and ten Raa (1990) for the implications of the choice of construct). Rueda-Cantuche (2011) suggests that this issue could be bypassed by performing IO-type calculations using SUTs directly. The idea was formalized and tested in Lenzen and Rueda-Cantuche (2012), where the authors derive an integrated supply-use framework analytically, in which multipliers and Leontief inverses can be reproduced with SUTs that do not need to be transformed into symmetric matrices. They also show that the framework can be used to comply with either the industry technology assumption (ITA) or the commodity technology assumption (CTA), and that the two approaches produce multipliers in both product-by-product and industry-by-industry resolution simultaneously.

The latter feature is used to extend Nakamura and Kondo's waste input output (WIO) framework (Nakamura & Kondo, 2002), which expands Leontief's augmented environmental IO (EIO) model (Leontief, 1970) with respect to waste flows. Both models endogenize environmental externalities by augmenting the IO model with additional product and industry categories corresponding to generation respectively treatment of waste/pollution. Since both the WIO and the EIO models follow IO formalism, both require that the tables be symmetric and thus assume a one-to-one correspondence between the waste/pollution types and the waste/pollution treatment sectors. One of the novelties of the WIO is the introduction of an exogenous waste allocation matrix that allows for different types of wastes to be treated by different treatment sectors. Nevertheless, the conversion to symmetric tables still entails some information loss and leads to certain limitations. For instance, Lenzen and Reynolds (2014) point out that an incineration sector producing heat and electricity as by-products would have to be accounted for using the Stone method (Stone, 1961), i.e. by reporting the by-products as negative entries into those sectors. Therefore, they extend the WIO framework with supply-use formalism and introduce the waste supply-use tables (WSUTs), which allow for keeping product and industry resolution throughout the compilation of multipliers. To test the model, they construct a simple WSUT containing a symmetric intermediate flow matrix as well as SUTs of waste generation and waste treatment. They show mathematically that the resulting WSUT inverses and multipliers are equivalent to the multipliers from the WIO model, and that the same results can be obtained using both approaches, but that the WSUT framework offers more transparency and detail. They conclude by showing that the framework can be generalized by keeping full SUT resolution for the intermediate consumption as well and by extending the waste account so that the model can differentiate between waste generation and recycling.

1.3 The Capital Supply-Use Table (KSUT)

In this paper, we will follow the conceptual idea behind the WSUTs (of keeping supply and use detail in the multipliers), but rather than endogenizing waste flows, we will endogenize capital flows. This will allow us to keep full transparency throughout the process of calculating multipliers, and, as a result, to differentiate between capital goods and current goods when performing impact analyses, thereby addressing an important problem prevalent in previous studies of IO models that endogenize capital. The results will enable a more specific interpretation of results, and ultimately we will be able to resolve our original dilemma of assigning different stressor intensities to goods belonging to different age cohorts.

The paper consists in the following parts. In the methods chapter, we describe the problem with the approaches used in previous empirical applications of capital endogenization, and show that the use of an extended KSUT framework will overcome these problems. We derive new multipliers in which capital goods can be differentiated from current goods, which allows us to assign different emission intensities to the different types of goods. To demonstrate the relevance of our framework, we implement it on a single-region worked example where we show that increasing the emission intensities of capital goods substantially increases the total consumption-based impacts of final consumption.

2 Materials and methods

2.1 Endogenization of capital in input-output tables

Traditional environmentally extended (EE) IOA uses the Leontief inverse

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{1}$$

(where $\mathbf{A}$ is the inter-industry requirement matrix) together with a stressor intensity matrix $\mathbf{s}$ to calculate direct and indirect impacts $\mathbf{\Lambda}$ associated with a certain final demand $\mathbf{y}$ through the well-established formula

$$\mathbf{\Lambda} = \mathbf{sLy} \tag{2}$$

(see Leontief (1986) for an overview of basic IOA). The stressor intensity matrix is sometimes referred to as a matrix of *direct multipliers*, since an element s_j of $\mathbf{s}$ describes the amount of stressor required to produce one unit of output from industry j. The stressor can be anything from production factors (employment, capital, land use, raw material use, etc.) to environmental burdens (emission of pollutants, production of waste, etc.). Elements of $\mathbf{sL}$ are called the *total* multipliers, since they account for both direct and indirect requirements per unit of final demand.

When the flow matrix method is applied, a layer of capital flows is added to the inter-industry matrix, so that the environmental impacts calculated with the new Leontief inverse $\mathbf{L}^{\mathrm{K}}$ account for both the current requirements $\mathbf{A}$ and the capital requirements $\mathbf{K}$, as such:

$$\mathbf{\Lambda}^{\mathrm{K}} = \mathbf{sL}^{\mathrm{K}}\mathbf{y} = \mathbf{s}(\mathbf{I} - (\mathbf{A} + \mathbf{K}))^{-1}\mathbf{y} \tag{3}$$

As explained in the introduction, since both current and capital requirements are embedded in $\mathbf{L}^{\mathrm{K}}$, the framework does not enable differentiation between them when calculating the total multipliers $\mathbf{sL}^{\mathrm{K}}$.

2.2 A new approach to endogenization of capital into SUT form (the KSUT)

We are starting with the regular SUT framework (Eurostat, 2008) illustrated in figure 1, containing the following variables:

- Supply matrix $\mathbf{V}$, the supply of products by industries. Dimension: industry-by-product (*ixp*)
- Use matrix $\mathbf{U}$, the intermediate current production structure. Dimension: product-by-industry (*pxi*)
- Final demand (FD) vector $\mathbf{y}$ (in product resolution)
- Value added (VA) row vector $\mathbf{w}$ (in industry resolution)
- Vectors of industry respectively product outputs $\mathbf{g}$ and $\mathbf{q}$ (and their respective transpose $\mathbf{g}'$ and $\mathbf{q}'$)

In this representation, $\mathbf{y}$ can be broken down into several subcomponents such as GFCF ($\mathbf{y}_{\mathrm{C}}$), FD of households and government expenditures. Likewise, $\mathbf{w}$ includes several distinct elements such as the CFC ($\mathbf{w}_{\mathrm{C}}$), compensation of employees, taxes and subsidies on production, etc.

The schematic representation on the left-hand side of figure 1a can be transcribed into an equation system that includes the production and industry balances of an economy:

$$\begin{bmatrix} \mathbf{0} & \mathbf{V} \\ \mathbf{U} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{e}_{\mathrm{i}} \\ \mathbf{e}_{\mathrm{p}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{y} \end{bmatrix} = \begin{bmatrix} \mathbf{g} \\ \mathbf{q} \end{bmatrix} \tag{4}$$

where $\mathbf{e}_{\mathrm{i}}$ and $\mathbf{e}_{\mathrm{p}}$ are summation vectors of appropriate lengths, in industry respectively product classification. As shown by Lenzen and Rueda-Cantuche (2012), this can be transformed into

$$\begin{bmatrix} \mathbf{g} \\ \mathbf{q} \end{bmatrix} = \left\{ \mathbf{I} - \begin{bmatrix} \mathbf{0} & \mathbf{D} \\ \mathbf{B} & \mathbf{0} \end{bmatrix} \right\}^{-1} \begin{bmatrix} \mathbf{0} \\ \mathbf{y} \end{bmatrix} \tag{5}$$

where $\mathbf{D} = \mathbf{V}\hat{\mathbf{q}}^{-1}$ and $\mathbf{B} = \mathbf{U}\hat{\mathbf{g}}^{-1}$ are the (*ixp*) market share and (*pxi*) use coefficient matrices, respectively.

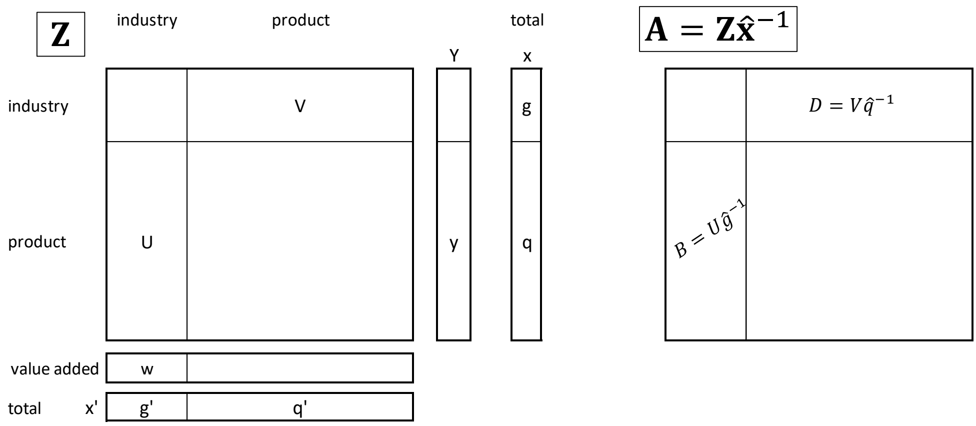

Figure 1: The SUT framework

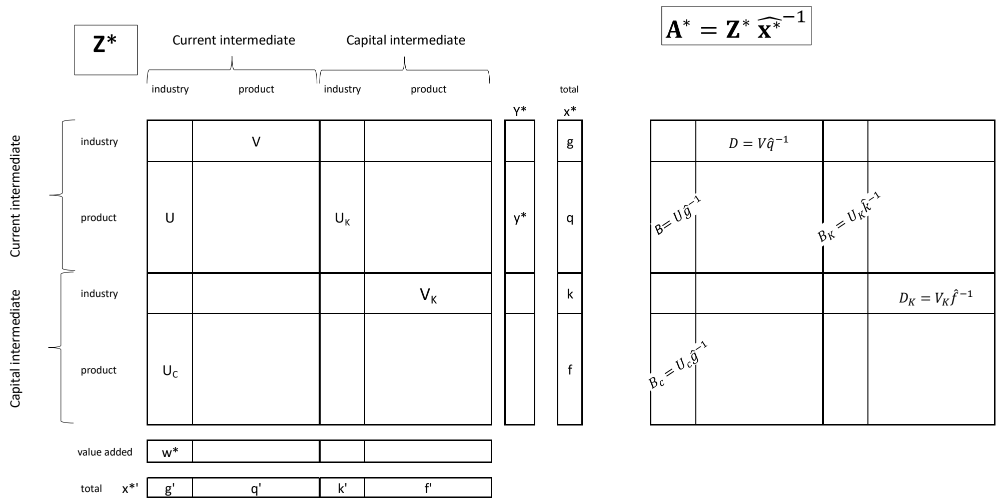

Figure 2: The KSUT framework

The conceptual idea behind the KSUT is to endogenize the capital transactions into the intermediate SUTs whilst keeping them distinct from the current transactions. Figure 2 illustrates how this is done. The GFCF is extracted from the FD and distributed across industries to form an *investment use matrix* $\mathbf{U}_\mathrm{K}$, which describes how newly invested capital is distributed across purchasing industries. This leads to a new FD vector $\mathbf{y}^* = \mathbf{y} - \mathbf{y}_\mathrm{C}$ (with $\mathbf{U}_\mathrm{K}\mathbf{e}_\mathrm{i} = \mathbf{y}_\mathrm{C}$) that contains the FD less the GFCF. Likewise, a row vector of capital consumption by industries is transferred from the value added and distributed across products to form a *stock use matrix* $\mathbf{U}_\mathrm{C}$ that describes the use of existing capital by current industries. Hence, the new row vector of value added $\mathbf{w}^*$ contains the original value added minus $\mathbf{U}_\mathrm{C}$. If we define $\mathbf{u}_\mathrm{c}$ as the row sum of $\mathbf{U}_\mathrm{C}$, that is

$$\mathbf{u}_\mathrm{c} \coloneqq \mathbf{e}'_\mathrm{p}\mathbf{U}_\mathrm{C}, \tag{6}$$

$\mathbf{w}^*$ can be written

$$\mathbf{w}^* = \mathbf{w} - \mathbf{u}_\mathrm{c}. \tag{7}$$

To satisfy the product and industry balances of the new KSUT, a matrix $\mathbf{V}_\mathrm{K}$ is added, describing the *supply of capital by capital industries*, and constructed so that its row sum $\mathbf{f}'$ equals the column sum $\mathbf{f}$ of $\mathbf{U}_\mathrm{C}$, and its column sum $\mathbf{k}$ equals the row sum $\mathbf{k}'$ of $\mathbf{U}_\mathrm{K}$. That is, $\mathbf{V}_\mathrm{K}\mathbf{e}_\mathrm{i} = \mathbf{k} = (\mathbf{e}_\mathrm{i}\mathbf{U}_\mathrm{K})^\mathrm{T}$ and $\mathbf{U}_\mathrm{C}\mathbf{e}_\mathrm{p} = \mathbf{f} = \left(\mathbf{e}_\mathrm{p}\mathbf{V}_\mathrm{K}\right)^\mathrm{T}$, where superscript T symbolizes matrix transpose.

Using the same formalism as for the SUTs, we get a new equation system for the production balance:

$$\begin{bmatrix} \mathbf{0} & \mathbf{V} & \mathbf{0} & \mathbf{0} \\ \mathbf{U} & \mathbf{0} & \mathbf{U}_\mathrm{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{V}_\mathrm{K} \\ \mathbf{U}_\mathrm{C} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{e}_\mathrm{i} \\ \mathbf{e}_\mathrm{p} \\ \mathbf{e}_\mathrm{i} \\ \mathbf{e}_\mathrm{p} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{y}^* \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{g} \\ \mathbf{q} \\ \mathbf{k} \\ \mathbf{f} \end{bmatrix} \tag{8}$$

which can be transformed into

$$\begin{bmatrix}\mathbf{g}\\\mathbf{q}\\\mathbf{k}\\\mathbf{f}\end{bmatrix}=\left\{\mathbf{I}-\begin{bmatrix}\mathbf{0}&\mathbf{D}&\mathbf{0}&\mathbf{0}\\\mathbf{B}&\mathbf{0}&\mathbf{B}_{\mathrm{K}}&\mathbf{0}\\\mathbf{0}&\mathbf{0}&\mathbf{0}&\mathbf{D}_{\mathrm{K}}\\\mathbf{B}_{\mathrm{C}}&\mathbf{0}&\mathbf{0}&\mathbf{0}\end{bmatrix}\right\}^{-1}\begin{bmatrix}\mathbf{0}\\\mathbf{y}^*\\\mathbf{0}\\\mathbf{0}\end{bmatrix}\Leftrightarrow\mathbf{x}^*=(\mathbf{I}-\mathbf{A}^*)^{-1}\mathbf{Y}^*=\mathbf{L}^*\mathbf{Y}^* \tag{9}$$

where

$$\mathbf{L}^*\coloneqq\left\{\mathbf{I}-\begin{bmatrix}\mathbf{0}&\mathbf{D}&\mathbf{0}&\mathbf{0}\\\mathbf{B}&\mathbf{0}&\mathbf{B}_{\mathrm{K}}&\mathbf{0}\\\mathbf{0}&\mathbf{0}&\mathbf{0}&\mathbf{D}_{\mathrm{K}}\\\mathbf{B}_{\mathrm{C}}&\mathbf{0}&\mathbf{0}&\mathbf{0}\end{bmatrix}\right\}^{-1} \tag{10}$$

is our KSUT inverse, and where the $\mathbf{D}$ and $\mathbf{B}$ matrices are the market share and use coefficient matrices, respectively. In addition, we introduce the investment use coefficient matrix $\mathbf{B}_{\mathrm{K}}=\mathbf{U}_{\mathrm{K}}\hat{\mathbf{k}}^{-1}$, the stock use coefficient matrix $\mathbf{B}_{\mathrm{C}}=\mathbf{U}_{\mathrm{C}}\hat{\mathbf{g}}^{-1}$, and the capital market share matrix $\mathbf{D}_{\mathrm{K}}=\mathbf{V}_{\mathrm{K}}\hat{\mathbf{f}}^{-1}$.

2.3 Construction of capital flow matrices

Since $\mathbf{U_C}$ is a measure of how much of the existing capital is being used by industries, it would be sensible to construct it by disaggregating the CFC, which is explicitly available (in nominal value) in many national statistics, over consuming industries. The CFC is the expected decline in the current value of the stock of fixed assets during the accounting period as a result of physical deterioration, normal obsolescence and normal accidental damage (OECD and UN, 2009). It is a measure of economic depreciation of existing capital stock due to the usage of it (Schreyer, 2009), and it can therefore be regarded as the use of capital by current industries, as it is done in other recent studies of capital endogenization such as (Z.-M. Chen, et al., 2018) and (Södersten, et al., 2018a). For a lengthier discourse about different measures of capital and capital use, see Ahmad (2004); Diewert (2005); Södersten, et al. (2018a); for more details about the measurement of capital, the reader is referred to the OECD capital measuring guide (Schreyer, 2009).

In order to obtain a balanced system, the total sums of $\mathbf{U}_{\mathrm{C}}$ and $\mathbf{U}_{\mathrm{K}}$ must be equal, i.e.

$$\sum_i\sum_j U_{C\,i,j}=\sum_i\sum_j U_{K\,i,j} \tag{11}$$

Or, in matrix notation,

$$\mathbf{e}_{\mathrm{p}}'\mathbf{U}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}=\mathbf{e}_{\mathrm{p}}'\mathbf{U}_{\mathrm{K}}\mathbf{e}_{\mathrm{i}} \tag{12}$$

While the CFC relates to the existing capital stock, the GFCF describes the new additions to the stock, comprising both capital required to maintain and upgrade the existing stock (the replacement investment), as well as the installment of new capital (the net capital formation). The GFCF and CFC are therefore different measures of capital, and their sums are not equal. To achieve equality and thereby a balanced system, we endogenize additional monetary flows from the GOS so that equation 11 is fulfilled. This is justified, as the GOS is the excess of gross output after the intermediate consumption, compensation of employees and taxes less subsidies have been deduced (ABS, 2016), containing dividends, interests and royalties, which are often reinvested into new capital[1].

To ensure that the sum of $\mathbf{U}_{\mathrm{K}}$ and $\mathbf{U}_{\mathrm{K}}$ are equal, the additional vector of flows $\mathbf{w}_{\mathrm{G}}$ that we extract from the GOS to construct $\mathbf{U}_{\mathrm{C}}$ must satisfy:

$$\mathbf{w}_{\mathrm{G}}\mathbf{e}_{\mathrm{i}} = \mathbf{e}_{\mathrm{p}}'\mathbf{U}_{\mathrm{K}}\mathbf{e}_{\mathrm{i}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}} = \mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}, \tag{13}$$

where $\mathbf{w}_{\mathrm{C}}$ is the row vector of CFC. Furthermore, to preserve the patterns of capital consumption by industries contained in the CFC, we add another constraint to ensure that $\mathbf{w}_{\mathrm{G}}$ is proportional to $\mathbf{w}_{\mathrm{C}}$:

$$\mathbf{w}_{\mathrm{G}} = \beta\mathbf{w}_{\mathrm{C}}. \tag{14}$$

Inserting equation 14 into equation 13 yields

$$\beta\mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}} = \mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}} \tag{15}$$

which leads to

$$\beta = \frac{\mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}{\mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}} \tag{16}$$

Hence $\mathbf{w}_{\mathrm{G}}$ is deduced as such:

$$\mathbf{w}_{\mathrm{G}} = \frac{\mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}{\mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}\mathbf{w}_{\mathrm{C}} \tag{17}$$

And $\mathbf{u}_{\mathrm{c}}$ will therefore satisfy

$$\mathbf{u}_{\mathrm{c}} = \mathbf{w}_{\mathrm{G}} + \mathbf{w}_{\mathrm{C}} = \frac{\mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}} - \mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}{\mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}\mathbf{w}_{\mathrm{C}} + \mathbf{w}_{\mathrm{C}} = \left(\mathbf{1} + \frac{\mathbf{e}_{\mathrm{p}}'\mathbf{y}_{\mathrm{C}}}{\mathbf{w}_{\mathrm{C}}\mathbf{e}_{\mathrm{i}}}\right)\mathbf{w}_{\mathrm{C}} \tag{18}$$

with $\mathbf{u}_{\mathrm{c}}$ as defined in equation 6. To populate $\mathbf{U}_{\mathrm{C}}$, the flows in $\mathbf{u}_{\mathrm{c}}$ need to be distributed across asset types. Likewise, to obtain a capital use matrix $\mathbf{U}_{\mathrm{K}}$, the GFCF $\mathbf{y}_{\mathrm{C}}$ needs to be distributed across purchasing industries. To do this, we adopt the approach of Södersten, Wood, and Hertwich (2018b), which uses the detailed matrices of capital use and capital formation published by the EUKLEMS database (O'Mahony & Timmer, 2009) as capital distribution proxies for both $\mathbf{U}_{\mathrm{C}}$ and $\mathbf{U}_{\mathrm{K}}$, which we disaggregate into the same classification as the supply and use tables $\mathbf{U}$ and $\mathbf{V}$ using CFC and GFCF data as weights (the procedure is explained in detail in Södersten, et al. (2018b)).

The capital supply matrix $\mathbf{V}_{\mathrm{K}}$ is a matrix of supply of capital goods by capital industries, created in order to balance the tables. Since all goods (including capital goods) are in fact produced by current industries, $\mathbf{V}_{\mathrm{K}}$ is a hypothetical matrix, and we construct it using a qualitative prior approach similar to Lenzen and Lundie (2012). The qualitative prior used in their study is a binary allocation matrix of zeros and ones that define whether an input may (one) or may not

[1] An alternative approach would be to keep the net capital formation (the residual capital) as a final demand component as is done in Södersten, et al. (2018a)

(zero) be required to produce an output. We use the supply matrix $\mathbf{V}$ as qualitative prior, with the matrix entries determining if and by what amount a capital good is produced by a capital industry. That is, zeros indicate that no production occurs, and non-zero values indicate that a capital good is supplied by an industry, with the values serving as production weights so that the production structure of the capital supply matrix is similar to that of the supply matrix. This weighted qualitative prior matrix is then balanced so that its row sum equals $\mathbf{f}'$ and column sum equals $\mathbf{k}$, using a RAS algorithm (Bachem & Korte, 1979), and the resulting balanced matrix constitutes our capital supply matrix $\mathbf{V}_{\mathrm{K}}$.

2.4 Derivation of KSUT multipliers

The objective of our research is to be able to discern between current intermediate goods and capital intermediate goods when performing footprint-type calculations, on the rationale that the technologies used to produce them were different. Therefore, we need to derive impact multipliers from the KSUT matrix so that we can assign different stressors to production inputs. Lenzen and Rueda-Cantuche (2012) used Miyazawa's partitioned-inverse method (Miyazawa, 1966, 1968) to show that Leontief's demand-pull calculus can be formalized on the basis of SUTs, enabling the derivation of impact multipliers for both products and industries. Their conceptual framework was applied to derive detailed multipliers for Lenzen and Reynold's WSUT framework (Lenzen & Reynolds, 2014), and we will use a similar approach to derive product and industry multipliers for both current and capital sectors of our KSUT.

2.4.1 Miyazawa's partitioned inverse

The Leontief inverse used in IOA describes a feedback that is trivial to interpret: an element $\mathbf{L}_{i,j}$ of the matrix represents the total direct and indirect amount of i required to produce one unit of final demand j. This is inherent to IOA, as the Leontief inverse can be expressed as an infinite sum of production tiers that describe the full supply chain of production (Leontief, 1986). The multipliers $\mathbf{m}$ are then calculated by pre-multiplying $\mathbf{L}$ with a stressor matrix $\mathbf{s}$ containing emission intensities for a chosen impact indicator. For instance, if $\mathbf{s}_i$ is the amount of impact emitted per unit output of sector i, an element $\mathbf{m}_j$ of $\mathbf{m} = \mathbf{sL}$ describes the total amount of impact emitted by *all* industries as a result of delivering one unit of j to final consumption.

The formulation of the KSUT inverse $\mathbf{L}^*$ in equation 10 lacks such trivial interpretation. Without explicit multipliers, we cannot perform the demand-pull calculus that is needed to answer our research questions. We will therefore adopt an approach similar to Lenzen and Rueda-Cantuche (2012) to derive our KSUT multipliers analytically. The results will enable us to distinguish between "current multipliers" (describing the impacts per unit output that occur as a result of the production of current goods) and "capital multipliers" (describing the impacts associated with the production of capital goods), and we will then be able to assign different stressor intensities to both categories of intermediate goods.

Lenzen and Rueda-Cantuche (2012) used Miyazawa's formula directly on a 2x2 partition matrix. Starting with a matrix $\left(\mathbf{I}-\begin{bmatrix}\mathbf{A} & \mathbf{C}\\ \mathbf{V} & \mathbf{E}\end{bmatrix}\right)$, the original formulation for the compound Leontief inverse is as such:

$$\begin{bmatrix}\mathbf{I}-\mathbf{A} & -\mathbf{C}\\ -\mathbf{V} & \mathbf{I}-\mathbf{E}\end{bmatrix}^{-1}=\begin{bmatrix}\mathbf{B}_1(\mathbf{I}+\mathbf{C}\mathbf{K}_1\mathbf{V}\mathbf{B}_1) & \mathbf{B}_1\mathbf{C}\mathbf{K}_1\\ \mathbf{K}_1\mathbf{V}\mathbf{B}_1 & \mathbf{K}_1\end{bmatrix}, \tag{19}$$

where $\mathbf{B}_1=(\mathbf{I}-\mathbf{A})^{-1}$, $\mathbf{K}_1=(\mathbf{I}-\mathbf{E}-\mathbf{V}\mathbf{B}_1\mathbf{C})^{-1}$ and $\mathbf{I}$ is an identity matrix of appropriate size. Miyazawa's formula hence transforms a compound multiple-partition inverse into several components containing only single-partition inverses, making them easier to interpret. Our KSUT inverse consists of a 4x4 partition matrix, and we will apply Miyazawa's formula iteratively by sub-grouping our partitions into intermediate blocks.

2.4.2 The KSUT partitioned inverse

Using multiple iterations of Miyazawa's formula, we find that

$$\mathbf{L}^{*}=\left\{\mathbf{I}-\begin{bmatrix}\mathbf{0} & \mathbf{D} & \mathbf{0} & \mathbf{0}\\ \mathbf{B} & \mathbf{0} & \mathbf{B}_{\mathrm{K}} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{D}_{\mathrm{K}}\\ \mathbf{B}_{\mathrm{C}} & \mathbf{0} & \mathbf{0} & \mathbf{0}\end{bmatrix}\right\}^{-1}$$

$$=\begin{bmatrix}\boldsymbol{\mathcal{L}}^{\mathrm{i}}+\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I}+\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I}+\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\\ \boldsymbol{\mathcal{L}}\left(\mathbf{B}+\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}}\right) & \boldsymbol{\mathcal{L}}(\mathbf{I}+\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I}+\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I}+\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\end{bmatrix} \tag{20}$$

Where

$$\boldsymbol{\mathcal{L}}=(\mathbf{I}-\mathbf{B}\mathbf{D})^{-1} \tag{21}$$

and

$$\boldsymbol{\mathcal{L}}^{\mathrm{i}}=(\mathbf{I}-\mathbf{D}\mathbf{B})^{-1} \tag{22}$$

are the *pxp* respectively *ixi* Leontief inverses, and where

$$\boldsymbol{\mathcal{L}}_{\mathrm{K}}=(\mathbf{I}-\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}})^{-1} \tag{23}$$

is a *pxp* feedback matrix that describes total direct and indirect capital requirements of the capital sector, which we call the Leontief capital matrix. The full derivation can be found in the appendix. Our Leontief matrices are here constructed using the industry technology assumption (Kop Jansen & ten Raa, 1990), but can also be constructed using the commodity technology assumption (as shown by Lenzen and Rueda-Cantuche (2012)).

2.4.3 Interpretation of the KSUT partitioned-inverse components

Each partition of the $\mathbf{L}^*$ matrix describes feedback loops that have physical interpretations. However, in our KSUT production function $\mathbf{x}^* = \mathbf{L}^*\mathbf{Y}^*$, the total final demand vector $\mathbf{Y}^*$ has non-zero entries only in the second block (see equation 9). This is an inherent feature of the way the economy is described in the model. Firstly, all goods and services are assumed to be produced by the current sectors (i.e. we do not differentiate between industries producing capital goods and industries producing non-capital goods), which explains why the third and fourth blocks are null. Secondly, final consumers are assumed to purchase outputs of products and not industries (fortunately – imagine the constant gamble it would be to fuel a car if the output of the pump would be a random product from the refinery sector), which explains why the first block is null. Hence, only the second column of the $\mathbf{L}^*$ matrix needs to be interpreted for our current research purposes.

The two upper partitions of the second column differ slightly but describe the same feedback loop, $\boldsymbol{\mathcal{L}} + \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}$. The first term is the well-known Leontief matrix that describes the direct and indirect current requirements per unit (product) final demand. The second term describes the direct and indirect current products required ($\boldsymbol{\mathcal{L}}$) to produce the capital inputs of the capital sector ($\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}$) needed to produce the total direct and indirect ($\boldsymbol{\mathcal{L}}_{\mathrm{K}}$) capital products ($\mathbf{B}_{\mathbf{C}}$) needed by the current industries ($\mathbf{D}$) to produce direct and indirect products ($\boldsymbol{\mathcal{L}}$) for (product) final demand. Pre-multiplying the expression with $\mathbf{D}$ as is done in the first row of the second column implies the same feedback loop but in terms of industry requirements rather than product requirements.

The two lower partitions also describe interpretable and similar feedback loops. $\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}$ describes the direct and indirect product requirements from the capital sectors ($\boldsymbol{\mathcal{L}}_{\mathrm{K}}$) to produce the capital goods used by the current industries ($\mathbf{B}_{\mathrm{C}}\mathbf{D}$) to produce the direct and indirect products needed ($\boldsymbol{\mathcal{L}}$) to produce goods for final demand. Pre-multiplying the expression with $\mathbf{D}_{\mathrm{K}}$ as is done in the third row of the second column to obtain $\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}$ implies the same feedback loop but in terms of industry requirements rather than product requirements.

Dimension tests can be performed to ensure that the multiplications are feasible. For instance, for the first partition of the second column:

$$\mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) = \mathbf{D}\boldsymbol{\mathcal{L}} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\,(\mathbf{I} - \mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}})^{-1}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \tag{24}$$

With all $\mathbf{D}_*$ matrices sized *ixp*, $\mathbf{B}_*$ matrices sized *pxi* and $\boldsymbol{\mathcal{L}}$ sized *pxp*, we can easily deduce that the dimension of the above formulation is sized *ixp* (where the * subscript symbolizes a wildcard). Similar tests can be done for all partitions of $\mathbf{L}^*$ as well as for the matrix as a whole.

The physical interpretations become somewhat cumbersome to describe with words, but the partitioned inverse now effectively distinguishes between current inputs and capital inputs (both in product and industry classification), and the framework can be extended with environmental stressors that account for the differences between them. To facilitate the assignment of different stressor intensities to the two types of goods, we split the KSUT inverse so that the different requirements are formulated explicitly, as such:

$$\mathbf{L}^{*} =$$
$$= \begin{bmatrix} \boldsymbol{\mathcal{L}}^{\mathrm{i}} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\left(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}}\right) & \boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix}$$
$$= \begin{bmatrix} \boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$
$$+ \begin{bmatrix} \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix} \quad (25)$$

The first part of the split KSUT,

$$\mathbf{L}^{*}_{cur} := \begin{bmatrix} \boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}, \quad (26)$$

describes the direct and indirect current requirements of production (i.e. the inter-industry requirements as calculated using traditional IOA according to equation (1)). Since all current requirements are thereby accounted for, we can deduce that the second part of the split KSUT,

$$\mathbf{L}^{*}_{cap}$$
$$:= \begin{bmatrix} \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix}, \quad (27)$$

describes the requirements related to capital.

2.4.4 Adjusting environmental stressors for different types of good

Let $\mathbf{s}^{i}_{cur}$ and $\mathbf{s}^{p}_{cur}$ be *1xi* respectively *1xp* stressor matrices describing impacts per unit of industry respectively product *current* output for one selected indicator, and $\mathbf{s}^{i}_{cap}$ and $\mathbf{s}^{p}_{cap}$ be stressor matrices describing impacts per unit of industry and product *capital* output for the same indicator. Then, with

$$\mathbf{s}_{cur} \coloneqq [\mathbf{s}_{cur}^{i} \quad \mathbf{s}_{cur}^{p} \quad \mathbf{0} \quad \mathbf{0}] \tag{28}$$

and

$$\mathbf{s}_{cap} \coloneqq [\mathbf{0} \quad \mathbf{0} \quad \mathbf{s}_{cap}^{i} \quad \mathbf{s}_{cap}^{p}], \tag{29}$$

the total impacts associated with the production of current goods required to produce a final demand $\mathbf{Y}^{*}$ are given by

$$\mathbf{\Lambda}_{cur}^{*} = \check{\mathbf{s}_{cur}} \mathbf{L}_{cur}^{*} \mathbf{Y}^{*}, \tag{30}$$

while the total impacts associated with the production of the capital goods required to produce a final demand $\mathbf{Y}^{*}$ are given by

$$\mathbf{\Lambda}_{cap}^{*} = \check{\mathbf{s}_{cap}} \mathbf{L}_{cap}^{*} \mathbf{Y}^{*}. \tag{31}$$

The upside-down hat on the stressor matrices symbolizes a block-diagonalization of the matrices as such:

$$\check{\mathbf{s}_{cur}} = \begin{bmatrix} \mathbf{s}_{cur}^{i} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{s}_{cur}^{p} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}. \tag{32}$$

The resulting matrices are constituted of block matrices containing impacts in both industry and product resolution, and the total impacts are obtained by summing either of them. For instance, for

$$\mathbf{\Lambda}_{cur}^{*} \coloneqq \begin{bmatrix} \boldsymbol{\lambda}_{cur}^{i} \\ \boldsymbol{\lambda}_{cur}^{p} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \tag{33}$$

and

$$\mathbf{\Lambda}_{cap}^{*} \coloneqq \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{\lambda}_{cap}^{i} \\ \boldsymbol{\lambda}_{cap}^{p} \end{bmatrix}, \tag{34}$$

the total impacts associated with the final demand $\mathbf{Y}^{*}$ are given by

$$\mathbf{\Lambda}_{tot}^{*i} = \boldsymbol{\lambda}_{cur}^{i} + \boldsymbol{\lambda}_{cap}^{i}, \tag{35}$$

alternatively by

$$\mathbf{\Lambda}_{tot}^{*p} = \boldsymbol{\lambda}_{cur}^{p} + \boldsymbol{\lambda}_{cap}^{p}. \tag{36}$$

Since both $\mathbf{\Lambda}_{tot}^{*i}$ and $\mathbf{\Lambda}_{tot}^{*p}$ account for all impacts, we have that

$$\sum \mathbf{\Lambda}_{tot}^{*i} = \sum \mathbf{\Lambda}_{tot}^{*p}. \tag{37}$$

2.4.5 Estimation of capital stressor intensities

The KSUT framework allows us to differentiate between the requirements of capital goods and current goods in the production of goods and services for final consumption, which in turn enables the assignment of the different stressor intensities $\mathbf{s}_{cur}^{p}$ and $\mathbf{s}_{cur}^{i}$, respectively $\mathbf{s}_{cap}^{p}$ and $\mathbf{s}_{cap}^{i}$, to the two types of goods. While the stressor intensities of current goods are available in EXIOBASE, estimating the stressor intensities $\mathbf{s}_{cap}^{p}$ and $\mathbf{s}_{cap}^{i}$ entails multiple challenges, as they should reflect the technology used at the time the goods were produced. However, the stock of capital currently used by industries is composed of goods originating from different age cohorts. While estimates on the size of the current capital stock are available in some national accounts, the age cohort composition is not. Knowledge about this composition is a prerequisite for constructing the capital stressor matrices, but determining the average age of the capital stock is a laborious and complex enterprise that requires the application of advanced dynamic stock models. The interested reader is referred to the one described by Pauliuk, et al. (2014), in which the authors create a theoretical dynamic IO model with age cohorts of assets that estimates the asset and age cohort composition of the current capital stock using lifetime and probability distribution functions of assets, utilization rates, age-efficiency factors, etc. This, however, is not the topic of this paper, and we have therefore resorted to creating stressor matrices that correspond to hypothetical scenarios regarding the age cohorts of capital goods rather than attempting to estimate them based on scarce and uncertain data.

3 Worked example

To illustrate the importance of our model, we present the results of a worked example in which we have applied the KSUT on a national level, using the domestic technology assumption to treat imports (i.e. assuming that they are produced using the same technology as the goods produced domestically).

Figure 3 shows the domestic direct and indirect impacts of Australian final demand, calculated following equation 36. Three indicators are shown: the GHG emissions (in kg CO_2 equivalent), aggregated according to the 100-year global warming potential as defined by the IPCC (Pachauri & Reisinger, 2007), the domestic extraction (in Mt), containing the sum of all raw materials extracted from the natural environment (Eurostat, 2018), and the land use change (LUC), expressed in km^2. The three curves that are plotted in each graph illustrate different scenarios regarding the emission intensities of capital goods, which in turn correspond to different scenarios of age cohort composition of the capital goods used in production processes. As explained in the methods chapter, we have not attempted to estimate the average age of the current stock of capital in this paper. Instead, we have created two hypothetical capital stressor matrices $\mathbf{s}_{cap}$ that correspond to an increase in the current stressor matrices $\mathbf{s}_{cur}$ by 50% (red curves) respectively 100% (green curves). The baseline scenario (blue curves) implies no change in emission intensities over time ($\mathbf{s}_{cap} = \mathbf{s}_{cur}$).

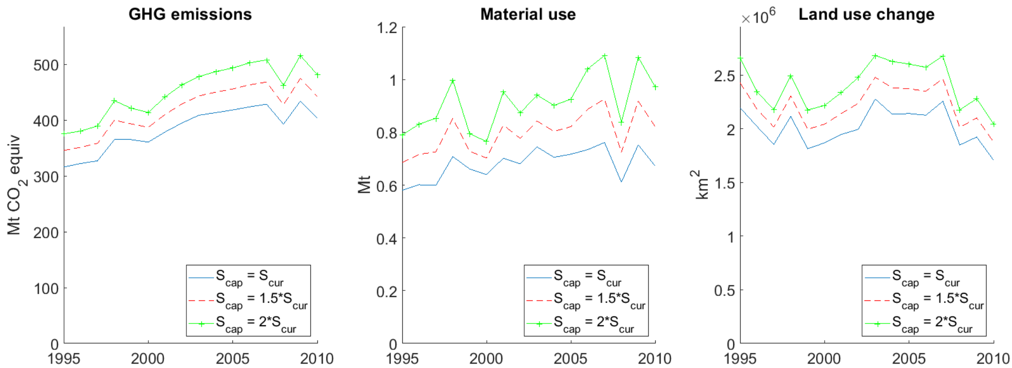

Figure 3: GHG emissions (Mt CO_2eq), material use (in Mt of domestic extraction) and land use change (in km^2) for Australia, with three scenarios of stressor intensities of capital ($\mathbf{s}_{cap} = \mathbf{s}_{cur}$; $\mathbf{s}_{cap} = 1.5\mathbf{s}_{cur}$; $\mathbf{s}_{cap} = 2\mathbf{s}_{cur}$).

Figure 3 shows that changing the stressor intensities of capital goods leads to substantial increases in the impacts associated with Australian final demand for all indicators. The change in material use is relatively larger than the change in GHG emissions and land use change, which indicates that the capital goods are responsible for a larger share of the total domestic extraction than of the other two indicators shown.

Since all products destined to final consumption have different production structures, the capital carbon, material and land intensity of goods and services varies. Hence, changes in stressor intensities of capital goods will affect individual product footprints differently. In Tables 1-3, we display the changes in product footprints between the baseline scenario and the scenario where we assume a 100% increase in emission intensity for capital goods for the same three indicators. Such an increase in stressor intensities may seem unrealistic, but it makes the interpretation of results easier: because the tables show the *difference* in individual product footprints between the two scenarios $\mathbf{s}_{cap} = \mathbf{s}_{cur}$ and $\mathbf{s}_{cap} = 2\mathbf{s}_{cur}$, a 100% change implies that the production processes use exclusively capital goods (or that only the capital goods utilized have an impact). Conversely, a 0% change implies that no capital goods are required (or that the capital goods utilized have no impacts). Only the ten largest (in terms of total impact) product categories are displayed for each indicator.

Table 1: Change in GHG emissions for the ten largest product groups (in terms of total GHG emissions) between the baseline scenario and the scenario with a 100% increase in $\mathbf{s}_{cap}$.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Electricity by coal	0,02	0,02	0,02	0,02	0,02	0,03	0,03	0,02	0,02	0,03	0,03	0,02	0,02	0,02	0,02	0,02
Public administration and defence services	0,32	0,32	0,34	0,34	0,28	0,24	0,25	0,26	0,26	0,27	0,26	0,27	0,31	0,28	0,35	0,36
Products of meat cattle	0,02	0,01	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,02	0,02
Real estate services	0,70	0,70	0,65	0,71	0,67	0,59	0,62	0,62	0,63	0,61	0,62	0,64	0,57	0,61	0,55	0,52
Health and social work services	0,29	0,28	0,30	0,30	0,27	0,24	0,25	0,25	0,26	0,27	0,27	0,31	0,29	0,24	0,26	0,28
Education services	0,25	0,20	0,21	0,19	0,16	0,17	0,18	0,18	0,18	0,19	0,20	0,21	0,20	0,19	0,39	0,27
Motor Gasoline	0,04	0,04	0,04	0,04	0,02	0,02	0,04	0,05	0,03	0,04	0,04	0,07	0,07	0,07	0,07	0,06
Hotel and restaurant services	0,18	0,17	0,19	0,19	0,14	0,12	0,13	0,14	0,13	0,15	0,14	0,16	0,16	0,13	0,14	0,14
Air transport services	0,08	0,11	0,09	0,09	0,10	0,08	0,08	0,09	0,09	0,11	0,10	0,09	0,11	0,08	0,09	0,09
Other waste for treatment: waste water treatment	0,29	0,27	0,24	0,29	0,20	0,16	0,18	0,18	0,15	0,14	0,11	0,12	0,07	0,06	0,07	0,07

Table 2: Change in material use for the ten largest product groups (in terms of total GHG emissions) between the baseline scenario and the scenario with a 100% increase in $\mathbf{s}_{cap}$.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Products of meat cattle	0,02	0,02	0,02	0,02	0,01	0,01	0,03	0,02	0,02	0,02	0,02	0,03	0,03	0,02	0,03	0,03
Public administration and defence services	0,60	0,61	0,64	0,59	0,37	0,31	0,45	0,36	0,35	0,36	0,37	0,49	0,58	0,53	0,59	0,63
Real estate services	0,95	0,93	0,92	0,94	0,88	0,72	0,81	0,75	0,77	0,77	0,77	0,84	0,84	0,83	0,81	0,81
Health and social work services	0,59	0,59	0,65	0,61	0,42	0,35	0,52	0,43	0,39	0,40	0,43	0,61	0,62	0,52	0,53	0,56
Motor Gasoline	0,06	0,07	0,07	0,06	0,02	0,02	0,07	0,05	0,04	0,05	0,07	0,14	0,13	0,14	0,16	0,12
Hotel and restaurant services	0,39	0,38	0,50	0,42	0,20	0,16	0,29	0,23	0,20	0,24	0,23	0,39	0,39	0,29	0,39	0,42
Education services	0,74	0,74	0,79	0,69	0,46	0,43	0,58	0,46	0,44	0,47	0,51	0,65	0,65	0,54	0,72	0,73
Food products nec	0,15	0,16	0,18	0,18	0,08	0,09	0,19	0,14	0,12	0,12	0,12	0,20	0,18	0,14	0,19	0,17
Natural gas and services related to natural gas extraction	0,01	0,02	0,02	0,02	0,01	0,01	0,02	0,01	0,01	0,02	0,02	0,03	0,04	0,02	0,03	0,02
Electricity by coal	0,80	0,82	0,90	0,48	0,34	0,63	0,79	0,70	0,50	0,72	0,78	0,46	0,36	0,21	0,30	0,62

Table 3: Change in LUC (land use change) for the ten largest product groups (in terms of total GHG emissions) between the baseline scenario and the scenario with a 100% increase in $\mathbf{s}_{cap}$.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Products of meat cattle	0,01	0,00	0,00	0,00	0,00	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,00	0,00	0,00	0,00
Hotel and restaurant services	0,17	0,12	0,19	0,13	0,12	0,10	0,09	0,13	0,09	0,13	0,12	0,14	0,10	0,08	0,10	0,12
Public administration and defence services	0,44	0,41	0,45	0,42	0,47	0,35	0,37	0,44	0,34	0,43	0,41	0,41	0,44	0,41	0,42	0,55
Dairy products	0,02	0,02	0,02	0,02	0,02	0,02	0,03	0,03	0,02	0,04	0,03	0,03	0,02	0,02	0,02	0,02
Food products nec	0,06	0,05	0,06	0,06	0,06	0,07	0,07	0,11	0,06	0,09	0,08	0,08	0,04	0,04	0,05	0,04
Health and social work services	0,42	0,33	0,38	0,42	0,47	0,41	0,40	0,52	0,40	0,48	0,47	0,48	0,39	0,32	0,23	0,30
Real estate services	0,91	0,85	0,87	0,89	0,91	0,80	0,80	0,85	0,79	0,84	0,81	0,82	0,75	0,77	0,69	0,73
Beverages	0,09	0,07	0,08	0,07	0,07	0,06	0,07	0,10	0,07	0,08	0,08	0,10	0,08	0,06	0,09	0,09
Products of forestry, logging and related services	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Vegetables, fruit, nuts	0,07	0,06	0,07	0,07	0,08	0,05	0,08	0,10	0,09	0,11	0,09	0,08	0,09	0,06	0,08	0,07

We note that the effects of changing the stressor intensities on different products are vastly different. Real estate services stand out as being affected the most by the change in capital emission intensities, averaging a 60% increase in GHG emissions and over 80% increase for domestic extraction and LUC. For GHG emissions and LUC, the change seen for real estate services is considerably larger than for all other product categories. For the indicators and product categories shown, service sectors are more affected by the change in stressors than non-service sectors. A noteworthy exception concerns the production of electricity by coal: because of the carbon intensity of coal combustion, the change in GHG emissions between the two scenarios remains insignificant, while the effects on material use are substantial.

4 Discussion, conclusions and outlook

In this paper, we introduced the KSUT framework, a new way to endogenize capital in IO models. Rather than using IOTs and conventional Leontief calculus to obtain the multipliers needed to perform consumption-based impact calculations, our framework is based on SUTs that are augmented with supply and use tables of capital goods. In order to preserve the full transparency of the model, we derived the Leontief inverse analytically, leading to distinct multipliers for the different types of intermediate goods used in production processes (current respectively capital goods), both in product and industry classification. This enabled us to tackle the recurrent problem with previous studies of capital endogenization that failed to incorporate the technological transformation of capital over time, i.e. that capital assets stem from different age cohorts and therefore were produced with technologies that had different emission intensities than the ones currently used. By differentiating between current and capital intermediate goods, our framework allows to assign different environmental stressors to the two types of goods, leading to consumption-based impacts that better capture the full life-cycle impacts of goods and services for final consumption. Furthermore, the SUT formalism allows for tables that are non-symmetric, circumventing the problems conventionally associated with the use of constructs that convert SUTs to symmetrical IOTs.

We provided a small worked example to illustrate the effectiveness of our framework, in which we calculated the impacts of Australian final demand from 1995 to 2010, both aggregated and on product level. We constructed three hypothetical scenarios for the change in emission intensities over time, corresponding to different scenarios of age cohort composition of capital goods, and implemented our framework on three selected indicators: GHG emissions, domestic extraction and land use change. The results showed that changing the stressor intensities of capital led to substantial changes in total impacts, particularly regarding the use of materials.

We also studied the effects on individual product level, and concluded that the effects varied vastly between different products, with service sectors being more affected than non-service sectors. These results have important implications on a variety of studies that involve footprint-type analyses. Service sectors came into the spotlight in the aftermath of the

Environmental Kuznets Curve hypothesis in the late 1990s, with some studies arguing that shifting consumption patterns towards an increased consumption of services could help to alleviate the negative impacts of human consumption on the environment (Bernardini & Galli, 1993; Jänicke, Binder, & Mönch, 1997; Pacala & Socolow, 2004), while other studies warned that the environmental impact of service sectors was, in fact, largely overlooked (Graedel, 1997). In the 2000s, the application of EE IO methods brought useful insights into the discussion as it enabled to quantify the upstream supply chain impacts of services (Heiskanen & Jalas, 2003; Nansai et al., 2009; Rosenblum, Horvath, & Hendrickson, 2000; Suh, 2006). These studies concluded that when upstream requirements are included in the quantification of impacts from service sectors, the gains of shifting towards a service-based economy are insignificant to negligible. Our study constitutes a relevant contribution to the debate, and the potential implications of our framework on footprint-type analyses (such as the typical environmental impact assessment of household studies) are substantial.

While the KSUT framework effectively solves one of the problems inherent to current endogenization models such as the flow matrix and augmentation methods, it has its limitations. The capital distribution matrices used to disaggregate the vectors of capital use and investment are currently based on an 8-by-21 resolution (asset-by-industry), which could be a bottleneck for performing more detailed analyses. For instance, the Australian data featured in EUKLEMS is still using the old NACE asset classification (Eurostat, 2013), where cultivated assets (such as dairy cattle) are not explicitly categorized but included in the "other" category. Australia is a large producer (and exporter) of a wide variety of agricultural products, and that asset distinction would certainly be valuable when creating the capital use matrices. Furthermore, stressor matrices for capital goods remain to be constructed; this requires not only detailed data on the age cohort composition of the current capital stock, but also reliable IOTs in constant prices (preferably product-specific and stretching further back in time than current MRIOs do), so that the stressor intensities (which are normalized per monetary output) can be compared over time.

In addition, the KSUT framework has limitations in terms of its application areas. While it suffices for ex-post analyses and environmental impact assessments like the one we performed in our worked example, it could be argued that a dynamic model may be better suited for ex-ante assessments, for instance estimations on future production capacity requirements (Duchin & Szyld, 1985), scenario analysis (Cole, 1988; Pan, 2006), projections of structural and technological change (Gurgul & Lach, 2016, 2018a; Pan, 2006), growth theory (Okuyama, 2017), etc.

Although we derived the framework for a single region, our method can be generalized and applied on multi-regional models as well. This constitutes a logical follow-up topic for future work on this study and is therefore not treated in this paper. Such a generalization would entail that the framework could be used to calculate consumption-based environmental impacts applying proper MRIO methodology instead of using the domestic technology assumption as we resorted to in the current study. This would extend the usefulness of the

KSUT framework, allowing to retrospectively distribute historical emissions from capital goods to the countries that are effectively responsible for them, enabling a fairer and more representative distribution of emissions across countries.

5 Appendix - detailed derivation of the KSUT partitioned inverse

We will start by deriving the generic formula for a 4x4 partition matrix and then apply the results to our KSUT framework. Consider the following 4x4 matrix

$$\boldsymbol{\Gamma} = \begin{bmatrix} \mathbf{A} & \mathbf{C} & \mathbf{E} & \mathbf{F} \\ \mathbf{G} & \mathbf{H} & \mathbf{J} & \mathbf{L} \\ \mathbf{M} & \mathbf{N} & \mathbf{O} & \mathbf{P} \\ \mathbf{Q} & \mathbf{R} & \mathbf{S} & \mathbf{T} \end{bmatrix} \tag{38}$$

By subgrouping matrices as such

$$\boldsymbol{\Gamma} \coloneqq \begin{bmatrix} \boldsymbol{\Gamma}_1 & \boldsymbol{\Gamma}_2 \\ \boldsymbol{\Gamma}_3 & \boldsymbol{\Gamma}_4 \end{bmatrix} \coloneqq \begin{bmatrix} \begin{bmatrix} \mathbf{A} & \mathbf{C} \\ \mathbf{G} & \mathbf{H} \end{bmatrix} & \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} \\ \begin{bmatrix} \mathbf{M} & \mathbf{N} \\ \mathbf{Q} & \mathbf{R} \end{bmatrix} & \begin{bmatrix} \mathbf{O} & \mathbf{P} \\ \mathbf{S} & \mathbf{T} \end{bmatrix} \end{bmatrix} \tag{39}$$

i.e. $\boldsymbol{\Gamma}_1 = \begin{bmatrix} \mathbf{A} & \mathbf{C} \\ \mathbf{G} & \mathbf{H} \end{bmatrix}$, $\boldsymbol{\Gamma}_2 = \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix}$, $\boldsymbol{\Gamma}_3 = \begin{bmatrix} \mathbf{M} & \mathbf{N} \\ \mathbf{Q} & \mathbf{R} \end{bmatrix}$ and $\boldsymbol{\Gamma}_4 = \begin{bmatrix} \mathbf{O} & \mathbf{P} \\ \mathbf{S} & \mathbf{T} \end{bmatrix}$,

Miyazawa's formula renders

$$\left(\mathbf{I} - \begin{bmatrix} \boldsymbol{\Gamma}_1 & \boldsymbol{\Gamma}_2 \\ \boldsymbol{\Gamma}_3 & \boldsymbol{\Gamma}_4 \end{bmatrix}\right)^{-1} = \begin{bmatrix} \mathbf{I} - \boldsymbol{\Gamma}_1 & -\boldsymbol{\Gamma}_2 \\ -\boldsymbol{\Gamma}_3 & \mathbf{I} - \boldsymbol{\Gamma}_4 \end{bmatrix}^{-1} = \begin{bmatrix} \mathbf{B}_1(\mathbf{I} + \boldsymbol{\Gamma}_2\mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1) & \mathbf{B}_1\boldsymbol{\Gamma}_2\mathbf{K}_1 \\ \mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1 & \mathbf{K}_1 \end{bmatrix} \tag{40}$$

With $\mathbf{B}_1 = (\mathbf{I} - \boldsymbol{\Gamma}_1)^{-1}$ and $\mathbf{K}_1 = (\mathbf{I} - \boldsymbol{\Gamma}_4 - \boldsymbol{\Gamma}_3\mathbf{B}_1\boldsymbol{\Gamma}_2)^{-1}$.

Replacing $\boldsymbol{\Gamma}_1$ with its subcomponents, $\mathbf{B}_1$ can be written $\left(\mathbf{I} - \begin{bmatrix} \mathbf{A} & \mathbf{C} \\ \mathbf{G} & \mathbf{H} \end{bmatrix}\right)^{-1}$. Applying Miyazawa's formula for a second time, we obtain

$$\mathbf{B}_1 = \begin{bmatrix} \mathbf{I} - \mathbf{A} & -\mathbf{C} \\ -\mathbf{G} & \mathbf{I} - \mathbf{H} \end{bmatrix}^{-1} = \begin{bmatrix} \mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) & \mathbf{B}_2\mathbf{C}\mathbf{K}_2 \\ \mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{K}_2 \end{bmatrix}, \tag{41}$$

with $\mathbf{B}_2 = (\mathbf{I} - \mathbf{A})^{-1}$ and $\mathbf{K}_2 = (\mathbf{I} - \mathbf{H} - \mathbf{G}\mathbf{B}_2\mathbf{C})^{-1}$.

Let $\boldsymbol{\Psi} = \boldsymbol{\Gamma}_3\mathbf{B}_1\boldsymbol{\Gamma}_2$, i.e. the third element of $\mathbf{K}_1$ (so that $\mathbf{K}_1 = (\mathbf{I} - \boldsymbol{\Gamma}_4 - \boldsymbol{\Psi})^{-1}$). Replacing the term with its subcomponents, we get

$$\begin{aligned} \boldsymbol{\Psi} &= \begin{bmatrix} \mathbf{M} & \mathbf{N} \\ \mathbf{Q} & \mathbf{R} \end{bmatrix} \begin{bmatrix} \mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) & \mathbf{B}_2\mathbf{C}\mathbf{K}_2 \\ \mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{K}_2 \end{bmatrix} \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{M}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{N}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{M}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{N}\mathbf{K}_2 \\ \mathbf{Q}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{R}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{Q}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{R}\mathbf{K}_2 \end{bmatrix} \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} \end{aligned} \tag{42}$$

Let

$$\begin{bmatrix} \boldsymbol{\Lambda}_1 & \boldsymbol{\Lambda}_2 \\ \boldsymbol{\Lambda}_3 & \boldsymbol{\Lambda}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{M}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{N}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{M}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{N}\mathbf{K}_2 \\ \mathbf{Q}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{R}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{Q}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{R}\mathbf{K}_2 \end{bmatrix}. \tag{43}$$

Then

$$\boldsymbol{\Psi} = \begin{bmatrix} \boldsymbol{\Lambda}_1 & \boldsymbol{\Lambda}_2 \\ \boldsymbol{\Lambda}_3 & \boldsymbol{\Lambda}_4 \end{bmatrix} \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Lambda}_1\mathbf{E} + \boldsymbol{\Lambda}_2\mathbf{J} & \boldsymbol{\Lambda}_1\mathbf{F} + \boldsymbol{\Lambda}_2\mathbf{L} \\ \boldsymbol{\Lambda}_3\mathbf{E} + \boldsymbol{\Lambda}_4\mathbf{J} & \boldsymbol{\Lambda}_3\mathbf{F} + \boldsymbol{\Lambda}_4\mathbf{L} \end{bmatrix}, \tag{44}$$

yielding

$$\mathbf{K}_1 = (\mathbf{I} - \boldsymbol{\Gamma}_4 - \boldsymbol{\Psi})^{-1} = \left(\mathbf{I} - \begin{bmatrix} \mathbf{O} & \mathbf{P} \\ \mathbf{S} & \mathbf{T} \end{bmatrix} - \begin{bmatrix} \boldsymbol{\Lambda}_1\mathbf{E} + \boldsymbol{\Lambda}_2\mathbf{J} & \boldsymbol{\Lambda}_1\mathbf{F} + \boldsymbol{\Lambda}_2\mathbf{L} \\ \boldsymbol{\Lambda}_3\mathbf{E} + \boldsymbol{\Lambda}_4\mathbf{J} & \boldsymbol{\Lambda}_3\mathbf{F} + \boldsymbol{\Lambda}_4\mathbf{L} \end{bmatrix}\right)^{-1}$$
$$= \left(\mathbf{I} - \begin{bmatrix} \mathbf{O} + \boldsymbol{\Lambda}_1\mathbf{E} + \boldsymbol{\Lambda}_2\mathbf{J} & \mathbf{P} + \boldsymbol{\Lambda}_1\mathbf{F} + \boldsymbol{\Lambda}_2\mathbf{L} \\ \mathbf{S} + \boldsymbol{\Lambda}_3\mathbf{E} + \boldsymbol{\Lambda}_4\mathbf{J} & \mathbf{T} + \boldsymbol{\Lambda}_3\mathbf{F} + \boldsymbol{\Lambda}_4\mathbf{L} \end{bmatrix}\right)^{-1} \tag{45}$$

Introducing

$$\begin{bmatrix} \boldsymbol{\Upsilon}_1 & \boldsymbol{\Upsilon}_2 \\ \boldsymbol{\Upsilon}_3 & \boldsymbol{\Upsilon}_4 \end{bmatrix} \coloneqq \begin{bmatrix} \mathbf{O} + \boldsymbol{\Lambda}_1\mathbf{E} + \boldsymbol{\Lambda}_2\mathbf{J} & \mathbf{P} + \boldsymbol{\Lambda}_1\mathbf{F} + \boldsymbol{\Lambda}_2\mathbf{L} \\ \mathbf{S} + \boldsymbol{\Lambda}_3\mathbf{E} + \boldsymbol{\Lambda}_4\mathbf{J} & \mathbf{T} + \boldsymbol{\Lambda}_3\mathbf{F} + \boldsymbol{\Lambda}_4\mathbf{L} \end{bmatrix}, \tag{46}$$

we obtain

$$\mathbf{K}_1 = \left(\mathbf{I} - \begin{bmatrix} \boldsymbol{\Upsilon}_1 & \boldsymbol{\Upsilon}_2 \\ \boldsymbol{\Upsilon}_3 & \boldsymbol{\Upsilon}_4 \end{bmatrix}\right)^{-1} \tag{47}$$

This calls for a third iteration of Miyazawa’s formula:

$$\mathbf{K}_1 = \left(\mathbf{I} - \begin{bmatrix} \boldsymbol{\Upsilon}_1 & \boldsymbol{\Upsilon}_2 \\ \boldsymbol{\Upsilon}_3 & \boldsymbol{\Upsilon}_4 \end{bmatrix}\right)^{-1} = \begin{bmatrix} \mathbf{I} - \boldsymbol{\Upsilon}_1 & -\boldsymbol{\Upsilon}_2 \\ -\boldsymbol{\Upsilon}_3 & \mathbf{I} - \boldsymbol{\Upsilon}_4 \end{bmatrix}^{-1} = \begin{bmatrix} \mathbf{B}_3(\mathbf{I} + \boldsymbol{\Upsilon}_2\mathbf{K}_3\boldsymbol{\Upsilon}_3\mathbf{B}_3) & \mathbf{B}_3\boldsymbol{\Upsilon}_2\mathbf{K}_3 \\ \mathbf{K}_3\boldsymbol{\Upsilon}_3\mathbf{B}_3 & \mathbf{K}_3 \end{bmatrix}, \tag{48}$$

with $\mathbf{B}_3 = (\mathbf{I} - \boldsymbol{\Upsilon}_1)^{-1}$ and $\mathbf{K}_3 = (\mathbf{I} - \boldsymbol{\Upsilon}_4 - \boldsymbol{\Upsilon}_3\mathbf{B}_3\boldsymbol{\Upsilon}_2)^{-1}$.

At this point, it is sensible to introduce our WSUT variables to simplify the expressions. Using the analytical description of figure 1b, we can establish that

$$\boldsymbol{\Gamma} = \begin{bmatrix} \mathbf{A} & \mathbf{C} & \mathbf{E} & \mathbf{F} \\ \mathbf{G} & \mathbf{H} & \mathbf{J} & \mathbf{L} \\ \mathbf{M} & \mathbf{N} & \mathbf{O} & \mathbf{P} \\ \mathbf{Q} & \mathbf{R} & \mathbf{S} & \mathbf{T} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{D} & \mathbf{0} & \mathbf{0} \\ \mathbf{B} & \mathbf{0} & \mathbf{B}_{\mathrm{K}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{D}_{\mathrm{K}} \\ \mathbf{B}_{\mathrm{C}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \tag{49}$$

Where $\mathbf{0}$ represents a null matrix of suitable dimensions.

This gives $\mathbf{B}_2 = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I}$ and $\mathbf{K}_2 = (\mathbf{I} - \mathbf{H} - \mathbf{G}\mathbf{B}_2\mathbf{C})^{-1} = (\mathbf{I} - \mathbf{B}\mathbf{B}_2\mathbf{D})^{-1} = (\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}$. We recognize this as a product-by-product (pxp) Leontief inverse constructed using the ITA, and therefore introduce $\boldsymbol{\mathcal{L}} \coloneqq \mathbf{K}_2 = (\mathbf{I} - \mathbf{B}\mathbf{D})^{-1}$.

Hence,

$$\begin{bmatrix} \boldsymbol{\Lambda}_1 & \boldsymbol{\Lambda}_2 \\ \boldsymbol{\Lambda}_3 & \boldsymbol{\Lambda}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{M}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{N}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{M}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{N}\mathbf{K}_2 \\ \mathbf{Q}\mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) + \mathbf{R}\mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{Q}\mathbf{B}_2\mathbf{C}\mathbf{K}_2 + \mathbf{R}\mathbf{K}_2 \end{bmatrix}$$
$$= \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix} \tag{50}$$

This gives

$$\begin{cases} \boldsymbol{\Upsilon}_1 = \mathbf{O} + \boldsymbol{\Lambda}_1\mathbf{E} + \boldsymbol{\Lambda}_2\mathbf{J} = \mathbf{0} \\ \boldsymbol{\Upsilon}_2 = \mathbf{P} + \boldsymbol{\Lambda}_1\mathbf{F} + \boldsymbol{\Lambda}_2\mathbf{L} = \mathbf{D_K} \\ \boldsymbol{\Upsilon}_3 = \mathbf{S} + \boldsymbol{\Lambda}_3\mathbf{E} + \boldsymbol{\Lambda}_4\mathbf{J} = \mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K} \\ \boldsymbol{\Upsilon}_4 = \mathbf{T} + \boldsymbol{\Lambda}_3\mathbf{F} + \boldsymbol{\Lambda}_4\mathbf{L} = \mathbf{0} \end{cases} \tag{51}$$

Hence $\mathbf{B}_3 = (\mathbf{I} - \boldsymbol{\Upsilon}_1)^{-1} = \mathbf{I}$ and $\mathbf{K}_3 = (\mathbf{I} - \boldsymbol{\Upsilon}_4 - \boldsymbol{\Upsilon}_3\mathbf{B}_3\boldsymbol{\Upsilon}_2)^{-1} = (\mathbf{I} - \mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K}\mathbf{D}_\mathrm{K})^{-1}$.

$\mathbf{K}_3$ is the formulation of a feedback mechanism that can be described as the direct and indirect ($\boldsymbol{\mathcal{L}}$) capital requirements of current industries ($\mathbf{B}_\mathrm{C}\mathbf{D}$) required to produce the capital inputs of the capital sector ($\mathbf{B}_\mathrm{K}\mathbf{D}_\mathrm{K}$). Although we separate capital requirements from current requirements in our framework, capital goods are still produced by "current" industries, and $\mathbf{K}_3$ describes, in other words, the total direct and indirect capital requirements of the capital sector, and we therefore introduce the Leontief (pxp) capital matrix $\boldsymbol{\mathcal{L}}_\mathrm{K} \coloneqq \mathbf{K}_3 = (\mathbf{I} - \mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K}\mathbf{D}_\mathrm{K})^{-1}$

Returning to the second iteration of Miyazawa's formula from equation (**Error! Reference source not found.**), we get

$$\mathbf{B_1} = \begin{bmatrix} \mathbf{B}_2(\mathbf{I} + \mathbf{C}\mathbf{K}_2\mathbf{G}\mathbf{B}_2) & \mathbf{B}_2\mathbf{C}\mathbf{K}_2 \\ \mathbf{K}_2\mathbf{G}\mathbf{B}_2 & \mathbf{K}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \tag{52}$$

And

$$\mathbf{K_1} = \begin{bmatrix} \mathbf{B}_3(\mathbf{I} + \boldsymbol{\Upsilon}_2\mathbf{K}_3\boldsymbol{\Upsilon}_3\mathbf{B}_3) & \mathbf{B}_3\boldsymbol{\Upsilon}_2\mathbf{K}_3 \\ \mathbf{K}_3\boldsymbol{\Upsilon}_3\mathbf{B}_3 & \mathbf{K}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{I} + \mathbf{D}_\mathrm{K}\boldsymbol{\mathcal{L}}_\mathrm{K}\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K} & \mathbf{D}_\mathrm{K}\boldsymbol{\mathcal{L}}_\mathrm{K} \\ \boldsymbol{\mathcal{L}}_\mathrm{K}\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K} & \boldsymbol{\mathcal{L}}_\mathrm{K} \end{bmatrix} \tag{53}$$

Let

$$\begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix} \coloneqq \begin{bmatrix} \mathbf{I} + \mathbf{D}_\mathrm{K}\boldsymbol{\mathcal{L}}_\mathrm{K}\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K} & \mathbf{D}_\mathrm{K}\boldsymbol{\mathcal{L}}_\mathrm{K} \\ \boldsymbol{\mathcal{L}}_\mathrm{K}\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K} & \boldsymbol{\mathcal{L}}_\mathrm{K} \end{bmatrix} = \mathbf{K_1} \tag{54}$$

Going back to our original formulation, equation (**Error! Reference source not found.**)

$$\left(\mathbf{I} - \begin{bmatrix} \boldsymbol{\Gamma}_1 & \boldsymbol{\Gamma}_2 \\ \boldsymbol{\Gamma}_3 & \boldsymbol{\Gamma}_4 \end{bmatrix}\right)^{-1} = \begin{bmatrix} \mathbf{B}_1(\mathbf{I} + \boldsymbol{\Gamma}_2\mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1) & \mathbf{B}_1\boldsymbol{\Gamma}_2\mathbf{K}_1 \\ \mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1 & \mathbf{K}_1 \end{bmatrix} \coloneqq \begin{bmatrix} \boldsymbol{\Phi}_1 & \boldsymbol{\Phi}_2 \\ \boldsymbol{\Phi}_3 & \boldsymbol{\Phi}_4 \end{bmatrix} \tag{55}$$

We get

$$\begin{aligned} \boldsymbol{\Phi}_1 &= \mathbf{B}_1(\mathbf{I} + \boldsymbol{\Gamma}_2\mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1) = \mathbf{B}_1\left(\mathbf{I} + \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix}\begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix}\begin{bmatrix} \mathbf{M} & \mathbf{N} \\ \mathbf{Q} & \mathbf{R} \end{bmatrix}\mathbf{B}_1\right) \\ &= \mathbf{B}_1\left(\mathbf{I} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{K} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix}\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{C} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix}\right) \\ &= \mathbf{B}_1\left(\mathbf{I} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{K} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix}\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix}\right) \\ &= \mathbf{B}_1\left(\mathbf{I} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_1 & \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2 \end{bmatrix}\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix}\right) \\ &= \mathbf{B}_1\left(\mathbf{I} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix}\right) \\ &= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix}\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{I} + \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}) \\ \boldsymbol{\mathcal{L}}\mathbf{B} + \boldsymbol{\mathcal{L}}\mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_\mathrm{K}\boldsymbol{\Omega}_2\mathbf{B}_\mathrm{C}\mathbf{D}\boldsymbol{\mathcal{L}}) \end{bmatrix} \end{aligned}$$

$$= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\big(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B})\big) & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) \\ \boldsymbol{\mathcal{L}}\big(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B})\big) & \boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) \end{bmatrix} \tag{56}$$

Similarly,

$$\begin{aligned} \boldsymbol{\Phi}_2 = \mathbf{B}_1\boldsymbol{\Gamma}_2\mathbf{K}_1 &= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \begin{bmatrix} \mathbf{E} & \mathbf{F} \\ \mathbf{J} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_{\mathrm{K}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_1 & \mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_2 \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_1 & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_2 \\ \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_1 & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\boldsymbol{\Omega}_2 \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix} \end{aligned} \tag{57}$$

And

$$\begin{aligned} \boldsymbol{\Phi}_3 = \mathbf{K}_1\boldsymbol{\Gamma}_3\mathbf{B}_1 &= \begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix} \begin{bmatrix} \mathbf{M} & \mathbf{N} \\ \mathbf{Q} & \mathbf{R} \end{bmatrix} \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{\Omega}_1 & \boldsymbol{\Omega}_2 \\ \boldsymbol{\Omega}_3 & \boldsymbol{\Omega}_4 \end{bmatrix} \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{B}_{\mathrm{C}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{\Omega}_2\mathbf{B}_{\mathrm{C}} & \mathbf{0} \\ \boldsymbol{\Omega}_4\mathbf{B}_{\mathrm{C}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\mathcal{L}} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{\Omega}_2\mathbf{B}_{\mathrm{C}} + \boldsymbol{\Omega}_2\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\Omega}_2\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\Omega}_4\mathbf{B}_{\mathrm{C}} + \boldsymbol{\Omega}_4\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} & \boldsymbol{\Omega}_4\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} \end{bmatrix} \end{aligned} \tag{58}$$

Finally,

$$\boldsymbol{\Phi}_4 = \mathbf{K}_1 = \begin{bmatrix} \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix} \tag{59}$$

Our KSUT partitioned inverse $\mathbf{L}^*$ becomes

$$\begin{bmatrix} \mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\big(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B})\big) & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\big(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B})\big) & \boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}(\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}) & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix} \tag{60}$$

As we saw earlier, $\boldsymbol{\mathcal{L}} = (\mathbf{I} - \mathbf{BD})^{-1}$. Using Taylor series expansion, we can write it as

$$\boldsymbol{\mathcal{L}} = (\mathbf{I} + \mathbf{BD} + (\mathbf{BD})(\mathbf{BD}) + \cdots) \tag{61}$$

and rewrite the expression $\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}$ as

$$\begin{aligned} &\mathbf{I} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B} = \mathbf{I} + \mathbf{D}(\mathbf{I} + \mathbf{BD} + (\mathbf{BD})(\mathbf{BD}) + \cdots)\mathbf{B} = \mathbf{I} + \mathbf{DB} + \mathbf{D}(\mathbf{BD})\mathbf{B} + \\ &\mathbf{D}(\mathbf{BD})(\mathbf{BD})\mathbf{B} + \cdots = \\ &\quad = \mathbf{I} + (\mathbf{DB}) + (\mathbf{DB})(\mathbf{DB}) + (\mathbf{DB})(\mathbf{DB})(\mathbf{DB}) \ldots = (\mathbf{I} - \mathbf{DB})^{-1} \coloneqq \boldsymbol{\mathcal{L}}^{\mathrm{i}} \end{aligned} \tag{62}$$

Which is the industry-by-industry (ixi) Leontief inverse constructed using the ITA.

Hence we get that

$$\mathbf{L}^{*} = \begin{bmatrix} \boldsymbol{\mathcal{L}}^{\mathrm{i}} + \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}\boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}\left(\mathbf{B} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}}\right) & \boldsymbol{\mathcal{L}}(\mathbf{I} + \mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}(\mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}) & \boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}}\mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathbf{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \mathbf{I} + \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \mathbf{D}_{\mathrm{K}}\boldsymbol{\mathcal{L}}_{\mathrm{K}} \\ \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\boldsymbol{\mathcal{L}}^{\mathrm{i}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}}\mathbf{B}_{\mathrm{C}}\mathbf{D}\boldsymbol{\mathcal{L}}\mathbf{B}_{\mathrm{K}} & \boldsymbol{\mathcal{L}}_{\mathrm{K}} \end{bmatrix} \tag{63}$$

which is the expression we use in the main manuscript.

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