

Accepted Manuscript

A Quantitative Model for Environmentally Sustainable Supply Chain Performance Measurement

Adolf Acquaye , Taofeeq Ibn-Mohammed , Andrea Genovese ,
Godfred A Afrifa , Fred A Yamoah , Eunice Oppon

PII: S0377-2217(17)30986-4
DOI: [10.1016/j.ejor.2017.10.057](https://doi.org/10.1016/j.ejor.2017.10.057)
Reference: EOR 14781



To appear in: *European Journal of Operational Research*

Received date: 28 July 2016
Revised date: 24 October 2017
Accepted date: 25 October 2017

Please cite this article as: Adolf Acquaye , Taofeeq Ibn-Mohammed , Andrea Genovese , Godfred A Afrifa , Fred A Yamoah , Eunice Oppon , A Quantitative Model for Environmentally Sustainable Supply Chain Performance Measurement, *European Journal of Operational Research* (2017), doi: [10.1016/j.ejor.2017.10.057](https://doi.org/10.1016/j.ejor.2017.10.057)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Highlights:

- ◁ An *industrial lifecycle thinking* analytical view of supply chains is presented.
- ◁ A supply chain model applied to global Metal Industries over 20 years is undertaken
- ◁ Carbon emissions performance outlook for selected countries are hypothesised.
- ◁ Effects of footprint, intensities and imports on performance are evaluated.
- ◁ Implications of supply chain modelling to management are discussed.

A Quantitative Model for Environmentally Sustainable Supply Chain Performance Measurement

Adolf Acquaye^{a,*}; Taofeeq Ibn-Mohammed^{b,c}; Andrea Genovese^d; Godfred A Afrifa^e; Fred A Yamoah^f; Eunice Oppon^{b, c}

^aKent Business School, University of Kent, Canterbury, CT2 7PE, UK

^bCentre for Energy, Environment and Sustainability, University of Sheffield, Sheffield, S10 1FL, UK

^cAdvanced Resource Efficiency Centre, University of Sheffield, Sheffield, S10 1FL, UK

^dLogistics and Supply Chain Management Research Centre, Management School, University of Sheffield, UK

^eThe Business School, Canterbury Christ Church University, Canterbury, CT1 1NX, UK

^fBrunel Business School, University of Brunel, London, Uxbridge, UB8 3PH, UK

Corresponding Author: Adolf Acquaye (Email: a.a.acquaye@kent.ac.uk)

A Quantitative Model for Environmentally Sustainable Supply Chain Performance Measurement

ABSTRACT

The development of robust mechanisms for supply chain performance measurement have been identified as an integral step needed for the transition towards sustainable supply chain systems and a greener global economy. However, measuring the environmental performance of supply chains is a challenging task, due to several factors, such as the lack of standardised methodologies and the inherent multi-criteria nature of the problem. By leveraging the capability of a Multi-Regional Input-Output framework to handle the complex and global nature of supply chains, the current work presents a robust environmental sustainable performance measurement model underpinned by *industrial lifecycle thinking*.

As a result, some theoretical insights are provided and an empirical application of the model to the Metal Products industry of the BRICS (Brazil, Russia, India, China, and South Africa) nations undertaken in an attempt to address some of the methodological and applied measurement challenges. In particular, this allowed the modelling of carbon emissions trends within, and between the BRICS nations and with the Rest-of-the-World over a 20-year period (1992-2011) as well as providing an opportunity to hypothesise on their future carbon emissions performances. Specific analyses of the Metal Product industry showed that demand represents the main driver for the increasing carbon footprint. However, the overall decline in reported carbon footprint was due to improvements in emissions intensity and efficiency gains induced by technology. The study further assesses the effects of imports and economic growth on carbon footprint and discusses the implications of the study to sustainability transition processes in the BRICS nations.

Keywords: Operational Research in Environment and Climate Change; Supply Chain; Sustainable Performance Measurement; Industry Lifecycle Thinking; BRICS

1. INTRODUCTION

The transition towards sustainable supply chains (Ding *et al.*, 2016) has encouraged businesses to align their operations to practices that are judged to be environmentally sustainable (Dey *et al.* 2011; Hassini *et al.* 2012, Jaehn, 2016). The development of models and their application to production and supply networks in order to measure environmental performance has therefore been identified as a key element towards such transition. Environmental performance measurement as used in this paper draws on the concept of the natural resource based-view proposed by Hart (1995); a concept that examines the use of natural resources and their resultant impact.

Taticchi *et al.* (2015) and Ahi and Searcy (2015) have reported on the importance of performance measurement for supply chain sustainability given the opportunities for continuous improvement (Zhu, 2014). Despite the reported importance, measuring the environmental performance of supply chains has become a challenge as reiterated by Lehtinen and Ahola (2010) and Hassini *et al.* (2012) who reported that incompatibilities exist between the known principles of performance measures and supply chains. The performance measurement literature appears to be biased towards intra-organizational measures of performance (Lehtinen and Ahola, 2010) as opposed to the extended, complex and dynamic network nature, which characterises supply chains (Gunasekaran *et al.*, 2004; Varsei *et al.*, 2014). All these issues imply that performance measurement models for sustainable supply chains focus only on direct impacts, and thus do not take a holistic view of the supply chain. Other issues that pose challenges for building reliable sustainable supply chain performance measurement approaches include, the multiple measures that must be employed to characterize the performance driven by data (Afful-Dadzie *et al.* 2016) and the focus on reporting green supply chain management initiatives implementation rather than outcomes (Zhu *et al.*, 2008). It has also been reported that performance measures are multi-faceted (Genovese *et al.*, 2017) and are characterized by inconsistent methodologies as expounded by Font and Harris (2004).

In order to address some of the highlighted issues, this paper leverages on the extended capability and visibility of the Multi-Regional Input-Output (MRIO) framework (Miller and Blair, 2009) in handling the complex and global nature of supply chains operations to present a robust environmental sustainable performance measurement model underpinned by *industrial lifecycle thinking*. This analytical viewpoint provides a holistic view and visibility of the global economy such that supply chain dependences and interactions are captured and assessed in a consistent

framework. An industry-level perspective of the global supply chain is adopted for this study because, most value-added activities of the supply chain take place at the industry level compared to the process, product or firm level of the supply chain (Gereffi *et al.*, 2005). The mathematical basis of the model is derived based on the MRIO framework (Miller and Blair, 2009) for supply chain carbon emissions quantification and analyses. Gonzalez *et al.* (2015) have reiterated how mathematical models and solution methods can provide quantifiable information and structured opportunities to evaluate, propose, test and implement action for the transition towards environmental sustainability.

To provide a context for the application of the environmental sustainability measurement model, an assessment is carried out over a 20-year period (1992-2011) in the BRICS nations (namely: Brazil, Russia, India, China and South Africa) with a focus on the Metal Industry in these countries. Attention is focused on the BRICS nations because, in the last decade, there have been growing international concerns on the environmental damage associated with the accelerated economic growth of these countries. These concerns have been reported in the scholarly literature (Lai and Wong, 2012; Wu *et al.*, 2015) as well as in the mainstream media platforms (Guardian, 2011; Washington Post, 2014). Insights into the low-carbon management of the supply chains of these nations have therefore become an issue of high importance in the current climate of sustainability awareness and international climate change debates. The Metal Industry was chosen, as it is a major heavy industrial sector, which received special attention for decarbonisation efforts in the recently published Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2014).

In this paper, the carbon emissions assessment process in the selected industrial supply chains is carried out from a consumption-based perspective (Takahashi *et al.*, 2014) between 1992 and 2011. This enables supply chain carbon emissions intensities (presented as a measure of the overall efficiencies of the considered industrial systems) of the BRICS nations to be assessed, thus providing a standardized way for similarly structured industries within these countries to be compared over time horizons. The time series analysis of carbon emissions intensities profiles provides the right context to discuss recent trends in economic growth in the BRICS countries and the environmental consequences of such growth. Additionally, based on the demand for final goods and services, this paper also presents and assesses the carbon emissions footprint in absolute terms, making provision for carbon emissions embodied in imported and exported goods and services.

In the light of the context presented above, the contributions of this paper can be summarised as follows:

- ◁ An *industrial lifecycle thinking* concept is introduced as a way of analysing environmental sustainability impacts through the general input-output methodological framework.
- ◁ Based on a 20-year time series analysis, the future industrial environmental sustainability performance outlooks of BRICS countries are hypothesised.
- ◁ Industry-level Supply Chain Efficiencies and Footprint accounts as well as targeted measurements of a specific industrial sector are generated, allowing for cross-country analyses in a consistent manner.
- ◁ The influences of indirect supply chain emissions on environmental sustainability performance are assessed.
- ◁ The development of a 20-year environmental performance model for any targeted industry in any country is exemplified, along with contextual assessment, discussions and implications of the findings.

To address fully the issues highlighted in this work, the remainder of the paper is organised as follows: In Section 2, a literature review is conducted on approaches for supply chains environmental impact assessment. The review provides the context and lays the foundation for the developments and contributions made in this paper. Details of the general methodological notes and theoretical formulations are provided in Section 3. In Section 4, key findings and results are analysed and discussed, highlighting the implications of the research to supply chain management. Some concluding remarks are drawn in Section 5.

2. LITERATURE REVIEW

2.1 Industry-level Carbon Emissions Measurement

The contemporary view of supply chain emphasises a network of multiple relationships where value can be added (Horvath, 2001). Such relationships can be between products (Ganesh *et al.*, 2014) or even processes, firms and industries as elaborated by Lambert and Cooper (2000). Gereffi *et al.*, (2005) however report on how the most value added activities within the global supply chain network occurs at the industry level. Azapagic et al. (2000) have also pointed out that industrial systems are an integral part of the economy since they determine the flows of materials and energy, rendering them a source of environmental degradation and resource depletion. Industrial supply chains, therefore, play a central role in identifying and implementing

more environmentally sustainable options. To this end, this study adopts an industrial-level perspective to the supply chain environmental performance measurement (Refer to Figure 1).

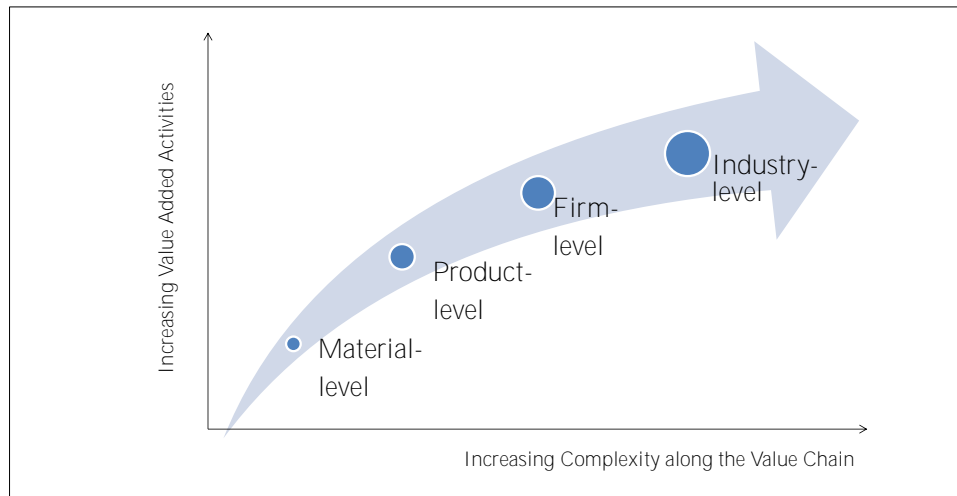


Figure 1: A hierarchal perspective of the value chain and complexity of supply chain systems

This viewpoint is taken because the industrial supply chains and systems are what binds nations together within the global economy and so it provides assistance in gaining an understanding of the interrelationship within cross-country supply chains. This is in line with the recommendation by Sundarakani *et al.* (2010) who stated that there is the need to study carbon footprint measurement across supply chains as a way to better understand the environmental impact in global production networks.

Frameworks such as Material Flow Analyses (Muller *et al.*, 2014), Product Life Cycle Accounting (Koh *et al.*, 2013) and Corporate Value Chain Accounting (WRI and WBCSD, 2013) have been employed respectively at the material, product and firm -levels of the value chain as highlighted in Figure 1. It should be noted that Life Cycle Assessment (LCA) has been used as one of the main general constructs for environmental performance measurements (Acquaye *et al.*, 2014; Ibn-Mohammed *et al.*, 2017). Ongoing work by the Life Cycle Impact Assessment workgroup of the United Nations Environmental Programme Life Cycle Initiative (Guinée, 2002) seeks to provide harmonisation and guidance in LCA studies. This LCA framework based on the ISO14000 series has been developed for product supply chains as reported by UNEP and SETAC (2011). As such, for industry-level supply chain analysis (which is higher up the value chain) the specifics of the LCA framework (International Standard Organisation, 1998) are not applicable.

The current research, therefore, argues for what it describes as *industrial lifecycle thinking*, which can be assumed as taking a similar logic of lifecycle thinking (Yang and Song, 2006; Hu and Bidanda,

2009) applicable to product supply chains. The *industrial lifecycle thinking* is presented as taking a holistic view of the global industrial supply chain in which the complex industry-level supply chain dependences and interactions (upstream) and their resultant impact as a result of demand (downstream) are recognised, thus allowing for strategies and policies to be developed and implemented.

Such *industrial lifecycle thinking* suggests that the interaction between industrial supply chains and the natural environment are characterised by the following:

- i. Industrial supply chains are at the highest level of the supply chain hierarchy and are therefore characterised by higher complexity and value-added activities (Timmer *et al.*, 2014).
- ii. The economies of different countries are connected and characterised by industrial supply chains (Neilson *et al.*, 2014). Accordingly, linkages and dependencies between economies of different nations can also be viewed from an industrial-level perspective.
- iii. For an industry to produce an output, resources are required from the same industry and from other industries, both within its country of origin and internationally. (Miller and Blair, 2009).
- iv. Any final product or service produced by any industry is the result of many other products or services used as inputs at different supply chain tiers (Acquaye *et al.*, 2016).
- v. Products and services that are produced by any industry can be used by the same industry, by other industries or as part of the final demand category consisting of households, government purchases, exports, stocks (Kucukvar *et al.*, 2014).
- vi. The assessment of dependences and impacts of industrial supply chains must inform the management of these impacts (Marchi *et al.*, 2013).

To gain an understanding of the assessments of carbon footprints, appropriate frameworks and methodologies must be used. The Intergovernmental Panel on Climate Change (2001) recommended two basic modelling approaches used to examine the linkages between a supply chain and the environment. These are the bottom-up (based on process modelling) and the top-down (based on macro-economic modelling) approaches.

Although the bottom-up process approach is based on LCA principles (Majeau-Bettez *et al.*, 2011) and is consistent with the logic of lifecycle thinking (Hu and Bidanda, 2009), the IPCC (2001) explains that in the top-down modelling approach, economic theory and techniques are applied to historical data on consumption and prices in order to model the final demand for

goods and services and their resultant environmental impacts. To this end, we adopt a top-down modelling approach in this study since it addresses system complexity issues (Ewing *et al.*, 2012) and system boundary completeness limitations (Ward *et al.*, 2016) by providing a holistic perspective (Abbasi and Nilsson, 2012) whilst addressing the aforementioned key challenges related to *industrial lifecycle thinking*.

2.2 Industry-level Carbon Emissions Management

In addition to pressure from three main stakeholder groups (civic society including consumers, media and regulatory bodies), the theory of Business Case for Sustainability (Schaltegger *et al.*, 2012) also explains why business now see the measurement and management of their supply chain impact as an important aspect of their operations. Such a theory emphasises how the links between voluntary environmental and economic success can be managed, advanced, or innovated.

While low-carbon supply chain management may initially begin with carbon emissions assessment, in terms of *industrial lifecycle thinking*, how this informs the management of the impacts must also be taken into account. In fact, it should be a continuous learning in which carbon footprint assessment feeds into low-carbon management and vice versa. It has been reported that no single policy can be used to adequately manage the impacts of carbon emissions on the environment (Heltberg *et al.*, 2009) and that decarbonisation efforts should consist of a portfolio of policies (Fischer and Newell, 2008).

Managing carbon emissions at the industry-level must therefore take into account these principles. In fact, in an attempt to identify different drivers of global industry-related greenhouse gas (GHG) emissions, the Intergovernmental panel on Climate Change in its 5th Assessment Report, decomposed GHGs using a *kaya-like* identity (Fischedick *et al.*, 2014). This was expressed as:

— — — —

Where:

GHG emissions of the industrial sector within a specific time frame

Industrial sector energy consumption

	Total global production of materials in that period
P	Stock of products created from these materials
S	Total demand for products and services

Since this *kaya-like* identity captures the drivers of emissions in industry, it can also be used to identify key mitigation opportunities available within industrial sectors.

- represents the emissions intensity of the industrial sector expressed as a ratio to the energy used. Emissions efficiency therefore means a reduction in the value of $\frac{E}{G}$.
- measures the energy intensity of energy input to industrial output (Freeman *et al.*, 1997, Arens *et al.*, 2012); that is the energy used to create materials from ores, oil and biomass, etc. The aim of energy intensity supply chain strategies or policies is to reduce $\frac{E}{G}$.
- identifies material intensity, namely a measure of the amount of material needed to create a product and maintain the stock of product (Allwood *et al.*, 2011). Material efficiency therefore means providing material services with less material production and processing.
- provides a measure on the intensity of use or the level of service provided by a product (Roy, 2000). A reduction in $\frac{G}{S}$ refers to a reduction in product-service intensity

S represents total demand for products and services and it is a function of variables such as population, wealth, lifestyle and the whole social system of expectation and aspiration (Hubacek *et al.*, 2011; Alcott, 2012). A reduction in total demand will lead to a decrease in industrial emissions.

Following the outline of these mechanisms by which industrial-level emissions can be addressed, supply chain emissions assessment must capture some of these drivers in such a way that there is a continuous learning and improvement process in which carbon footprint assessment feeds into low-carbon management and vice versa.

This study, therefore, argues that in order to implement *industrial lifecycle thinking* approaches, the developments made in carbon footprint assessment using top-down models consisting of macro-economic techniques (as discussed in Section 2.1) should be used to inform industry-level carbon emissions management (as highlighted in Section 2.2).

Insight into the industrial-level supply chain efficiency or carbon emissions intensity also pointed to the fact that despite the reduction in emissions intensity (or improvement in supply chain emissions efficiency) of most industries, the cumulative sum of carbon footprint of all industries are increasing. We, therefore, report that despite the reduction in the carbon emissions intensity representing a positive low-carbon mitigation achievement, the biggest impact towards achieving low-carbon supply chains will come from developing strategies that will assist in reducing the consumption of goods and services since this is generally the main factor, which drives up carbon footprint of the BRICS nations. Despite this acknowledgement, an in-depth analysis of the Metal Products industry used as a case study in this paper suggests an exception to this view. This is because, for such a technology driven industry which is heavily dependent on the Electricity industry, the gains of improved carbon emissions intensity towards the total carbon footprint in the Metal Products industry outweighs the negative effects of the increase in the demand of its products. This is a clear case where the use of technology within an economic sector delivers reduction in carbon footprint.

Further insight into the Metal Products industry suggests that although the total carbon footprint has reduced significantly between 1992 and 2011, the carbon footprint imported from one BRICS nation to another has increased over the same period. This reinforces the fact that there is significant increase in the supply chain interaction among the BRICS nations over the last 20 years. In line with reported integrated and collaborative approach of contemporary supply chain thinking, we accentuate that the formation of the BRICS nations should also be seen as a platform for better cooperation in any low carbon supply chain joint efforts. We also report that given the RoW industry imports more than 10% of its emissions from the BRICS nations, any global efforts to address carbon emissions related impacts should have these nations central to it.

The paper also provides some insight into the impacts that economic growth can have on the carbon footprint of the BRICS nations. We highlight that given the historical and present positive correlation between total carbon footprint and GDP, the carbon emissions impacts, which will be associated with the BRICS nations who together will account for 30% of the world GDP will be significant.

Finally, the paper presents some supply chain implications of the study. In particular, it suggests a rethink of the lack of emphasis placed on industrial supply chains in mainstream supply chain management literature. As such, the implications of the study to the higher level supply chains (or industrial-level) which are characterised by increased complexity and added value activities

are presented in addition to industrial lifecycle thinking perspective, consumption-based approach to carbon footprint analyses, embodied emissions in goods and services and the need for an integrated and collaborative supply chain cooperation even at the high level of the value chain as highlighted in the case of the BRICS nations.

As part of future research development of this work, the use of Structural Decomposition Analysis within a MRIO can facilitate the understanding of the key drivers of the carbon emissions profile of the BRICS nations.

REFERENCES

Abbasi, M. and Nilsson, F. (2012), Themes and challenges in making supply chains environmentally sustainable *Supply Chain Management: An International Journal*, Vol. 17 No. 5, pp 517-530.

Ó Súilleabháin, S. (2013), An input-output analysis of Irish construction sector embodied carbon emissions *Journal of Environmental Planning and Construction*, Vol. 15 No. 3, pp.784-791.

Acquaye, A., Feng, K., Oppon, E., Salhi, S., Ibn-Mohammed, T., Genovese, A. and Hubacek, K., (2017). Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. *Journal of Environmental Management*, 187, pp.571-585.

Acquaye, A., Genovese, A., Barrett, J. and Koh, L. (2014), Benchmarking Carbon Emissions Performance in Supply Chains *Supply Chain Management: An International Journal*, Vol. 19 No. 3, pp. 306-321.

Afful-Dadzie, A., Afful-Dadzie, E. & Turkson, C. (2016) A TOPSIS extension framework for re-conceptualizing sustainability measurement. *Kybernetes*, 45(1):70-86.

Chen, M., and Ghisellini, M. (2015) Carbon footprint based on input-output analysis: A review *Journal of Cleaner Production*, 105, pp. 1-16.

Ahi, P. & Searcy, C. (2015) Assessing sustainability in the supply chain: A triple bottom line approach. *Applied Mathematical Modelling* 39(10):2882-2896.

Akashi, O., Hanaoka, T., Matsuoka, Y. and Kainuma, M. (2015) Estimating CO₂ emissions from the industrial sector through 2030 based on activity level and technology *Energy*, 86, 1855-1867.

Alcott, B. (2012), Population matters in ecological economics *Ecological Economics*, Vol. 80, pp. 109-120.

Allwood, J. M., Ashby, M. F., Gutowski, T. G. and Worrell, E. (2011), Material efficiency: A white paper *Resources, Conservation and Recycling*, Vol. 55 No. 3, pp. 362-381.

Chen, M., and Ghisellini, M. (2015) Carbon footprint based on input-output analysis: A review *Journal of Cleaner Production*, 105, pp. 1-16.

Aref, A. H., Marilyn, M. H. and Joseph, S. (2005), Performance measurement for green supply chain management *Benchmarking: An International Journal*, Vol. 12 No. 4, pp. 330-353.

Arens, M., Worrell, E. and Schleich, J. (2012), Energy intensity development of the German iron and steel industry between 1991 and 2007 *Energy*, Vol. 45 No. 1, pp. 786-797.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.O., Levin, S., Lugo, A., May, R., Moench, M., Peterson, G.J., Pridemore, D., Raskin, J., Shaver, G.R., Woodwell, G.M., Zimmerman, J.K. & Zedler, J.B. (1985), 'Common Property, the Commons, and the Environment', *Ecological Economics*, 5(2), pp. 93-107.

Azapagic, A. and Perdan, S. (2000), 'Indicators of Sustainable Development for Industry: A General Framework', *Process Safety and Environmental Protection*, Vol. 78 No.4, pp. 243-261.

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K. and Le Quéré, C. (2013), 'Consumption-based GHG emission accounting: a UK case study', *Climate Policy*, Vol. 13 No. 4, pp. 451-470.

Bazan, E., Jaber, M. Y. & Zanoni, S. (2015) Supply chain models with greenhouse gases emissions, energy usage and different coordination decisions. *Applied Mathematical Modelling* 39(17):5131-5151.

Beamon, B. M. (1999), 'Measuring supply chain performance', *International Journal of Operations & Production Management*, Vol. 19 No. 3, pp. 275-292.

Beske, P. & Seuring, S. (2014), 'Putting sustainability into supply chain management', *Supply Chain Management: An International Journal*, Vol. 19 No. 3, pp. 322-331.

Bhagwati, J. and Panagariya, A. (1996), 'The theory of preferential trade agreements: historical evolution and current trends', *The American Economic Review*, pp. 82-87.

Bosetti, V., Carraro, C. and Tavoni, M. (2009), 'Climate change mitigation strategies in fast-growing countries', *Energy Economics*, 31(1), pp. 14-31.

BRICS6. (2014), 'Sixth BRICS Summit - Fortaleza Declaration', available at: <http://brics6.itamaraty.gov.br/media2/press-releases/214-sixth-brics-summit-fortaleza-declaration> (accessed 15 April 2015).

Cerri, C. C., Maia, S. M. F., Galdos, M. V., Cerri, C. E. P., Feigl, B. J. and Bernoux, M. (2009), 'Brazilian greenhouse gas emissions: the importance of agriculture and livestock', *Scientia Agricola*, Vol. 66 No. 6, pp. 831-843.

Chakraborty, D. and Mukhopadhyay, K. (2014), 'The Methodology', In *Water Pollution and Abatement Policy in India*, Springer, Netherlands, Vol. 10, pp. 47-51.

Court, C. D., Munday, M., Roberts, A. & Turner, K. (2015) Can hazardous waste supply chain management be improved? *European Journal of Operational Research*, 241(1):177-187.

Daly, H. E. & Farley, J. (2011), *Ecological Economics: Principles and Applications*. Island Press, Washington

Devika, K., Jafarian, A. & Nourbakhsh, V. (2014) Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. *European Journal of Operational Research*, 235(3):594-615.

Dey, A., Laguardia, P. & Srinivasan, M. (2011) Building sustainability in logistics operations: a research agenda. *Management Research Review*, 34(11):1237-1259.

Ding, H., Liu, Q. & Zheng, L. (2016) Assessing the economic performance of an environmental sustainable supply chain in reducing environmental externalities. *European Journal of Operational Research*, 255(2):463-480.

EAPSA. (2013), 'South African Government Position on Climate Change', available at: <http://www.climateaction.org.za/cop17-cmp7/sa-government-position-on-climate-change> (accessed 8th April 2015).

Ebiefung, A. and Kostreva, M. (1993), 'The generalized Leontief input-output model and its application to the choice of new technology', *Annals of Operations Research*, Vol. 44 No. 2, pp. 161-172.

Harvard International Review, 36(2), 12

Ewing, B.R., Hawkins, T.R., Wiedmann, T.O., Galli, A., Ercin, A.E., Weinzettel, J. and Steen-Olsen, K., (2012), Integrating ecological and water footprint accounting in a multi-regional input-output framework. *Ecological Indicators*, 23, pp.1-8.

Fawcett, S. E. and Magnan, G. M. (2002), 'The rhetoric and reality of supply chain integration' *International Journal of Physical Distribution & Logistics Management*, Vol. 32 No. 5, pp. 339-361.

Fischedick M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y., Lanza, H. K. A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., and Tanaka, K., (2014) 'Industry' *In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fischer, C. & Newell, R. G. (2008), 'Environmental and technology policies for climate mitigation' *Journal of Environmental Economics and Management*, Vol. 55 No. 2, pp. 142-162.

Font, X. and Harris, C. (2004), 'Rethinking standards from green to sustainable' *Annals of Tourism Research*, Vol. 31 No. 4, pp. 986-1007.

Fourcade, M. (2013), 'The material and symbolic construction of the BRICs: Reflections inspired by the RIPE Special Issue' *Review of International Political Economy*, Vol. 20 No. 2, pp. 256-267.

Freeman, S. L., Niefer, M. J. & Roop, J. M. (1997), 'Measuring industrial energy intensity: A new methodology' *Energy Policy*, 25(10):1017-1024.

Ganesh, M., Raghunathan, S., & Rajendran, C. (2014). The value of information sharing in a multi-product, multi-level supply chain: Impact of product substitution, demand correlation, and partial information sharing. *Decision Support Systems*, 58, 79-94.

Genovese, A., Morris, J., Piccolo, C., & Koh, S. L. (2017). Assessing redundancies in environmental performance measures for supply chains. *Journal of Cleaner Production*; doi.org/10.1016/j.jclepro.2017.05.186

Gereffi, G., Humphrey, J. & Sturgeon, T. (2005) The governance of global value chains. *Review of International Political Economy*, 12(1):78-104.

Gonzalez, E. D. R. S., Sarkis, J., Huisingh, D., Huatuco, L. H., Maculan, N., Montoya-Torres, J. R. & De Almeida, C. M. V. B. (2015) Making real progress toward more sustainable societies using decision support models and tools: introduction to the special volume. *Journal of Cleaner Production*, 105:1-13.

Guardian. (2011), BRICS' emergence raises the environmental stakes. Available at: <http://www.theguardian.com/sustainable-business/brics-economies-emerging-markets-global-values>, accessed (20th March 2015).

Guinée, J. B. (2002), 'Handbook on life cycle assessment operational guide to the ISO standards' *The International Journal of Life Cycle Assessment*, Vol. 7 No. 5, pp. 311-313.

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International Journal of Production Economics*, 87(3), 333-347.

Gunasekaran, A., Patel, C. and Tirtiroglu, E. (2001), 'Performance measures and metrics in a supply chain environment' *International Journal of Operations & Production Management*, Vol. 21 No. 1, pp. 71-87.

* XWRZVNL 7 * 6DKQL 6 \$OOZRRG - 0 \$VKE\ 0) | required to produce materials: constraints on energy-intensity improvements, parameters *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 371, 20120003.

Hanley, N., Shogren, J. and White, B. (2013), *Introduction to environmental economics*. Oxford University Press. Oxford, UK

+ DUW 6 / -resource EDWKG DQL HZ A W K H H U P P Review, 20(4), pp.986-1014.

+ DUWH 0 - '(FRORJ\ V XVWDLQDE EDLW DQG HQY *Ecological Economics* 15(2):157-164.

Hassini, E., Surti, C. & Searcy, C. (2012) A literature review and a case study of sustainable supply chains with a focus on metrics. *International Journal of Production Economics* 140(1):69-82.

Heltberg, R., Siegel, P. B. and Jorgensen, S. L. (2009), 'Addressing human vulnerability to climate change', *Climate Change*, Vol. 19 No. 1, pp. 89-99.

+RHN VWUD \$ < DQG :LHG PDQQ 7 2 ' +XPDQLW
 IRRW SWLQW (188), pp.1114-1117.

Holweg, M., Disney, S., Holmström, J. DQG 6PnURV Supply Chain Collaboration:: Making Sense of the Strategy Continuum *European Management Journal* , Vol. 23 No. 2, pp. 170-181.

Horvath, L. (2001), 'Collaboration: the key to value creation in supply chain management' *Supply Chain Management: An International Journal*, Vol. 6 No. 5, pp. 205-207.

Hu, G. and Bidanda, B. (2009), 'Modeling sustainable product lifecycle decision support systems' *International Journal of Production Economics*, Vol. 122 No. 1, pp. 366-375.

+XDQJ < \$:HEHU & / DQG ODWWKHZV + 6 ' &DW
 VWUHD POLQH G HQWHUSUWVH. Fedd, ERQ, 43 (2), pp. 8515-8515

Hubacek, K., Feng, K. and Chen, B. (2011), 'Changing Lifestyles Towards a Low Carbon Economy: An IPAT Analysis for China' *Energies*, Vol. 5 No. 1, pp. 22-31.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. & Acquaye, A. (2014), 'Modeling the environmental impact of a low carbon economy' *Journal of Cleaner Production*, Vol. 84, pp. 1-11.

' , QWHJUDWLQJ HFRQRPLF FRQVHPSHUWV LQVWURGXJLQJ A ZLWK R :
 GHFLVLRQ VXSSRUW V\WHP IRU WKH RSWLPLDQ UDQN
Environment, Vol. 72, pp. 82-101.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2013). 'Energy and Buildings', Vol.66 pp. 232-245.

Ibn-Mohammed, T., Koh, S.C.L., Reaney, I.M., Acquaye, A., Schileo, G., Mustapha, K.B. and Greenough, R., 2017. Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. *Renewable and Sustainable Energy Reviews*, 80, pp.1321-1344.

Intergovernmental Panel on Climate Change, IPCC (2001), Section 7.6.3: Costing Methodologies: Top-down and Bottom-up Models. Available at: <http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=310>. (accessed 15 March 2015).

International Standard Organisation, ISO. (1998), *ISO 14041: Environmental management – Lifecycle assessment – Goal and scope definition and Inventory analysis*. ISO. Geneva.

IPCC (2014), Summary for Policymakers, In: *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jaehn, F. (2016) Sustainable Operations. *European Journal of Operational Research*, 253(2):243-264.

Jakob, M., Steckel, J. C. and Edenhofer, O. (2014), 'Consumption-Versus Production-Based Emission Policies' *Annual Review of Resource Economics*, Vol. 6 No. 1, pp. 297-318.

Kagawa, S., Suh, S., Hubacek, K., Wiedmann, T., Nansai, K. & Minx, J. (2015), 'CO₂ emission clusters within global supply chain networks: Implications for climate change mitigation' *Global Environmental Change*, doi:10.1016/j.gloenvcha.2015.04.003.

Khanna, P. (2014), 'New BRICS Bank a Building Block of Alternative World Order' *New Perspectives Quarterly*, Vol. 31 No.4, pp. 46-48.

Kucukvar, M., Egilmez, G. and Tatari, O., (2014). Sustainability assessment of US final consumption and investments: triple-bottom-line input-output analysis μ *Journal of Cleaner Production*, 81, pp.234-243.

Koh, S.C.L., Ibn-Mohammed, T., Acquaye, A., Feng, K., Reaney, I.M., Hubacek, K., Fujii, H. **DQG .KDWDE .** toxicological footprint trajectory 1998 ² μ *Scientific Reports*, 6: 39514

Lai, K.-H. and Wong, C. W. Y. (2012), 'Green logistics management and performance: Some empirical evidence from Chinese manufacturing exporters μ *Omega*, Vol. 40 No. 3, pp. 267-282.

Lambert, D. M. and Cooper, M. C. (2000), 'Issues in Supply Chain Management μ *Industrial Marketing Management*, Vol. 29 No. 1, pp. 65-83.

Leal-Arcas, R. (2013), The BRICS and climate change. In *International Affairs Forum*, Taylor & Francis, Vol. 4, pp. 22-26.

Lehtinen, J. & Ahola, T. (2010) Is performance measurement suitable for an extended enterprise? *International Journal of Operations & Production Management* 30(2):181-204.

Lenzen, M., Moran, D., Kanemoto, K. & Geschke, A. (2013), 'Building Eora: A Global Multi-Region Input-Output Database at High Country and Sector Resolution μ *Economic Systems Research*, Vol. 25 No. 1, pp. 20-49.

Leontief, W. (1936) Quantitative input and output relations in the economic systems of the United States. *The Review of Economic Statistics*, Vol. 18 No. 3, pp. 105-125.

Mahlberg, B. & Luptacik, M. (2014) Eco-efficiency and eco-productivity change over time in a multisectoral economic system. *European Journal of Operational Research*, 234(3):885-897.

Majeau-Bettez, G., Strømman, A. H. and Hertwich, E. G. (2011), 'Evaluation of process-and input-output-based life cycle inventory data with regard to truncation and aggregation issues μ *Environmental Science & Technology*, Vol. 45 No. 23, pp. 10170-10177.

ODUFLK 9 ' ODULD (' DQG OLFHOOL 6 '(QYLU
FRPSHWLWLYH DGYDQW *Business Strategy and Environmental Management*, 22(1)
pp.62-72.

ODWKHZV - \$ 7DQ + '&LUF&KLDU'FRQRPP. /HVVRQ\
McDonough, W. and Braungart, M. (2002), 'Cradle to Cradle: Remaking the Way We Make Things. North Point Press, New York, NY

Miller, R. E. & Blair, P. D. (2009) *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press, Cambridge.

Min, S., Roath, A. S., Daugherty, P. J., Genchev, S. E., Chen, H., Arndt, A. D. and Glenn Richey, R. (2005), 'Supply chain collaboration: what's happening? μ *The International Journal of Logistics Management*, Vol. 16 No. 2, pp. 237-256.

Mu **OOHU (+LOW\ / 0 :LGPHU 5 6FKOXHS 0 DQG)D**
stocks and flows: A review of dynamic material flow analysis methods. *Environmental*
6FLHQFH 7HFKQRORJ μ **SS**

Napp, T., Gambhir, A., Hi **OOV 7)ORULQ 1 DQG)HQQHOO 3**
technologies, economics and policy instruments for decarbonising energy-intensive
PDQXIDFWXULQJ QGSXWUHQV *Renewable and Sustainable Energy Reviews*, 30, 616-640.

Nayyar, D., (2016). 'BRICS, developing countries and global governance μ *Third World Quarterly*, 37(4), pp.575-591.

1HLOVRQ - 3ULWFKDUG % DQG <HXQJ + : & '*O
networks in the changing international political economy: An introductory μ *Review of International Political Economy*, 21(1), pp.1-8.

O'Mahony, M. and Timmer, M. P. (2009) 'Output, input and productivity measures at the industry level: the EU KLEMS database μ *The Economic Journal* 119(538):F374-F403.

Paroussos, L., Fragkos, P., Capros, P. & Fragkiadakis, K. (2015), 'Assessment of carbon leakage through the industrial sector', *Energy Economics*, Vol. 50, pp. 104-119.

Peters, G. P. (2010), 'Carbon footprints and embodied carbon at multiple scales', *Current Opinion in Environmental Sustainability*, Vol. 2 No. 4, pp. 245-250.

Porter, M. (1985), *Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press, New York, NY

Prell, C., Feng, K., Sun, L., Geores, M. and Hubacek, K. (2014), 'The Economic Gains and Environmental Losses of US Consumption: A World-Systems and Input-Output Approach', *Social Forces*, Vol. 93 No. 1, pp. 405-428.

Qiang, Q., Ke, K., Anderson, T. and Dong, J. (2013), 'The closed-loop supply chain network with competition, distribution channel investment, and uncertainties', *Omega*, Vol. 41 No. 2, pp. 186-194.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H.J. and Nyberg, L. (2009), 'A Safe Operating Space for Humanity', *Science*, Vol. 326, pp. 65-72.

Roy, R. (2000), 'Sustainable product-service systems', *Futures*, Vol. 32 No. 3, pp. 289-299.

Schaltegger, S., Lüdeke-Fekke, S. & Wagner, M. (2005), 'Sustainable Business Models: Innovation and Sustainable Development', *Journal of Business Ethics*, Vol. 62, pp.95-119.

Serrenho, A. & O'Rourke, D. (2014), 'The influence of UK emissions reduction targets on the emissions of the global steel industry', *Resources, Conservation and Recycling*, 107, 174-184.

Shaw, N. (2013), BRIC by BRIC: How our emerging markets are tackling carbon emissions?, available at: <http://www.sustainablebusiness toolkit.com/bric-countries-carbon-emissions/> (accessed 20th March 2015)

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Ramanathan, R., Woodwell, G., Zeyringer, A., Shaver, G.R., Moore, B., Losch, S., Soto, M., Lucht, W., Sumner, M., Janssen, R., Garnett, S.J., Steiner, J., Zech, M., Gruber, S., Gollub, M., Luck, V., Sheehy, M., Moyle, P., Arp, H., Winkel, L., de Wit, M. (2015), 'Planetary Boundaries: Guiding Human Development in the 21st Century', *Science*, Vol. 347, pp. 755-762.

Sundarakani, B., De Souza, R., Goh, M., Wagner, S. M. and Manikandan, S. (2010), 'Modeling carbon footprint of a multinational corporation', *International Journal of Production Economics*, Vol. 128 No. 1, pp. 43-50.

Taticchi, P., Garengo, P., Nudurupati, S. S., Tonelli, F. & Pasqualino, R. (2015) A review of decision-support tools and performance measurement and sustainable supply chain management. *International Journal of Production Research* 53(21):6473-6494.

Takahashi, K., Nansai, K., Tohno, S., Nishizawa, M., Kurokawa, J.-I. and Ohara, T. (2014), 'Production-based emissions, consumption-based emissions and consumption-based health impacts of PM2.5', *Atmospheric Environment*, Vol. 87, pp. 406-415.

Taylor, M. P. (2003), 'The World as a System', *Economic Perspectives*, 28(2), pp.99-118.

Tukker, A. & Dietzenbacher, E. (2013), 'Global Multiregional Input-Output Frameworks: An Application to the European Union', *Journal of Economic Surveys*, Vol. 27, pp. 1-19.

UNEP and SETAC (2011), 'Global Guidance Principles for Life Cycle Assessment Databases: A Basis for Greener Processes and Products'. Programme, United Nations Environment Programme, Milan, Italy, available at: <http://www.unep.org/pdf/Global-Guidance-Principles-for-LCA.pdf>. (accessed 15 March 2015).

US Energy Information Administration (2013), Country Analysis: Brazil. Available at: <http://www.eia.gov/beta/international/country.cfm?iso=BRA>. (accessed 10 March 2015)

Varsei, M., Soosay, C., Fahimnia, B. and Sarkis, J., (2014), Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Management: An International Journal*, 19(3), pp.242-257.

Ward, H., Burger, M., Chang, Y.J., Fürstmann, P., Neugebauer, S., Radebach, A., Sproesser, G., Pittner, A., Rethmeier, M., Uhlmann, E. and Steckel, J.C., (2016), Assessing carbon dioxide emission reduction potentials of improved manufacturing processes using multiregional input output frameworks. *Journal of Cleaner Production*; <https://doi.org/10.1016/j.jclepro.2016.02.062>.

Washington Post (2014) Xi confident in BRICS future, available at: <http://chinawatch.washingtonpost.com/2014/07/xi-confident-in-brics-future/>. (accessed: 20th March 2015)

West, G. R. and Jackson, R., W. (2015), Simulating Impacts on regional Economies: A Modelling Alternative. In (Association, I. R. M. (Ed.), *Hospitality Travel and Tourism: Concepts, Methodologies, Tools and Applications*. IGI Global, PA, USA.

Wiedmann, T. and Minx, J. (2008), A Definition of 'Carbon Footprint', In Pertsova, C. C. (Ed.), *Ecological Economics Research Trends*, Nova Science Publishers, Hauppauge NY, USA, pp. Chapter 1, pp. 1-11.

Wilson, D., Purushothaman, R. & Goldman, S. (2003) *Dreaming with BRICs: the path to 2050*. Goldman, Sachs & Company.

World Bank (2015), World Bank Open Data μ Washington, USA, available at: <http://data.worldbank.org/>. (accessed 2nd May 2015)

:RUOG %DQN ' :RUOG %DQN 2SHQ 'DWD 5XVVLDQ)HG
at: <http://data.worldbank.org/country/russian-federation?view=chart>. (accessed: 1 March 2017)

World Resources Institute (WRI) and World Business Council for Sustainable Development :% & 6 ' '&RUSRUDWH 9DOXH &KDLQ 6FRSH 6WDQGDUG μ 6XSSOHPHQW WR WKH *+* 3URWRFRO & Standard, Available at: <http://www.ghgprotocol.org/standards/scope-3-standard>

:RUOG 6WHHO \$VVRFLDWLRQ '6WHHO VteelPittQ
Paper.

Wu, L., Liu, S., Liu, D., Fang, Z. and Xu, H. (2015), Modelling and forecasting CO₂ emissions in the BRICS (Brazil, Russia, India, China, and South Africa) countries using a novel multi-variable grey model, *Energy*, Vol. 79, pp. 489-495.

Wu, X. and Zhang, Z., (2005) Input 2output analysis of the Chinese construction sector. *Construction Management and Economics*, 23(9), pp.905-912.

Yang, Q. and Song, B. (2006), Eco-Design for Product Lifecycle Sustainability μ In *Industrial Informatics, IEEE International Conference on 16-18 August 2006, Singapore*, pp. 548-553.

Yuan, Z., Bi, J. and Moriguchi, Y. (2006) The circular economy: A new development strategy in China μ *Journal of Industrial Ecology*, Vol. 10 No. 1 2, pp. 4-8.

Zhu, J., (2014) Quantitative models for performance evaluation and benchmarking: data envelopment analysis with spreadsheets (Vol. 213). Springer.

Zhu, Q., Sarkis, J., & Lai, K.-h. (2008). Confirmation of a measurement model for green supply chain management practices implementation. *International Journal of Production Economics*, 111(2), 261-273.

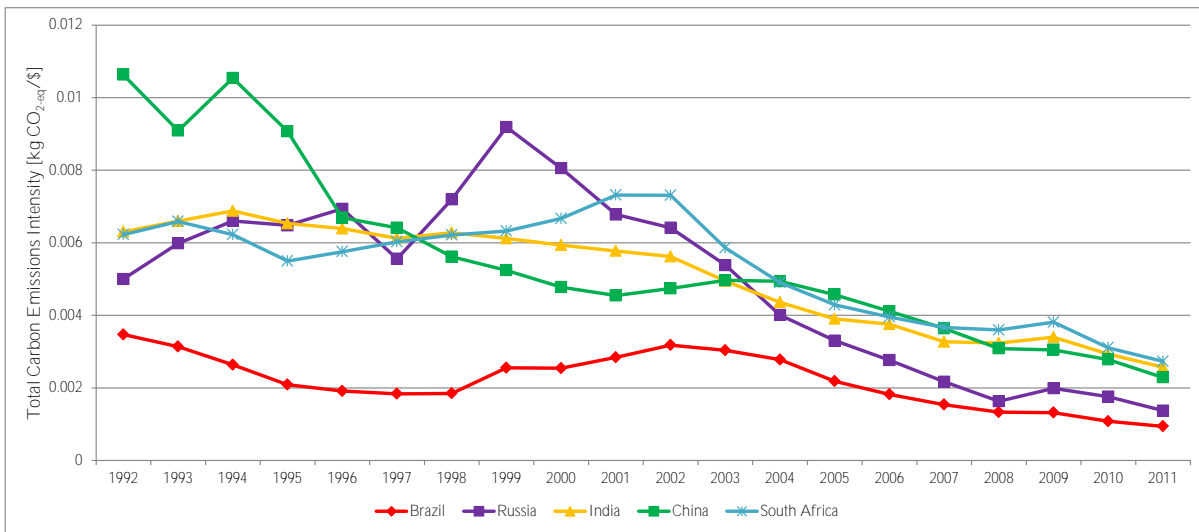
LIST OF APPENDICES

Appendix 1: Breakdown of Industrial Sectors

1	Agriculture
2	Fishing
3	Mining and Quarrying

4	Food & Beverages
5	Textiles and Wearing Apparel
6	Wood and Paper
7	Petroleum, Chemical and Non-Metallic Mineral Products
8	Metal Products
9	Electrical and Machinery
10	Transport Equipment
11	Other Manufacturing
12	Recycling
13	Electricity, Gas and Water
14	Construction
15	Maintenance and Repair
16	Wholesale Trade
17	Retail Trade
18	Hotels and Restaurants
19	Transport
20	Post and Telecommunications
21	Financial Intermediation and Business Activities
22	Public Administration
23	Education, Health and Other Services
24	Private Households
25	Others

Appendix IV: Carbon Emissions Intensities of the BRICS Metal Industries [kg CO_{2-eq}/\$]



Miller, R. E. & Blair, P. D. (2009) *Input-output analysis: Foundations and extensions*. Cambridge, Cambridge University Press.