An Ecological-Thermodynamic Approach to Urban Metabolism

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Declaration

All work presented within this thesis is the author's own work except where specific reference has been made to the work of others.

Some research material produced during the course of this project has been published and/or is currently undergoing peer-review for publication. Where a chapter includes reproductions of such material, which may with the explicit permission of relevant co-author(s) be featured wholly or in parts, these are indicated at the outset of the chapter.

Signature:

Ling Min Tan

Date: 30 June 2020

Acknowledgement of collaborative work within the thesis

The candidate confirms that the work submitted is her own, except where work that has formed part of jointly authored publications has been included. The contribution of the candidate to this work has been explicitly indicated below.

1. **Tan, L. M.**, Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.
   In this publication, the candidate contributed to the design of the study, undertook the study and critically analysed the results and wrote the manuscript.

2. **Tan, L. M.**, Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.
   In this publication, the candidate designed the study, undertook the study and wrote the manuscript.

3. Arbabi, H., Punzo, G., Meyers, G., **Tan, L. M.**, Li, Q., Densley Tingley, D. & Mayfield, M. (2020). On the Use of Random Graphs in Analysing Resource Utilisation in Urban Systems.*Royal Society Open Science*, *7*, 200087.
   In this publication, the candidate undertook the numerical study and contributed to the writing of the manuscript.

4. **Tan, L. M.**, Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectivness across urban systems.
   In this publication, the candidate designed the study, undertook the study and wrote the manuscript.

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Summary

Cities have evolved as centers of economic growth but are also responsible for high resource consumption and greenhouse gases emission. Rapid urbanisation due to increasing human population and resource-intensive economic activities draw concerns on urban sustainability issues in future development. In the urban metabolism framework, cities are often described as open systems where the intake of resources is heavily dependent on flows imported from the external environment to sustain economic growth. However, this raises a key question: *how much of the resource available in cities is effectively consumed?*

To investigate the effectiveness of urban resource use, an ecological-thermodynamic approach is taken to develop an open system network effectiveness analysis (OSNEA) framework as a novel tool for urban sustainability assessment. The contributions of resources imported are maximised when the usefulness of the energy available, namely exergy[1], is fully utilised by destroying exergy through energy conversion processes or exported to other regions in exchange for generated capital flows into the city. Meanwhile, only a minimal amount of low-quality energy is rejected out of the system as waste. In this aspect, OSNEA introduces a set of effectiveness performance metrics to assess the ability of a system to utilise high exergy (high quality energy) and convert the resources available into economic benefits. Having incorporated the techniques from material flow analysis, ecological flow analysis, input-output analysis, exergy analysis and extended-exergy analysis, the framework formulates and translates the incoming flows into a network based on the material exchanges between different urban processes and economic activities in order to account for the metabolism of the whole system. On the downside, the use of exergy as a metric for resource effectiveness is open to challenge as it is an extensive thermodynamic property derived from the study of energy systems and may be regarded as metaphorical and not literally applicable to physical processes in reality.

The thesis first presents an initial case study of the cities in England and Wales in Chapter 3 to investigate intra-city metabolism of the urban economies (monetary exchanges between economic sectors) by showing the degree of consumption-control and production-dependency relationships in their hierarchical structure. The case study addresses the shortcomings of existing urban metabolism methods when using input-output monetary transactions as resource supply and use to account for the metabolic activities in cities. However, a framework that considers the differentials in energy and material intakes through urban systems is absent from the existing assessments. OSNEA has been developed to fill this gap, Chapter 4 outlines details of the development workflow and data requirements of this new method demonstrated in this work. To verify and validate the framework,

[1]Brockway P.E., Dewulf J., Kjelstrup S., Siebentriit S., Valero A., Whelan C. *In a Resource-constrained World: Think Exergy, not Energy.* Science Europe. Available at: https://www.scienceeurope.org/our-resources/in-a-resource-constrained-world-think-exergy-not-energy

Chapter 5 demonstrates the application of OSNEA in a case study of Singapore representing a single-city model to account for the effectiveness of resource use in the city-state. The trajectory of effectiveness results throughout the years suggests a trade-off relationship between the producers and consumers to balance the production and consumption of resources in the city. Chapter 6 extends the application of OSNEA to study the urban systems of Great Britain as a multi-city model and develop a clustering taxonomy of resource use behaviours of the cities across the whole systems of cities. Next, Chapter 7 provides a synthesis of the key findings and discussion from all studies. Finally, Chapter 8 gives a conclusion and recommendations for further work.

The essence of this work is the introduction of *effectiveness* indicators as a set of novel performance metrics to evaluate the states of resource use in the network based on the differential in resource quantity and quality between the cross-boundary inflows and outflows of the system. OSNEA promotes strategic resource management and transition to circular economy by enabling greater understanding of the sectoral interdependencies within the economy based on their supplies and demands to facilitate flow redirection to where the resources can be utilised effectively. The goal is to provide pathways for retaining and circulating resources in flow cycles for as long as possible to promote higher utilisation rate and reduce the demand for new material extraction. This will help in driving national and urban development towards the United Nation's Sustainable Development Goals for Sustainable Cities and Communities (SDG 11) and Responsible Consumption and Production (SDG 12).

Keywords: urban metabolism; exergy analysis; extended-exergy accounting; input-output analysis; open system network; ecological network analysis; urban sustainability; resource efficiency; sustainable development

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To all my friends and Victor, thank you for being my inspirations and distractions at times.

When opening this thesis as a PDF, two-page view display option is recommended as mirrored margins are used for facing pages and the chapters start are on odd numbered pages.

Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

CA	Control allocation
CE	Circular economy
CExC	Culmulative exergy consumption
CExENE	Cumulative exergy extraction from the natural environment
CPA	Statistical classification of product by activity
DA	Dependency allocation
EEA	Extended-exergy analysis
EEIO	Environmental-extended input-output
EF	Ecological footprint
EIO-LCA	Economic input-output life cycle assessment
EMF	Ellen Macarthur Foundation
ENA	Ecological network analysis
EW-MFA	Economy wide-material flow analysis
ExIO	Exergy-based input-output analysis
FUA	Functional urban area
GB	Great Britain
GDP	Gross domestic product
GFCF	Gross fixed capital formation
GFN	Global Footprint Network
GHG	Greehouse gas
GVA	Gross value added
HDI	Human Development Index
HS-4	4-digit Harmonised Commodity Sescription and Coding System

IOA Input-output analysis

IOT Input-output table

ISO International Organization for Standardization

LAU Local administrative unit

LCA Life cycle assessment

MFA Material flow analysis

MRIO Multiregional input-output

NUTS Nomenclature of territorial units for statistics

ONS Office for National Statistics

OSNEA Open system network effectiveness analysis

PIOT Physical inout-output table

PSUT Physical supply and use table

SDG Sustainable development goal

SOHO Self-organising holarchic system

SSIC Singapore Standard Industrial Classification

SUT Supply and use table

UK SIC Standard Industrial Classification of Economic Activities

UM Urban metabolism

UN United Nations

UN-DESA United Nations Department of Economic and Social Affairs

UNEP United Nations Environment Programme

WIOD World Input-Output Database

Nomenclature

$atm.$	Standard atmosphere, unit for pressure
CA	Control allocation matrix, $[ca_{ij}]$
D	Direct utility intensity matrix, $[d_{ij}]$
DA	Dependence allocation matrix, $[da_{ij}]$
E_{in}	Total incoming exergy flux
e_{surv}	Exergy consumption required for survival, $e_{surv} \approx 10^7$ $Joule\ per\ person\ per\ day$
ee_K	Exergy equivalent of capital
EE_{K_i}	Extended-exergy of services for a sector or node i
ee_L	Exergy equivalent of labour output
EE_{L_i}	Extended-exergy of domestic labour for a sector or node i
F	Exergy consumption amplication factor
$f_{destroyed_i}$	Exergy destruction at a sector or node i
f_{export_i}	Exergy export to a sector or node i
$f^{FUA}_{import_i}$	Exergy import to a sector or node i for a FUA
$f^{FUA}_{import_i}(A)$	Exergy import to a sector or node i for a FUA from abroad
$f^{FUA}_{import_i}(I-C)$	Exergy import to a sector or node i for a FUA from the inter-city system
f_{ij}	Flow from node j to node i
f_{import}	Vector of exergy import
f_{import_i}	Exergy import to a sector or node i
f_{input_i}	Exergy input to a sector or node i
$f^{NUTS2}_{import\ i}$	Exergy import to a sector or node i for a NUTS2 area
$f^{NUTS2}_{import\ i,K}$	Exergy import of services to a sector or node i for a NUTS2 area
$f^{NUTS2}_{import\ i,M}$	Exergy import of manufacturing goods to a sector or node i for a NUTS2 area

$f_{import\ \ i,P}^{NUTS2}$	Exergy import of production goods to a sector or node i for a NUTS2 area
f_{output_i}	Exergy output from a sector or node i
$f_{import_i}^{UK}$	Exergy import to a sector or node i for the whole UK
$f_{import_{i,M}}^{UK}$	Exergy import of manufacturing goods to a sector or node i for the whole UK
$f_{import_{i,P}}^{UK}$	Exergy import of production goods to a sector or node i for the whole UK
f_{waste_i}	Waste exergy emitted from a sector or node i
$\mathbf{G}$	Input-oriented inter-compartment flow matrix, $[g_{ij}]$
$\mathbf{G'}$	Output-oriented inter-compartment flow matrix, $[g'_{ij}]$
GVA_i	GVA of a sector or node i within a defined system boundary
GVA_i^{FUA}	GVA of a sector or node i within a FUA
GVA_i^{LAU}	GVA of a sector or node i within a LAU
GVA_i^{NUTS2}	GVA of a sector or node i within a NUTS2 area
i	An arbitruary node in the network
j	All other nodes in the network except the node i
J	Joule, unit for energy
kg	kilogram, unit for mass
M	Mutualism index
$\widehat{\mathbf{M}}_{ij}$	Normalised input-output matrix
$\mathbf{M_{ex}}$	Exergy-based input-output matrix , $[f_{ij}]$
$M2$	Cumulative monetary circulation
$\mathbf{N}$	Input-oriented integral flow intensity matrix, $[n_{ij}]$
$\mathbf{N'}$	Output-oriented integral flow intensity matrix, $[n'_{ij}]$
N_h	Population
η_{ideal}	Theoretical maximum efficiency
N_w	Number of employed workers
N_{wh}	Total number of work-hours
$\dot{Q}_{in}$	Rate of heat energy input
R	Overall resource effectiveness

R_{limit}	Upper limit of R
S	Synergism index
S_-	Total number of negative utilities
S_+	Total number of positive utilities
S_w	Wages
T_h	Temperature at the hot source
$T_i^{(in)}$	Sum of all inflow at node i
$T_i^{(out)}$	Sum of all outflow at node i
T_l	Temperature at the cold sink
$\mathbf{U}$	Utility matrix, $[u_{ij}]$
$\dot{W}$	Rate of work or power
$\dot{W}_{ideal}$	Theoretical maximum power
W_w	Average workload per worker
y_i	Cross-boundary inflow to node i
z_i	Cross-boundary outflow from node i
$£^{NUTS2}_{import\ i,K}$	Monetary import values of services to a sector or node i for a NUTS 2 area
$£^{NUTS2}_{import\ i,P}$	Monetary import values of manufacturing goods to a sector or node i for a NUTS 2 area
$£^{NUTS2}_{import\ i,M}$	Monetary import values of production goods to a sector or node i for a NUTS 2 area
$£^{UK}_{import\,i,M}$	Monetary import values of manufacturing goods to a sector or node i for the whole UK
$£^{UK}_{import\,i,P}$	Monetary import values of production goods to a sector or node i for the whole UK
α	First econometric factor
β	Second econometric factor
ε_C	Effectiveness of conversion
$\varepsilon_{C,limit}$	Thermodynamic limit of ε_C
ε_U	Effectiveness of utilisation
$\varepsilon_{U,limit}$	Thermodynamic limit of ε_U
θ	Overall effectiveness balance
$^{\circ}C$	Degree Celsius, unit for temperature

Chapter 1

Introduction

The current chapter contains materials that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.

Tan, L. M., Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.

Arbabi, H., Punzo, G., Meyers, G., **Tan, L. M.**, Li, Q., Densley Tingley, D. & Mayfield, M. (2020). On the Use of Random Graphs in Analysing Resource Utilisation in Urban Systems.*Royal Society Open Science*, *7*, 200087.

Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectiveness across urban systems.

1.1. Chapter introduction

Cities are enablers of economic growth, sinks of resource consumption and major contributors to global energy consumption and greenhouse gas emissions. Resource use in cities plays a key role to maintain the metabolism and proper functions of urban systems, in exchange for delivery of products or services and wealth generation through economic activities. Improving how cities utilise their resources is important for maximising the use of limited resources available to reduce intake. Incentive for more effective use of resources in cities is instrumental to improve resource efficiency of urban systems and reduce extraction of new resources from the natural environment to promote sustainable development.

This chapter constitutes of an opening section (1.2) to address the sustainability challenges of cities which set up the research motivation of this work. The following section (1.3) covers the research questions, aims and objectives to achieve throughout this study. The last section (1.4) gives an overview of the whole thesis and outlines the narrative structure of all following chapters.

1.2. Sustainability challenges of cities

Cities are metabolic systems, like living organisms, that require inputs of natural resources to sustain the livelihood and growth of the systems. Undeniably as cities develop, the benefits create a desirable living environment in terms of higher education levels , job opportunities and infrastructure services. On the other hand, increasing population dwelling in cities leads to higher demands for resources in the forms of land use for housing, infrastructure facilities, provisions of basic services, and also in the forms of physical materials such as foods, fuels, and clean water to support all daily activities. Disposal of the by-products from urban metabolic activities, such as burning fossil fuels, exposes the well-being of the world's populations to health and environmental risks due to deteriorating air pollution and global warming as results of rapid urbanisation. These issues related to urban metabolism stress the needs to create a model for managing resource-efficient cities to achieve sustainable development.

Resource use has become a topical issue in discussing environmental regulations through urban governance and a central policy concern in the sustainable development plan for both developed and developing cities sharing the responsibility to protect the planet from environmental damage. To understand and monitor the metabolism of resource-efficient cities, the European Environmental Agency (2015, p.8) has recognised that "*one of the major challenges to overcome to achieve sustainable cities is minimising the use of resources and developing a circular model that recovers local waste closely in line with the needs of the local economy*". To address this challenge, this work studies the pathways of resource flows through interconnected urban processes to retain high-quality resources in the system and prolong the use of resources available in cities in an effective manner to achieve a circular urban metabolism for sustainable development.

1.2.1. Rapid urbanisation and resource consumption

Urbanisation is a global trend of continuously growing population residing in urban areas and increase in land use for urban activities. Since 1950, urban populations has increased from 751 million to 4.2 billion in 2018, which is equivalent to 55% of the total world population at that time (2018), and this proportion is expected to reach 68% by 2050, according to the population statistics released by the United Nations Department of Economic and Social Affairs (UN-DESA) (2019).

A report from the United Nations Environment Programme has warned further urbanisation could raise the annual intake of resources to nearly 90 billion tonnes through urban material consumption by 2050, that is a 125% increase from 40 billion tonnes in 2010 (Swilling *et al.*, 2018). If the demand for resources continues to grow, without an intervention, resource requirements of urban areas may exert tremendous strain on the natural environment, as an estimated four out of nine planetary boundaries have been surpassed causing irreversible change to the environment (International Resource Panel, 2017; Rockström *et al.*, 2009; Steffen *et al.*, 2015).

To create a long-term sustainable living environment in cities, urban consumption patterns must be reorganised and regulated through more effective ways of using the existing resources to reduce the demands for new material extraction. This means a global transition towards low-carbon resource-effective cities is crucial in urban governance to stay within the planetary boundaries and be in line with the Sustainable Development Goals (SDGs) (United Nations, 2015a).

1.2.2. Decoupling growth from resource consumption

Due to rapid urbanisation and population growth, cities' demands for resource intakes have substantially exceeded the biocapacity of how much they could generate. In 2019, the World Overshoot Day lands on 29th July, the earliest ever according to the Global Footprint Network's (GFN) (2019) accounts. It marks the date when humanity has consumed more ecological resources than the earth can generate in the entire year. This is akin to consuming all of the resources generated by 1.75 Earths in one year due to humanity's ecological footprint. To assess sustainable development, Figure 1.1 shows the correlation between nations' ecological footprint (in number of Earth) and Human Development Index (HDI) which acts as a proxy to measure human well-being (where HDI above 0.8 indicates achievement of "living well") based on three criteria: education level, life expectancy and economic income (GFN, 2013).

Urbanisation and increasing resource intakes by cities are phenomena to generate economic growth and social benefits for improving the standards of living. It has been established by UN-DESA (2019, p.1) that "*urban growth is closely related to the three dimensions of sustainable development: social, economic, and environmental*". Progress towards sustainable development can be measured by monitoring its two core components: (1) economic and social development and (2) environmental sustainability (GFN, 2019). The New Climate Economy (2014) has reported that urban economies generated 80% of the global gross domestic product but also contributed 70% of the global energy consumption and greenhouse gases emissions. Developed and high income cities have significantly exceeded planetary capacity (Calcott and Bull, 2007). Revisiting the City's Limit report (Forward, 2002), the ecological footprint of London is 49 million global hectares, which is equivalent to 42 times the city's biocapacity and 293 times of its land area (twice the size of the UK). This means if everyone in the world consumed natural resources at the same rate as the average person in the UK, three planets would be required to support this standard of living (Bioregional, 2018). Projections show 91% of global consumption growth from 2015 to 2030 will be generated by people living in cities due to increasing household incomes and consumer spending (Dobbs *et al.*, 2016). Urban lifestyle and disposal of fast-moving consumer goods also accelerated municipal waste generation (Ellen Macarthur Foundation, 2013).

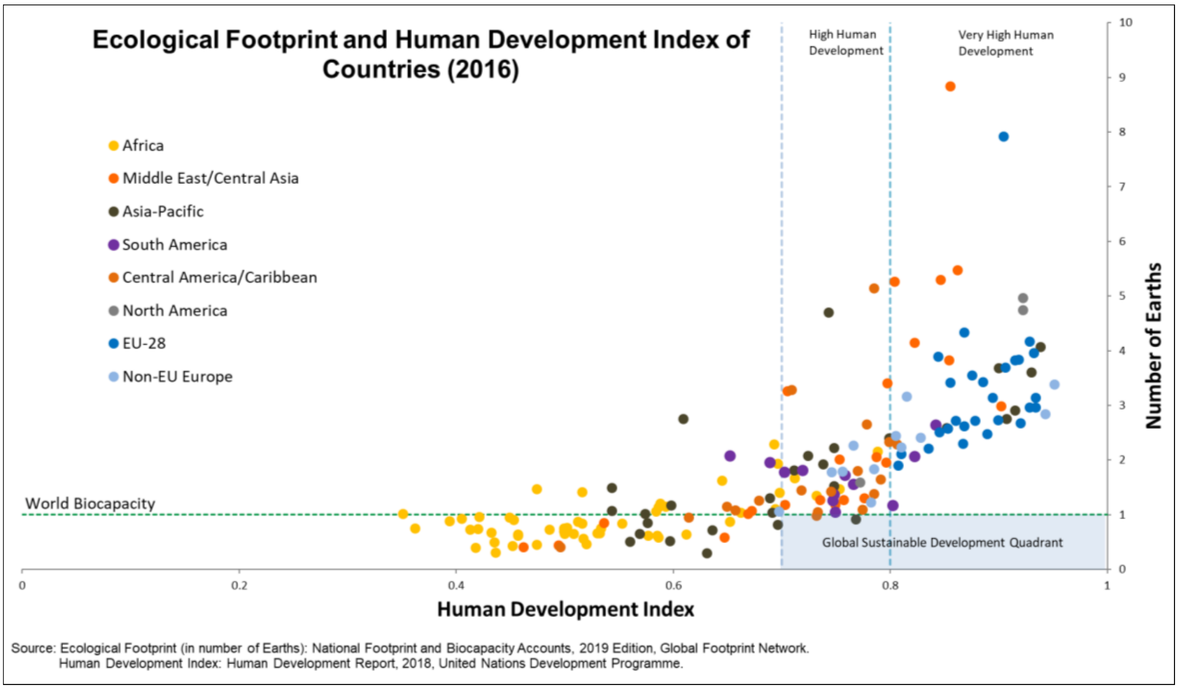

Figure 1.1: Ecological footprint and HDI of countries based on 2016 data, image sourced from GFN (2019).

For a limited amount of resources available, maximising the work done extracted through effective resource use serves as a catalyst for decoupling urban economic growth from resource consumption in cities to achieve the same targets with less resource inputs. To enable this, new standards and methods need to be introduced to move urban economies from a linear-consumption model to a circular-regenerative model. A systematic change is required to reduce economic dependence on natural resources in a long-term development plan for sustainable growth.

1.2.3. Towards the Sustainable Development Goals

Sustainable development is perceived as a major challenge in the trends of global urbanisation and strategic resource management remains as a key consideration of environmental policies for planning resource distribution in cities. As part of the United Nation's (UN) sustainable resolution, *Transforming our world: the 2030 agenda for Sustainable Development* (UN, 2015c), countries in the UN agreed to adopt the SDGs with a shared global mission to bring an end to poverty, protect the planet and ensure prosperity for all. As the world's urban population continues to rise, demand for natural resources is expected to accelerate with the pace of urbanisation to meet the growing needs for materials and essential services such as housing, transportation, communication, energy systems, education and healthcare. To address these sustainability challenges, a collection of 17 global goals is included in the blueprint for sustainable development, intended to be achieved by 2030, as shown in Figure 1.2.

Figure 1.2: The 17 Sustainable Development Goals designed as part of the UN's 2030 Agenda for Sustainable Development to secure a better future for all, image sourced from UN (2015a).

These goals are all interconnected and designed to link the challenges related to climate change, environmental degradation, inequality, poverty, peace and justice issues. Out of all 17 goals created, two goals to be highlighted in this work are:

- **SDG 11**: Make cities inclusive, safe, resilient and sustainable
- **SDG 12**: Ensure sustainable consumption and production patterns

In addition to the SDGs above, the following two goals are also relevant to the wider contexts of this work:

- **SDG 8**: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- **SDG 10**: Reduce inequality within and among countries

Meeting the SDGs is challenged by current consumption patterns and the rapid trends of global urbanisation. These goals are aiming at making cities a better place to live and at the same time, encouraging urban regulations to take the responsibility for their resource consumption and waste production.

1.2.4. Research motivation

This research is driven by the lack of understanding of the supply and use of resources in cities with the change in its physical and chemical energy contents during the resource delivery to its final end-users. In most cases, resources are imported into cities and delivered through a series of exchanges and transformations in its energy supply pathway to maintain the cities' functions and promote economic growth, resembling an open system in an analogy between cities and thermodynamic systems. The thermodynamic analogy is sometimes employed in other fields to resemble physical processes in energy systems and the concept of exergy is hence established as an extensive thermodynamic property derived from the studies of energy transformation. Although such analogy may be regarded as metaphorical and not literally applicable outside the realm of energy systems, it offers a qualitative descriptor to account for availability of work and irreversibility of thermodynamic processes for assessing resource efficiency and environmental sustainability. Moreover, the network of resource flows in cities possess high degrees of complexity and uncertainty as it is constantly changing with the interdependencies of urban socio-economic processes and dynamics of flows among the sectors. This means resource connections in the urban network play a significant role in influencing the cities' performances on their patterns of resource use and economic growth.

Strategic resource management and waste reduction can be achieved by incorporating the principles of circular economy in the urban network to harness useful materials from the waste streams through regenerative system to create a circular urban metabolism. The current measures of resource planning and the existing tools for assessing urban resource sustainability focus on measuring material consumption and capturing emission data (UN Statistical Commission, 2017), rather than describing the states of resource utilisation in cities and evaluating the work done delivered from the resources available to achieve higher resource efficiency. Urban dwellers are urged to address the challenges by reformulating their sustainability objectives to achieve decoupling of economic growth from resource-intensive activities in cities. As such, new tools and methods for understanding and assessing urban sustainability are imperative to ensure decision-making drives our societies towards these goals.

1.3. Research question, aim and objectives

From the resource use problems and research motivations stated in Section 1.2 that highlight the issues of urbanisation and the sustainability challenges in cities, the next step is to set up a research question that defines the research scopes. The research question for this work is: *How much of the resources available in cities is effectively consumed due to thermodynamic utilisation and energy degradation as the results of metabolic flow exchanges in the urban ecological networks?* This will be explored and answered by measuring the effectiveness of urban systems which assesses the ability of a system to utilise high quality energy by extracting work done from resources available and convert the resources into economic benefits.

This project tackles the urban sustainability problems from the ecological-thermodynamic perspective of a city. Understanding flow exchanges within an urban economy helps in accounting for the actual needs of consumers and losses in the flow pathways to give an insight into cities' performances and inform the decision makers for strategic resource management. The outcomes of this research can act as a novel urban resource sustainability assessment framework and assist the policymakers in implementation of new energy and environmental policies to regulate the consumption and production, and to encourage sustainable resource use management for urban development.

The aim of this work is "*to develop a novel ecological-thermodynamic approach for accounting resource flows in urban systems and evaluating the ability of the systems to extract the maximum work done from resources available in cities*" in order to reduce the needs of extracting new resources. To achieve the aim, the following objectives are listed in the following order corresponding to the contents in Chapters 2-6:

1. Review the scholarly research literature in the related fields to conceptualise the ecological-thermodynamic approach as an industrial ecology method in the urban metabolism framework to assess urban sustainability - **Chapter 2**
2. Inspect the advantages and drawbacks of the existing network analysis methods to study the metabolism of resource flows in cities - **Chapter 3**
3. Formulate a set of performance metrics for urban sustainability assessment based on the effectiveness of resource use in cities - **Chapter 4**
4. Investigate the effectiveness of resource use across the whole urban system including a single-city system - **Chapter 5**, and a multi-city system - **Chapter 6**

1.4. Thesis outline and structure

The narrative of the chapters in this thesis are organised as shown in Figure 1.3 to address the problem statement and research question, and to achieve the designated aim and objectives.

The following chapter, **Chapter 2**, presents a literature review of existing studies of the urban metabolism paradigm, as well as the applied methods in industrial ecology to analyse metabolic resource flows in cities. The literature review is summarised to outline the research needs to develop a resource effectiveness assessment tool for better understanding of urban processes and resource sustainability.

Chapter 3 presents a case study of all 35 cities in England and Wales to investigate intra-city metabolism of urban economies (monetary exchanges between economic sectors) by implementing ecological network analysis (ENA). The case study addresses the key shortcomings of ENA to assess the actual quantity of resource intake that is utilised by the cities.

This leads to the development of an open system network effectiveness analysis (OSNEA) as a novel assessment framework in **Chapter 4** which demonstrates the development workflow and the formulations of the performance indicators introduced in the analysis. A section for the data requirements to perform an OSNEA application is also included in this chapter.

To verify and validate the new framework developed in Chapter 4, **Chapter 5** applies OSNEA in a case study of Singapore representing a single-city model to account for the resource use based on the total aggregated imports and exports across boundary of the urban system. A comparison between monetary-based and exergy-based analyses is included in the results generated for this case study.

Next, **Chapter 6** extends the application of OSNEA by studying all 38 cities in the Great Britain as a multi-city model for the systems of cities. The findings reveal the taxonomy of resource use behaviours exhibited by the cities across the whole urban systems.

At the end of each chapter, a brief discussion and the intermediate conclusion are provided along with the case studies results to highlight the implications and limitations of the studies. In addition to these, **Chapter 7** provides a synthesis of the key findings and discussion in the earlier chapters to consider the practicality, applicability and versatility of the OSNEA method. The first part of Chapter 7 gives a general review to examine the practicality of the framework from an ecological-thermodynamic perspective. The second part addresses the limitations of the method and explores the opportunities to improve the applicability of OSNEA while the third part discusses the versatility of the framework to be applied as a universal urban sustainability assessment tool to investigate the effectiveness of resource use in cities.

Last but not least, **Chapter 8** concludes this work by emphasising the important contributions of this work and outlining the recommendations for potential research areas in future work.

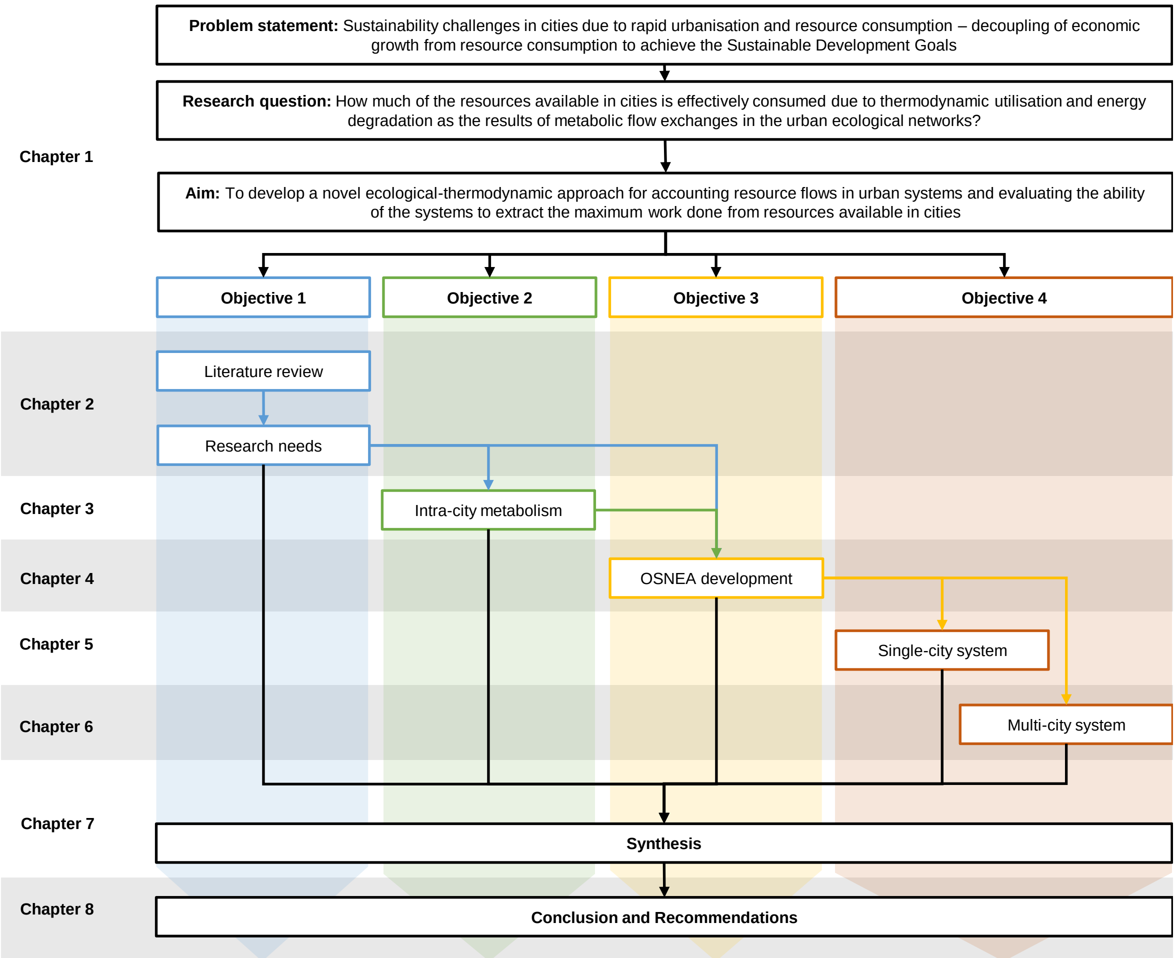

Figure 1.3: Outline of the thesis structure showing the flows of chapter narratives to deliver each of the objectives.

Chapter 2

Literature Review

The current chapter contains materials that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.

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Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectiveness across urban systems.

2.1. Chapter introduction

This chapter begins with a review of the urban metabolism concept in Section 2.2, introducing the main topic of this work and the conceptual development of the idea to establish a system-based analytical framework for studying the complex interactions between urban systems and the environment. This leads to the overview of a collection of industrial ecology applied methods (in Section 2.3) to manage energy and material flows through industrial consumption and production processes in an economy, and these sum up to make contributions to the implementation of circular economy in urban metabolism. Section 2.4 focuses on the thermodynamic analogy of urban systems as open thermodynamic systems, which rely on continuous input of resources from the external environment, to explain the emergence of self-organising behaviours in developing ecosystems in order to maximise resource utilisation of the system. Next, Section 2.5 provides a critical review of existing tools and indicators to assess urban sustainability in terms of the resource management to reflect the states of resource utilisation in cities and identify opportunities for improvements towards sustainable cities and communities. Lastly, Section 2.6 summarises the research needs based on the preceding literature review to address the gaps in current knowledge of understanding urban metabolism and methods for assessing resource utilisation in cities.

2.2. The concept of Urban Metabolism

The metabolic interactions between human society and nature was first discussed by Karl Marx in 1883 using the idea of metabolism to describe the exchanges of materials and energy in his critique of industrial capitalism (Marx *et al.*, 1981). The term "*Urban Metabolism*" (or rather "*The Metabolism of Cities*") was first used by Wolman (1965, p.179) with the definition given as "*all materials and commodities needed to sustain the city's inhabitants at home, at work and at play*". His work compares cities with biological organisms based on their similarities in terms of basic needs and mechanisms such that resource intakes are essential to perform work and by-products are emitted as wastes from the systems. He developed a hypothetical model for one million people to assess the flows of material supplied and waste produced from urban activities in response to deteriorating air quality and water pollution in American cities. This pioneering work on the concept of Urban Metabolism (UM) provides a fundamental framework to understand problems related to physical urban processes and develop solutions for sustainable cities.

In the era of rapid urbanisation, scholarly studies on developing the UM framework accelerated due to increasing urban resource use, the framework was expanded to applications in variable scales and wider scopes with more advanced and improvised strategies. Adaptations of industrial ecology with UM framework emphasises the importance of ecological and environment management to sustain a growing system (Girardet, 1996). The concept of "*Industrial Metabolism*" focuses on understanding the use of natural resources and their impacts on the environment to accelerate industrial transition towards sustainable practices (Anderberg, 1998). Some researchers interpreted cities as human-dominant, coupled, complex ecosystem governed by the complex interactions among its components which lead to a unique mechanism in shaping of the socio-ecological structure of cities (Andersson, 2006; Bai, 2016; Faeth *et al.*, 2005; Grimm *et al.*, 2000, 2008; J. Liu *et al.*, 2007). Further work on urban ecology revealed a strong link between UM and urban ecosystems by modelling the hierarchical metabolism of energy and material flows in cities (Bai and Schandl, 2010; Decker *et al.*, 2000; Newman, 1999).

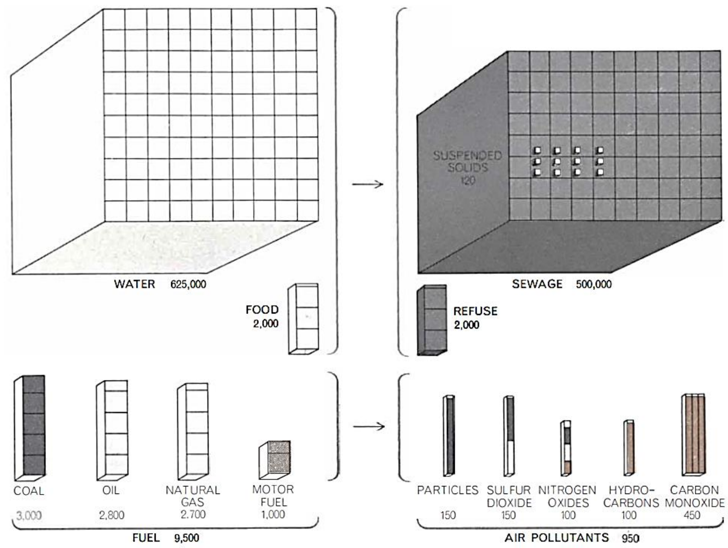

Figure 2.1: Wolman's hypothetical model for accounting urban metabolism showing the common inputs to cities including water, food and fuels consumed (on the left) and the particles emitted into the atmosphere as air pollutants (on the right), image sourced from Wolman (1965).

Within the research fields of industrial ecology, metabolic-flow analysis is of significant contribution in understanding UM by tracking the supply and use of resources in cities. Industrial ecology is a relatively young discipline for the study of materials and energy flows to understand how industrial ecosystem works and its interactions with the external environment. Kennedy *et al.* (2007, p.44) had given UM the definition, "*the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" in their study on sustainable urban design. In addition, scholarly reviews of the concept demonstrated a broad range of impactful applications of industrial ecology applied methods in the UM accounting frameworks to study sustainable resource management, environmental assessment and urban planning (Bancheva, 2014; Baynes and Wiedmann, 2012; Cui, 2018; Pincetl *et al.*, 2012; Y. Zhang, 2013).

To identify the wider scopes of related research areas, a bibliometric analysis is used to conduct an initial investigation into the coupling of the main topic "*urban metabolism*" using the Bibexcel shareware (Persson *et al.*, 2009). Figure 2.2 shows a co-occurrence map of top 10 author's keywords (with the highest co-occurrence frequencies) from a total of 628 records published in the period between 1990 to 2020, found on the Web of Science platform. Size of the nodes scales proportionally with the weighted-degree of each keyword and the thickness of the edges reflects the frequency of the co-occurrence between two keywords. The map shows the most relevant keyword to "*urban metabolism*" is "*industrial ecology*" followed by "*sustainability*" while majorities of the rest are related to industrial ecology methods and resource flow management in urban systems. These findings imply an interdisciplinary nature for the subject areas covered in this work.

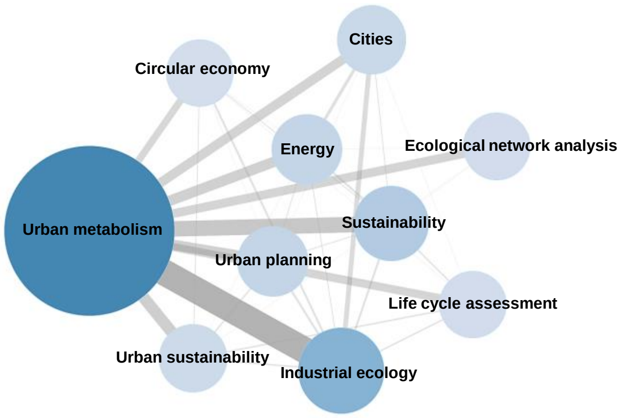

Figure 2.2: Co-occurrence map generated from a bibliometric analysis of keywords for the topic of "*urban metabolism*" (showing the top 10 keywords with the highest co-occurrence frequencies).

2.3. Industrial ecology approaches to Urban Metabolism

Sustainability has become an essential consideration of urban development with increasing pressure on the planetary limits, a wide range of industrial ecology approaches have been developed to analyse or to account for the metabolic performance of a city using the UM framework. These include material flow analysis, emergy approach, exergy analysis, life cycle assessment, input-output analysis and ecological network analysis. These approaches are closely related to the root of circular economy principles in the field of industrial ecology. Table 2.1 provides a summary of the industrial ecology methods applied in different UM case studies.

Figure 2.3: The global publication map captured from open source platform, Metabolism of Cities (2016), showing the locations of UM studies based on a total of 387 cities-linked publication records from the Global Urban Metabolism Database (Hoekman *et al.*, 2019).

Table 2.1: Summary of existing industrial ecology methods and indicators.

Method	Description	Drawback	Indicators and Examples
Material flow analysis	Quantifies material input-output across the boundary	Overly simplified and linear nature, ignoring the differential in qualities	Material inputs and emissions (Kennedy *et al.*, 2007), material consumption and production (Hendriks *et al.*, 2000b)
Emergy approach	Converts the energy embodied in different carriers into their equivalent solar energies	Neglects qualitative factors in derivations of material transformity	Emergy use (S.-L. Huang and Hsu, 2003)
Exergy analysis	Useful in resource budgeting based on the embodied energetic content in the conversion processes	Lacks unified conversion for waste products in the system	Exergy inputs and outputs (G. Chen and Chen, 2009), exergy conversion (Gong and Wall, 2016)
Life cycle assessment	Includes all direct and indirect resources consumed and impact in all life associated with the product	Not suitable for application at an urban scale due to inadequate data to build a life cycle inventory for all resource types	Life cycle impact assessment indicators (Goldstein *et al.*, 2013)
Input-output analysis	Accounts for all direct and indirect inputs as embodied energy in the products and waste	Requires large amount of data in specific format, data are published on an annual basis	Sectoral flows and consumption (Wang *et al.*, 2017, 2019), embodied energy in national final demand (Rocco and Colombo, 2016)
Ecological network analysis	Incorporates flow analysis by tabulating the inter-compartmental transactions as a matrix	Monetary transactions data is often used to estimate the weight of flows so may not represent the actual amount of resources	Total system throughflow (Finn, 1976), network environ properties (Yang *et al.*, 2014), spatial variations (Y. Zhang *et al.*, 2016)

Despite the abundance of UM case studies covering world-wide locations (as shown in Figure 2.3), the applications of UM resource accounting are often intended as flow-specific or case-specific to the particular implemented methods. This is due to the distinctive characteristics of each city in terms of socio-economic structures, climate conditions, biodiversity and data availability at a given timeframe (Bahers *et al.*, 2018; Forkes, 2007; Obernosterer and Brunner, 2001; Sun *et al.*, 2016; Sviden and Jonsson, 2001). Furthermore, Kennedy *et al.* (2011) have presented a chronological review of UM studies from 1965 to 2009, covering 27 cities across five continents, highlighting the unique contributions of these studies for better understanding metabolism of flows in cities. Examples of these include a comprehensive case study of Hong Kong by Warren-Rhodes and Koenig (2001) for its role as the centre of economic development in the region during 1971-1979, and a case study of Paris by Barles (2009) to study the metabolism of nitrogen flows due to increasing food consumption.

2.3.1. *Material flow analysis*

Material flow analysis (MFA) method can be used in tracking material flows across various spatial and temporal scales to gauge the pace of development and change in material demand. This is important for understanding urban resource consumption to facilitate economy transformation by decoupling service provision from material inputs (Pauliuk and Müller, 2014). MFA originates from industrial ecology where materials are taken into a system and transformed into different products while other residuals flow out from the system (Fischer-Kowalski and Hüttler, 1998). MFA is described as "*a systematic assessment of the flows and stocks of materials within a system defined in space and time*" based on the law of mass conservation (Brunner and Rechberger, 2004, p.3). By this definition, MFA serves as an accountant that determines and quantifies resource deposits and withdrawals from the system (Graedel, 2019). In short, MFA provides a quantification overview of input and output flows across the boundary of an urban space to gain an understanding of the environmental and economic functioning interactions with its surroundings (Bancheva, 2014), as illustrated in Figure 2.4.

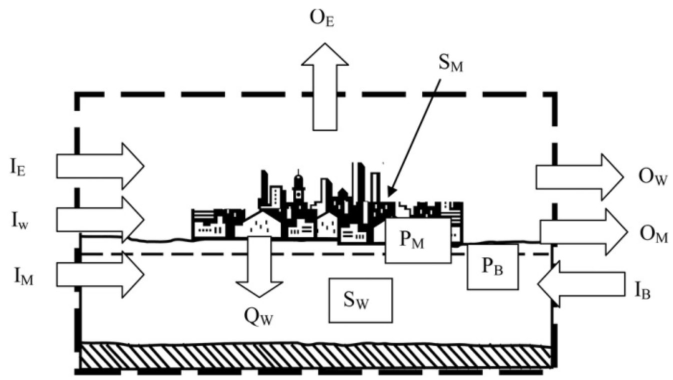

Figure 2.4: Schematic diagram of MFA showing inflows (I), outflows (O), internal flows (Q), storage (S), and production (P) of biomass (B), minerals (M), water (W), and energy (E), image sourced from Kennedy and Hoornweg (2012).

MFA is a well-recognised and commonly used method in the scientific community of industrial ecology for studying sustainable resource management strategies (Fischer-Kowalski and Hüttler, 1998; Hunt *et al.*, 2014; Schulz, 2007). The techniques of MFA has proven to be useful in improving environmental performances related to urban planning policies (Baccini, 1997; Barles, 2010; Niza *et al.*, 2009). Furthermore, MFA can be used to track the flow of a specific substance around a city including heavy metals in Stockholm (Hedbrant, 2001), Nitrogen in Paris (Barles, 2007) and Phosphorus in Chinese cities (G.-L. Li *et al.*, 2012).

The methods applied in present MFA case studies can be distinguished based on what data and how data is being collected and generally classified into four main approaches to MFA. Firstly, the top-down method refers to determination of material intake by using economy-wide inflow and outflow statistics over a series of time as aggregated inflow and outflow through a system. In economy-wide material flow analysis (EW-MFA), domestic material consumption is defined as the total amount of physical materials used in an economy, which is equal to the sum of all direct material inputs including domestic extraction and the imports, minus the exports (Krausmann *et al.*, 2011; Patrício *et al.*, 2015). In some studies, inputs and outputs of material flows are divided into categories of material groups based on material intensities of the products or emissions related to a specific economic activity to determine its metabolic rate and productivity (Fischer-Kowalski *et al.*, 2011; Kennedy *et al.*, 2009). This method can be applied to different types of material and the framework describing the method is documented in Eurostat's handbook for EW-MFA (Eurostat, 2018).

Secondly, the bottom-up method, as suggested by its name, collects the inventory of all items and traces the flows and stocks of materials at different stages of their life cycles from extraction to disposal present within a defined area or an bounded system (Brunner and Rechberger, 2004). In this approach, material intensity (quantity of material per capita, per unit area, per unit economic output) is often calculated based on the average amount of material input per unit item for a smaller sample in the inventory to estimate material flows and stocks by extrapolating the amount of materials to the total area in the whole system. For instance, urban construction stocks can be estimated from the material intensity obtained by studying the characteristics of typical building types and identify the quantity of each item in the sampled buildings then extrapolate to cover the whole area of the city (Shi *et al.*, 2012; Tanikawa and Hashimoto, 2009). Bottom-up accounts provide a static snapshot of the material stocks within the timeframe of a study, often with a time scale of one year.

In addition to the conventional top-down and bottom-up approaches, the third method, remote sensing, gathers static satellite readings of land surfaces which are usually processed using a geographical information system to identify the locations and spatial patterns of human activities (Tanikawa *et al.*, 2015). These observations give a preliminary estimate of the spatial distribution of in-use building stocks and intensity of urbanisation, filling the gap of data scarcity in some regions due to incomplete statistical data. Furthermore, night-time lights observing is an extension to the remote sensing technique utilising night-time lights observation data as a proxy for spatial distribution of in-use material stocks across different spatial scales of imaging resolutions captured on the satellite, including rural, urban, national, regional and global levels (H. Liang *et al.*, 2017).

Fourthly, in a dynamic MFA, relationships between material stocks and flows are assessed in a demand-driven model to simulate temporal changes and estimate the effects on past and future material use (Augiseau and Barles, 2017; D. Müller, 2006; E. Müller *et al.*, 2014). Dynamic modelling considers the demand and supply of materials in a long-term as well as the material replacement, mortality and lifespan of in-use stocks (Heeren and Hellweg, 2019). Extracting retrospective historical data of inflow information in the model results in an accumulative sum of total stocks built up within the system and combining with the outflow from the past data gives the result of net material addition (Fishman *et al.*, 2014). For a prospective approach, dynamic modelling offers insights of future patterns of material stocks and flows to support sustainable development and provide early warnings of environmental risks for crossing the planetary limits (T. Huang *et al.*, 2013).

Although MFA serves as one of the most common techniques used in UM studies to improve urban environmental planning (Hendriks *et al.*, 2000a; Niza *et al.*, 2009), a critique of MFA arises due to its overly simplified and linear nature, hence ignoring the differential in qualities of material which is a crucial in configuring material transformation processes (Barles, 2010; Kennedy *et al.*, 2007). The fundamental MFA method is arguably a "*black-box*" technique lacking details of the internal topologies and differential of material qualities. In a top-down approach, the system is conceptualised as a "*black-box*" bounded within the defined urban spaces to measure system throughflow from the net differences between total inputs and outputs. The bottom-up approach investigates in-use stocks through surveys or questionnaire to acquire details of the itemised materials, but the data collection often takes a long duration. Moreover, reliability of MFA method should be taken into account carefully as drawing assumptions and extrapolations to estimate the amount of materials often subject to accounting errors and uncertainties. The remote sensing approach provides a convenient tool to capture a large area but does not hold information of the age and composition of material types in the satellite images, and also very much relies on the availability of data sources.

2.3.2. Emergy approach

In the UM framework, metabolic-flow accounting methods fundamentally comprise of energy and material flow analyses. In addition to MFA, an emergy approach, developed by Odum (1971, 1975, 1983) in his theory on the functioning of ecological system, is established based on the concept of embodied energy in the flows of certain materials. It converts different types of resources into their equivalent solar energy to a single standardised unit called *solar emergy joule* by considering the solar transformity of these materials (as shown in Figure 2.5). This allows researchers to combine and compare the flows using a unified objective function in the flow unit of emergy. In a case study of Taipei metropolis, Huang (1998) applied the emergy approach to investigate the energetic hierarchies and ecological economics of the urban ecosystem.

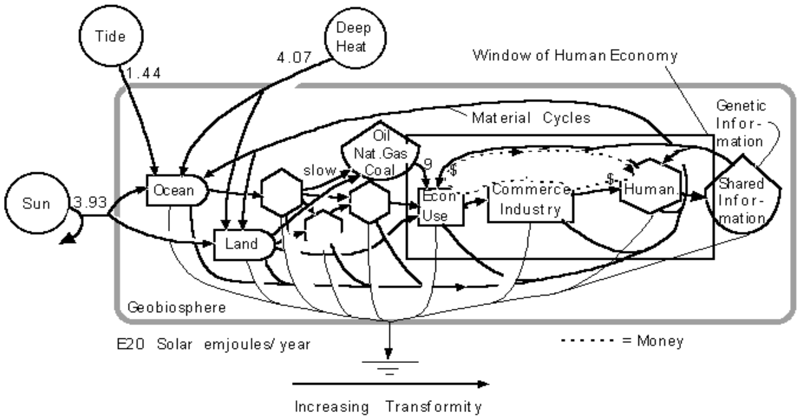

Figure 2.5: Aggregated view of the main energy hierarchy for emergy evaluation, image sourced from Odum (1998).

The concern for such approach lies on the use of an appropriate measurement in converting the units of energy and must be determined for all flows to ensure a unified standard and consistency of results. It is also lacking a unified procedure to determine the embodied energy of waste products.

2.3.3. Exergy analysis

In the regime of societal flow analysis, exergy-based resource accounting methods emerged as a convenient tool to model complex ecological systems by using the concept of exergy as a unified measure inclusive of both quantity and quality of resources (Ayres *et al.*, 1998; Finnveden and Östlund, 1997; Gong and Wall, 2001; Lozano and Valero, 1993). In relation to the thermodynamic principles of irreversibility and work availability, exergy is generally defined as "*the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment*" by Sciubba and Wall (2007) to reflect the level of resource availability. The origin of exergy can be traced from Carnot's (1824) statement of "*the work that can be extracted*" and Gibbs's (1871) availability function of "*available energy*" until the term "*exergy*" was first used by Rant (1956). Some early contributions are derived exergy values in fuels (Baehr, 1979) and optimisation of heat exchange processes (Bejan, 1982). Sciubba and Wall (2007) have presented a commented history of exergy from the beginnings in their work.

According to the Second law of thermodynamics, the gradient of exergy destruction is proportional to the amount of entropy produced. The term "*exergy destruction*" refers to the dissipated work in an energy conversion process due to irreversibility (Nicolis, 1977). This is then linked to the evaluation of exergy efficiency using the ratio of exergy input to output of a process (Szargut, 2005). Theoretical development of the concept contributes to a more thorough understanding and broadens its applications from chemical processes of combustion to loss mechanism in engineering devices (Çomakli *et al.*, 2004; Saxena *et al.*, 2013; Som and Datta, 2008). These require a standard notation system for exergy conversion from common energy and hence, Szargut (1989) has introduced a system whereby the primary energy can be converted to exergy via "*chemical equivalent*" conversion factors for different energy carriers (such as fossil fuels and renewable energy sources), as demonstrated in Figure 2.6. Such method of accounting exergy cost and cumulative exergy consumption (CExC) of chained processes provide a useful tool as part of an exergy analysis to study complex energy systems (Valero, Lozano, *et al.*, 1986; Valero, Muñoz, *et al.*, 1986; Wall *et al.*, 1994).

Exergy analysis has evolved as a powerful tool in various engineering applications to improve their performance in terms of industrial efficiencies by considering thermodynamic irreversibility stated in the Second law, which was neglected in traditional energy analysis based on the First law only. However, there is no formal procedure to evaluate and optimise system performance (Tsatsaronis, 1999). For studies on complex systems like cities and the interconnected flows within the open system networks, exergy analysis is not sufficient to account for UM performance from the socio-economic-environmental aspects of the society and for planning purposes.

For the purpose of exergy budgeting, an extended-exergy accounting (EEA) method was developed (Sciubba, 1999, 2005) as an approach to industrial ecology to include the non-energetic externalities in an industrialised society such as labour, capital and environmental remediation costs associated with the processes. The concept of EEA resulted from significant efforts by Sciubba (2001) for optimising the design of thermal systems, and then revised by Rocco (2014) to implement the input-output methodology in the accounting for open system flow exchanges among the components of an ecological network. The EEA framework integrates thermo-economics in CExC accounting to allow quantifications of non-energetic flows such as labour workforces and capital funds due highly active economic activities in a region. It can also act as a direct measure of environmental impacts resulted from industrial processes or complex systems. In general, EEA provides a comprehensive tool for measuring consumption of "*extended-exergy*" based on the equivalent exegetic value of primary flows as well as the socio-economic-environmental production factors in UM modelling. The applications of EEA in UM-related studies have been verified through case studies of societal metabolism (Dai and Chen, 2011; Sciubba *et al.*, 2008).

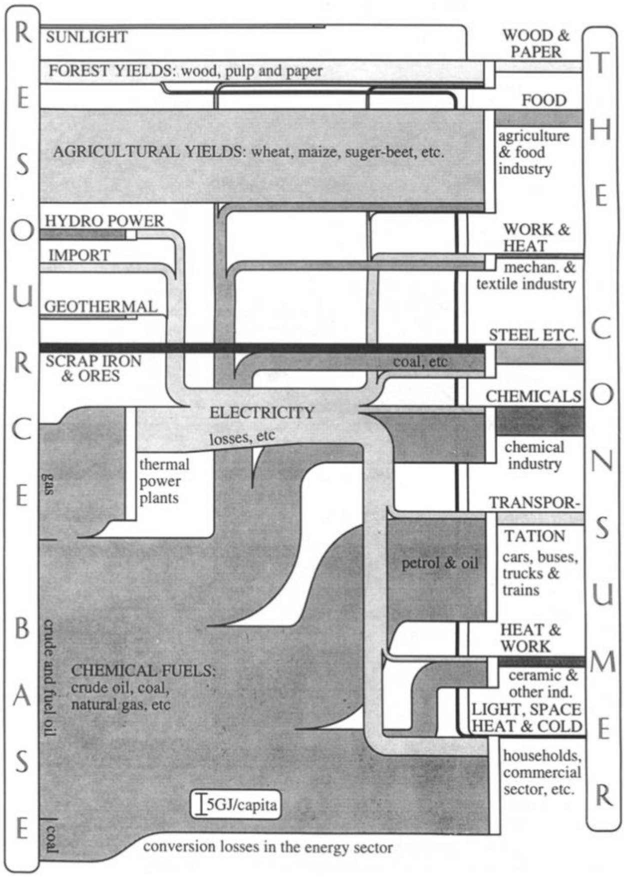

Figure 2.6: Exergy conversion system in the Italian society in 1990 to account for the total input and net output of resources, image sourced from Wall *et al.* (1994).

Exergy analysis and EEA can be applied in multi-scale resource accounting, ranging from industrial sectors (Cooper *et al.*, 2017; Dincer and Rosen, 2004; Manso *et al.*, 2017) to complex systems in a built environment (Causone *et al.*, 2017; G. Liu, Yang, Chen, Su, *et al.*, 2011), nation-wide societies (B. Chen *et al.*, 2006; Ertesvåg, 2005; Gong and Wall, 2016; Hammond and Stapleton, 2001), or at the global and planetary levels (Nakićenović *et al.*, 1996; Rocco *et al.*, 2018; von Spakovsky and Frangopoulos, 1993). Since EEA is a relatively young methodology and hence, the use of EEA has not been fully explored and could possibly become a standard engineering accounting method for studying societal metabolism and tackle resource-related problems in cities due to rapid urbanisation.

2.3.4. *Life cycle assessment*

Life cycle assessment (LCA) is also known as "*cradle-to-grave*" analysis as it provides a full life-cycle accounting of all direct and indirect resources consumed and the environmental impacts associated with all life stages involved in a process from material extraction, processing, manufacture, distribution, use and final disposal. Compared to MFA, LCA covers all processes in the entire life-cycle while MFA investigates the quantity of material flows at different life stages (Y. Zhang, Yang, and Yu, 2015). LCA is formalised and documented in the International Organization for Standardization (ISO) as standard 14044 with a definition, "*A systematic tool for identifying and evaluating the environmental aspects of products and services from extraction of resource inputs to the eventual disposal of the products of its waste*" (ISO, 2006). In the case for UM, LCA accounts for all metabolic activities in cities including construction, transportation and waste management to assess the environmental impacts resulted from these activities, as shown in Figure 2.7. The impact assessment stage involved measuring and characterising the impacts as mid-point impacts (with physio-chemical indicators) and end-point impacts (with socio-economic indicators). The impacts considered in LCA include climate change, land use, resource depletion and human toxicity potential.

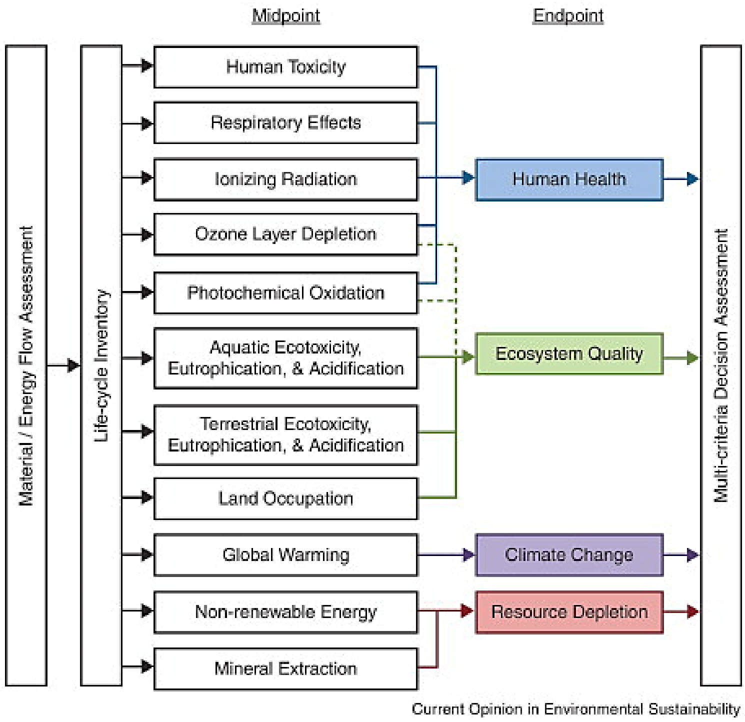

Figure 2.7: An integrated model of UM and LCA to evaluate life cycle impacts from assessments of energy and material flows in cities, image sourced from Chester *et al.* (2012).

LCA is applied as an accounting tool for materials and wastes associated with UM processes in different cities such as Beijing, Cape Town, Hong Kong, London, Toronto (Goldstein *et al.*, 2013). The main limitation of LCA is the data-intensive requirement as the method is heavily dependent on the availability of data as it requires data collected at all stages of the life cycle and very time-consuming, especially at the urban scale.

2.3.5. Input-output analysis

For input-output analysis (IOA), the techniques are adapted from Leontief input-output model (W. W. Leontief, 1951, 1986) which was developed to analyse the interdependence of the industries in an economy based on economic data. IOA traces all direct and indirect inputs of metabolic flows embodied in the products and services delivered (Rocco *et al.*, 2018; Rocco and Colombo, 2016), as well as the waste emitted. (S. Chen *et al.*, 2010; S. Liang and Zhang, 2012; Lindner and Guan, 2014). The economic data is tabulated in the form of a matrix or an input-output table (IOT) where the rows represent the supplying sides to account for the production of flows supplied to others while the columns represent the receiving sides to account for the consumption of flows received from others. IOTs show the flows of final and intermediate goods and services according to industry outputs (industry-by-industry) to describe the sale-and-purchase relationships between the producers and consumers within an economy (Organisation for Economic Co-operation and Development, 2020). In contrast, a supply-and-use table (SUT) records the production and consumption of commodities according to product outputs (product-by-product) instead of industries like IOT. The final expenditure of the entire economy includes private consumption of domestic households, capital formation and exports. Value added from the economic activities is also added as primary input to the industries which is considered as an economic resource. Figure 2.8 shows a comparison between the structures of IOT and SUT.

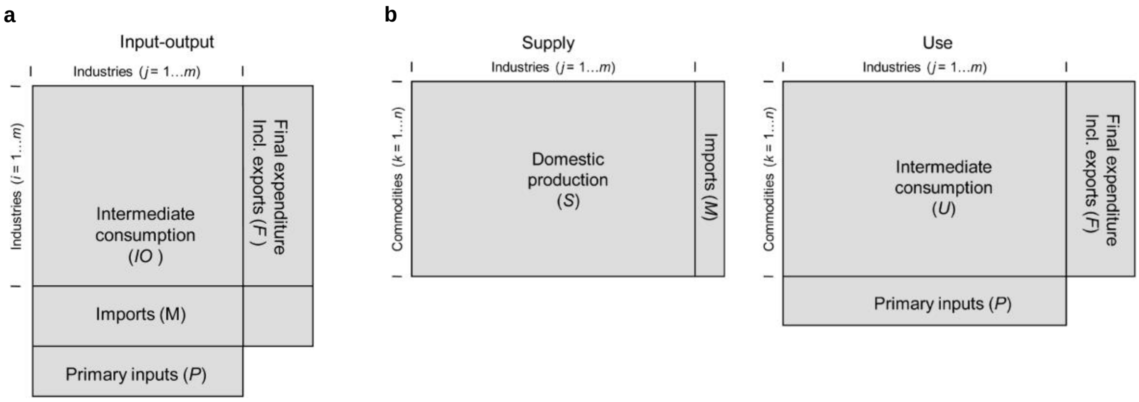

Figure 2.8: Comparison between (a) IOT and (b) SUT, showing the structure of the tables including the consumption, production, final expenditure and primary inputs of the economy, image adapted from Kazemier *et al.* (2012).

Nearly all of the earlier IOA applications are based on monetary flows as a unified measure to account for flow exchanges between the industrial sectors within an economy (Bailey *et al.*, 2004). This is because of the lack of data accounting for physical flows at a large scale, such as an entire urban system or at the national level (Bullard and Herendeen, 1975). For this reason, most of the existing statistics and databases for IOA are compiled in monetary terms.

From the conventional monetary input-output model, the principles of IOA have been adapted and expanded to different variations of analytical frameworks which offer a complementary extension to provide extra components such as spatial and temporal scaling, impact analysis or a combination of flow types to study the metabolic flows through an urban system and the associated environmental impacts. For example, physical input-output tables (PIOTs) and physical supply-and-use tables

(PSUTs) comprise of the actual quantity of resource outputs in the physical units of a product such as mass, volume or the unit for energy equivalents (Heun *et al.*, 2018; S. Liang and Zhang, 2012). Following the principles of mass balance, the PIOT framework allows integration of different data sources to account for various quantities of resource flows such as commodities trade flows, industrial output production, energy carriers, waste recycling and emissions (Hoekstra and van den Bergh, 2006). These form the foundation to the environmental-extended input-output (EEIO) model to enable evaluation of the associated impacts due to environmental externalities in the analysis such as extraction of natural resources from the environment and carbon emissions from human activities (Kitzes, 2013). For instances, some UM case studies (Dias *et al.*, 2014; Larsen and Hertwich, 2010) demonstrate the application of EEIO application to assess the associated environmental impacts of intensive municipal economic activities and identify the target areas or the sectors causing those impacts. Furthermore, economic input-output life cycle assessment (EIO-LCA) model is a combined technique to assess economy-wide industrial activities by tracing all direct and indirect environmental impacts associated with the products and services from the industries throughout their life cycles (Ochoa *et al.*, 2002).

At broader scales, a multi-regional input-output (MRIO) model is proven to be a useful tool for analysing global trade links across an interconnected network of complex systems to derive consistent and comprehensive data on traded commodities and resource consumption (Bruckner *et al.*, 2012). The MRIO models have been applied in existing studies to estimate the environmental issues associated with carbon dioxide emissions, air pollution, land use, energy consumption and carbon footprint embodied in international trades across multiple countries and continents (Lenzen *et al.*, 2004; Wiedmann, 2009, Y. Zhang, Zheng, Yang, *et al.*, 2015).

To evaluate energetic contents of the flows, the input-output matrix is treated with the embodied energy intensity of their respective product types. This approach enables a comprehensive estimation for production and consumption of UM by considering the input–output table as a matrix representation of an economy (Wall, 2003). Integrating exergy analysis in IOA allows the network analysis of UM to be conducted at an elevated level with the additional extended production factors of an urban ecosystem. Thus, this suggests a more complete and robust UM assessment method based on exergy cost theory and efficiency of energy conversion system using exergy data (G. Liu *et al.*, 2010, G. Liu *et al.*, 2012). Rocco's (2016a) formulation of exergy-based input-output analysis (ExIO) provides a systematic evaluation to the exergy cost of goods and services delivered through a thermodynamic characterisation of the resource flows in an economy.

In UM-related case studies, urban-level IOA can be applied to assess the distributions of one or multiple types of substances at the same time for different regions to enable comparison between different cities (Mi *et al.*, 2019; Zheng *et al.*, 2019). This method provides an alternative in accounting energy and material flows to assess UM, however, the drawbacks of IOA would be its strict requirements on the format of data entry. The limitations of data availability at city-level add constraints on the study as well as the high level of complexity and time taken to combine all energy and material flows related to UM assessment.

2.3.6. Ecological network analysis

For analysing complex urban metabolic systems, network approaches have been adopted to assess resource distribution within urban ecosystems. From the perspective of ecological networks, urban ecosystems are governed by the complex interactions among its components which lead to a unique mechanism in shaping of the ecological structure and social communities of a city (Bai, 2016; S.-L. Huang, 1998; Newman, 1999).

In network approaches, urban systems are appropriately represented as inter-connected networks in many studies to investigate the functionality of the systems (Baynes and Wiedmann, 2012; Pincetl *et al.*, 2012). The formation of internal linkages, in the form of a multi-directional network, is constructed by connecting smaller entities within a system, sharing a similar hierarchical setting with a natural ecosystem. Hannon's (1973) theoretical work on the structure of ecosystems is an important advancement in ecosystem modelling by integrating with Leontief's input-output model (W. W. Leontief, 1951) in network analysis to study the direct and in-direct contributions at different trophic levels (such as the producers, primary consumers and secondary consumers in an ecosystem). Subsequently, the concept of "*environ*" was generated to study the behaviours of ecological networks (as shown in Figure 2.9) with the pre-determined input and output flows at each component (Fath and Killian, 2007) and a network "*environ*" analysis was developed by incorporating flow analysis (Finn, 1976; Jørgensen *et al.*, 1995; Patten, 1982) in network analysis to address the total system throughflow, average path-length and cycling index of the network.

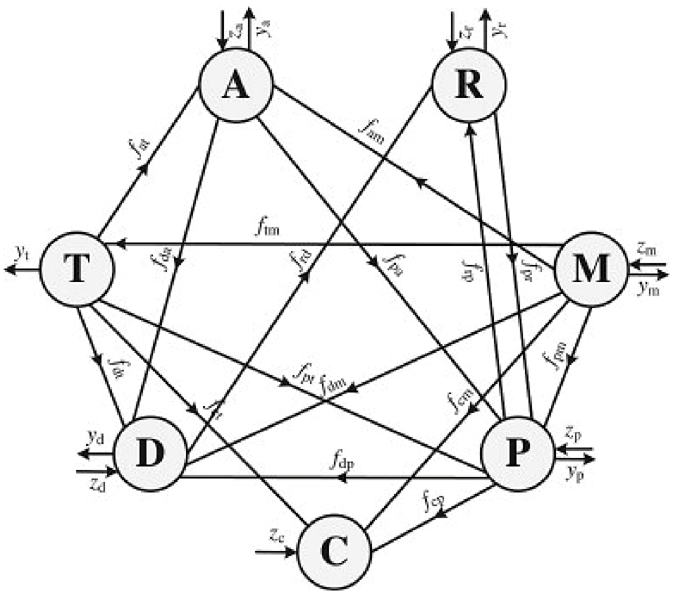

Figure 2.9: Schematic diagram of an ecological network with each node represents an economic sector and the arrows indicate flow direction, where f refers to inter-sectoral flows, y refers to exports out of the network and z refers to imports into the network through the sector, image sourced from S. Li *et al.* (2012).

Such development contributes to formulations of the functional analysis in ecological network analysis (ENA) to investigate the functionality and total system throughflow by tabulating the inter-compartmental transactions as an input-output adjacency matrix (Fath and Borrett, 2006; Y. Zhang *et al.*, 2010; Y. Zhang, Zheng, Fath, *et al.*, 2014). Among the industrial ecology approaches, ENA has been proven to be an effective tool in assessing the distribution of metabolic flows in the contexts of ecological relationships (S. Chen and Chen, 2015; Fan *et al.*, 2017; S. Li *et al.*, 2012; Yang *et al.*, 2014) and their spatial variations (Xia *et al.*, 2016; Y. Zhang *et al.*, 2016; Y. Zhang, Linlin, *et al.*, 2014). Moreover, ENA explores the dynamics of linkage formation in a resource flow network (Bodini *et al.*, 2012; J. Li *et al.*, 2018; G. Liu, Yang, Chen, and Zhang, 2011, 2012) based on the hierarchical structure and the interrelations between different trophic levels in an ecological pyramid.

ENA method dissects the problems of an urban ecosystem at each hierarchical level of the system based on its respective functioning roles and the rates of resource consumption. The technique of ENA is not limited to intra-system flows scaled on a single level such as city, region or country but also applied to study interregional energy flows between connected cities at combined levels, as demonstrated in the case study of the wider regions of Beijing-Tianjin-Hebei in China (Y. Zhang *et al.*, 2017). However, implementation of ENA at city level requires large amount of data at consistent granularity and strict format in terms of the flow units and sectoral classifications to conduct a reliable case study.

2.3.7. Implementation of circular economy in urban metabolism through industrial ecology approaches

The concept of circular economy (CE) has received increasing attention from the communities of industrial ecologists as an emerging framework to tackle the global sustainability problem through better informed waste and resource management strategies for creating a balanced integration of environmental resilience, economic prosperities and social inclusiveness for sustainable development. Ellen MacArthur Foundation (2017, para.1) stated "*a circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems*". According to the definition given by Geissdoerfer *et al.* (2017, p.759), CE is "*a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops*". A vast volume of scholarly reviews of CE evolves around conceptual development of the concept (Andersen, 2007; Blomsma and Brennan, 2017; Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2017; Morseletto, 2020), strategy implementation (Bressanelli *et al.*, 2019; Elia *et al.*, 2017; Kalmykova *et al.*, 2018; Schroeder *et al.*, 2019) and assessments of the indicators (Di Maio and Rem, 2015; Gravagnuolo *et al.*, 2019; Haupt and Hellweg, 2019; Helander *et al.*, 2019; Howard *et al.*, 2019; Iacovidou *et al.*, 2017; Ngan *et al.*, 2019; Saidani *et al.*, 2019; Sassanelli *et al.*, 2019). The purpose of CE, in general, seeks to reduce resource consumption and minimise waste emissions by extending the use of existing resources, closing the loops to retain circulation of materials within the system for as long as possible (Stahel, 2016), as shown in Figure 2.10.

The concepts of CE and UM are often interlinked with industrial ecology approaches, as shown in bibliometric map of those keywords in Figure 2.2. In the current UM framework, implementation of CE principles at the urban level is useful to facilitate the transition from linear metabolism to circular metabolism in order to relieve the pressure caused by resource intensive economic activities in cities, healing the cities by making use of resources locally (Girardet, 1996). For instance, Kalmykova and Rosado (2015) have adopted an UM framework (using the findings from industrial ecology methods such as LCA and MFA) to inform the CE design in cities by quantifying the flows and connecting the stakeholders based on the life cycle impacts with drivers of the flows to support strategic interventions. Lucertini and Musco (2020) have proposed a new framework called "*Circular Urban Metabolism*" to simplify the complexity for integrating CE principles in the UM framework in order to provide a resource management tool for redesigning urban activities within the urban-rural space through time. Other scholarly contribution includes a case study on the role of renewable energy in the promotion of circular urban metabolism and sustainable urban energy management system to reduce the cities' dependence on non-renewable resources (Barragán-Escandón *et al.*, 2017). These works are among the efforts devoted to foster the idea of circular cities through implementation of CE initiatives in the urban transition agenda for sustainable development (Prendeville *et al.*, 2018).

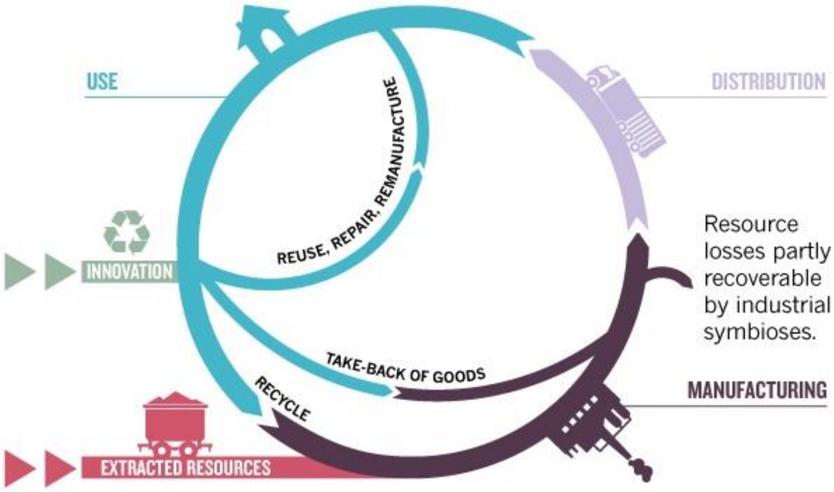

Figure 2.10: CE framework for closing the loops in industrial ecosystems and minimising waste by extending the manufacturing, distribution and use cycles of goods, image adapted from Stahel (2016).

For economy-wide applications, the development of CE models has provided a practical tool for measuring the circularity of metabolic resource flows within a system. In this context, Mayer *et al.* (2018) have developed a framework to monitor economy-wide CE progress towards closing the circularity loops in the European's Union. Their work provides a comprehensive picture of material loop closing across all types of material flows used by the society which is scalable (to the urban or sector level) to highlight the hotspot of resource flows or any under-performing industries in the economy. Besides this, Arora *et al.* (2019) have conducted an city-wide case study for Singapore to estimate building stock in the urban system and assess material circularity at component-level to promote CE in the building sector. This also allows an analytical evaluation of the impacts of CE strategies in different sectors for various types of resource streams in an urban economy.

In an analogy to thermodynamics, the use of energy and exergy metrics acts as a complementary evaluation of resource efficiency in a metabolic system for monitoring CE progress to reduce demands for resource inputs of industrial processes (Cooper *et al.*, 2017). Such metrics brings great benefits in understanding the efficiencies of resource transformation by reflecting the embodied energy in the flows and estimate the potential energy savings of applying CE strategies. In a similar context, Huysman *et al.* (2017) have adopted the accounting of cumulative exergy extraction from the natural environment (CExENE) as an impact assessment method for developing a CE performance indicator in treating plastic waste.

In addition, the Ellen MacArthur Foundation (EMF) and ARUP company have jointly launched a project called "*Circular Economy in Cities*" (EMF, 2019) to explore the opportunities for implementation of CE in urban systems highlighting the potentials in the aspects of buildings, mobility, and consumer products to accelerate CE transition in future urban development. According to the hierarchy of resource use, CE strategies may be prioritised in the following order: prevention (including reduce, refurbish and remanufacture), reuse, recycle waste material, followed by incineration and lastly, resolved to landfill (Nilsen, 2017; Pires and Martinho, 2019). However, the main barrier to CE implementation lies within the technological constraints of preserving the CE values in waste materials and reprocessing the materials to produce high quality consumer goods at affordable economic and environmental costs with minimal inputs of new materials.

2.4. Cities as open system networks

Cities are often described as complex open systems where the intake of resources is heavily dependent on flows imported from regions outside cities (Bristow and Kennedy, 2013; Salat and Loeiz, 2011). Open thermodynamic systems allow cross-boundary exchanges of energetic and material flows with their external environments, as opposed to an isolated or closed system . For a bounded urban system, resource inputs from outside the system and outputs to other systems can be considered as inter-city or international imports and exports, whereas waste emissions are treated as wasteful losses ejected from the system. These imports and exports, together with input-output flows between the inner components, would fulfil the conditions of constructing an ecological flow network (Kay *et al.*, 1989) which can then be used to describe the distribution and utilisation of metabolic flows in the system with an open system network approach. Using a thermodynamic analogy to describe resource use in urban systems, Girardet (2014, p.69) has portrayed cities as "*entropy accelerators*" as "*they deplete and downgrade the resources they depend on, in the process of using them*".

The Second law of thermodynamics states that the total entropy in the universe always increases. In an irreversible process, the rate of entropy production is always positive when energy is being converted to work done (Bejan, 2006). In terms of exergy, quality degradation occurs as exergy is being destroyed in a dissipative transformation process. Applying thermodynamics laws to ecology, Kay's work on non-equilibrium thermodynamic framework suggests when the system is being forced away for its equilibrium due to external inputs (applied gradient), it will grow and evolve by developing more structures and processes to increase its total dissipation in order to maximise the use of resources (Kay, 1991; Schneider and Kay, 1994a). For an open system, the greater the inflows captured from outside, the greater the potential for degradation and dissipation (Schneider and Kay, 1994b). These are known as self-organisational behaviours in ecosystems, at which the rate of entropy production and exergy destruction increases with resource intake into the systems (Nicolis and Prigogine, 1977; Schneider and Kay, 1994a). Such realisations of thermodynamics principles are of significant importance in improving the design and efficiency of energy utilising systems (Morris *et al.*, 1994; Szargut, 2005).

Linking back to Kay's work (2000), thermodynamic flow networks can be portrayed as self-organising holarchic open (SOHO) systems due to their similarities in interrelated entities and trophic attributes, representing the hierarchical nature of an ecosystem. According to the observation from a conceptual model of SOHO system, the rates of resource utilisation and exergy destruction act as evaluating criteria for growth and development in an ecosystem. In summary, according to their observations (Schneider and Kay, 1994b), the organisational level of an ecosystem increases with further growth and developments, causing its characteristics to change so there is:

- More energy capture and higher exergy inflow
- More effective use of energy due to higher exergy destruction rate
- More flow activity within the system to increase the total system throughput
- Higher number of cycles and longer average cycle length
- Less outflow from the system

As such, in an urban metabolic flow network, formations of internal linkages are organised to create flow pathways to promote the operations of maximising dissipation and exergy destruction (Muller, 2000). Hence, a more developed network with higher structural density and flow activity are equipped with higher capacity to dissipate and destroy more exergy, as it being more effective in terms of resource utilisation. Bristow and Kennedy (2013) has devoted efforts on finding the right organisation structure to study the impact of network topologies on resource use .

Urban ecosystems are considered as self-organising open system networks formed by connecting exergy dissipating entities of the functioning socio-economic sectors in the cities (Kay *et al.*, 1999. The aforementioned self-organisational behaviours of ecosystems appear as an order for the systems to counteract the gradient of applied inputs by dissipating more exergy in response to any movement away from the equilibrium. Thus, the development of organisational level and exergy dissipating capabilities of such systems are closely related in the fundamental UM framework. Borrowing the techniques from ENA, such behaviours can be observed within the network's organisation of a natural ecosystem or an urban system by improving the rate of exergy destruction and entropy production for better resource utilisation. To avoid vocabulary confusion and to clarify the concept, Kay (2002) introduces the term "*effectiveness*" to address system's ability to destroy exergy where the definition of "*effectiveness*" is also used by Salat and Bourdic (2011, p.2) to describe "*how able the system is to fully use the high-quality energy (high exergy) and only reject a low-quality energy*".

Structural circularity and continuity in a network prolong the cycles of resource flows to promote more energy transformation and exergy destruction through cascading processes. From a thermodynamic perspective, cities grow as results from organisational development of urban ecosystems. The system capacity increases by developing longer pathways to retain and circulate metabolic flows in the system, allow passing on of useful resources to other sectors in the network to enhance intra-system flow activity (Bristow and Kennedy, 2015). In the interests of industrial ecology, the open system network approach is coherent with the principles of CE to reuse and recycle useful material for as long as possible, in order to maximise the use of resources imported into cities, and ultimately reduce the demand of extracting new resources (Butterworth *et al.*, 2013; Lee *et al.*, 2016).

2.5. Urban sustainability assessment

The importance of sustainability assessment at urban-level was addressed in the United Nations-Environment Report (Musango *et al.*, 2017) to lead a global shift towards sustainable resource efficiency, proposing an ecological approach on resource management using UM framework. The motivation of such assessment is to enable future projections of environmental footprint based on well-studied trajectories generated using historical data. This will provide a robust tool to assist the urban planners in setting a carbon budget to restrict the demand for resources, at the same time promote economic growth, and for the benefits of all in a long-term, to decouple economic growth from natural resource consumption and environmental impacts.

For accounting metabolic activities in cities, comparative studies of energy utilisation revealed that exergy analysis is a more suitable technique than energy analysis and capable of detecting inefficiencies of resource flow through an economy (Rosen, 1992, 2013). Exergy-based assessment is a powerful tool and indication of the limiting factors in resource utilisation, which could be due to technology constraints and consumer behaviours based on the hierarchical characteristics of different socio-economic sectors in the urban ecosystem (Dincer and Rosen, 2004; Rosen, 2007). For example, Gong and Wall described exergy as an ecological indicator in their comparative study of waste emitted from the production of polystyrene and porcelain mugs by taking into account of exergy destruction in the processes to evaluate the environmental harmfulness (Gong and Wall, 2001; Wall and Gong, 2001). Alternatively, ecological footprint (EF) is a commonly accepted indicator used in sustainability assessment of measuring the land area required to sustain a population's resource consumption compared to the biocapacity of the land available (Wackernagel and Rees, 1998). EF assessment has high degree of applicability and flexibility on the spatial scale, however as a "*black-box*" metric, it lacks of the information concerning the differential resource quality and functional diversity, as shown in Figure 2.11. Comparing to "*black-box*" metrics, "*grey-box*" metrics such as input-output analysis and network approaches offer higher transparency showing the internal structure and transformation processes, presenting a more precise indicator to assess the performance of complex urban systems (Ravalde and Keirstead, 2017b).

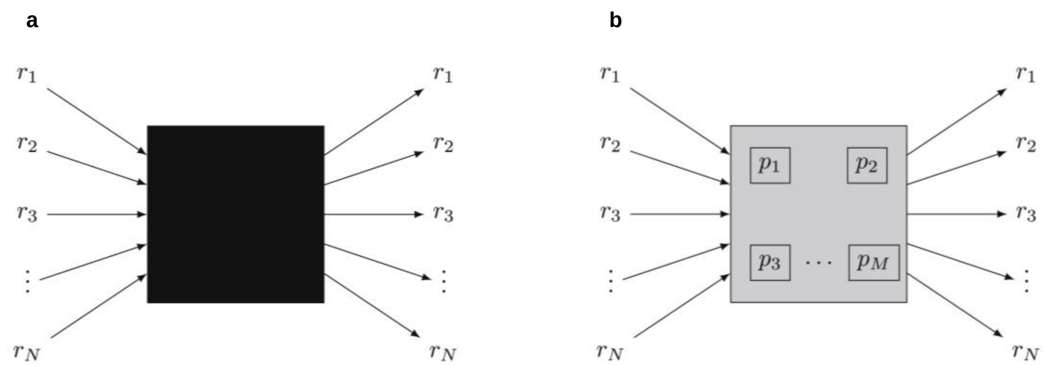

Figure 2.11: Schematic diagrams of multi-resource system showing (a) a "*black-box*" representation and the lack of transparency with no information of internal system processes, and (b) a "*grey-box*" representation with the internal linkages and transformation of resources, r_{ij} (where $i, j = 1, 2, 3, \ldots, N$) through M processes, $p_1, p_2, p_3, \ldots, p_M$ (where M represents the number of processing components in the system), image adapted from Ravalde and Keirstead (2017b).

In recent literature, sustainability assessment methods emerge as dedicated inter- and trans-disciplinary approaches by joining efforts from different academic disciplines to develop solutions for sustainable futures (Bourdic *et al.*, 2012). A wide variety of accounting tools has been developed to assess societal performance, and the choices of tool varied with the designated assessment priorities. Scholarly contributions to existing sustainability assessment methods can be broadly categorised based on the parameters used: monetary, biophysical and indicator tools (Gasparatos and Scolobig, 2012). In conjunction with the resource accounting methods in UM framework (for instances, the emergy approach, MFA, exergy analysis and EF), biophysical evaluation tools account for physical resources, land area, urbanised area and the climate conditions. Other than conventional monetary evaluation, socio-economic performances is also closely related to public welfare in terms of infrastructure provision and social equality, highlighting the interrelations between environmental, economic and social issues. These are also advocated to integrate UM studies to sustainability research through transformations in human well-being, economic activities, environmental health, and social justice (John *et al.*, 2019).

A multi-layered indicator set was introduced by Kennedy *et al.* (2014) with a collection of standardised parameters for UM investigations in megacities, however the framework presents a challenge in data acquisition especially in some of the middle- and low-income developing countries with fast growing populations (Kennedy and Hoornweg, 2012). For these reasons, among the UM accounting tools, many were developed in a data-scarce environment, nonetheless, developments and implementation of UM research are often subjected to assumptions limited by data availability and accessibility (Ravalde and Keirstead, 2017a).

The emergence of CE assessment tools shapes a new sustainability paradigm for governing and planning considerations concerning their influences on resource supply chain, industrial efficiency and economic productivity (Blomsma and Brennan, 2017; Geissdoerfer *et al.*, 2017). CE indicators offer an alternative perspective for practitioners and decision makers based on the resource throughputs and waste emissions from the economic activities to leverage urban resource and waste management. Assessment of CE strategies in cities is fundamentally related to the UM framework to track and monitor resource flows in industrial systems and urban ecosystems. Elia *et al.* (2017) have reviewed the performance metrics used in the UM methodologies to address the incompliance between the UM and CE frameworks in terms of their application levels. Furthermore, in a taxonomy of CE indicators developed by Saidani *et al.* (2019), they argue that many of the CE indicators at macro-level (city, region, nation and beyond) have a stronger focus on recycling waste than on other CE strategies. This aligns with a comparative case study by Guo *et al.* (2017) which assesses the CE development levels of four Chinese megacities (Beijing, Chongqing, Shanghai and Urumqi) with a unified indicator system based on resource consumption intensity, waste emission intensity, waste recycling and utilisation rate, and waste disposal level in the cities. From these, despite the growing interests of researchers and practitioners towards the CE paradigm, indicators and methodologies for adopting the CE strategies at broader application levels still require further development to enable CE assessment for measuring urban sustainability based on the states of resource utilisation and circulations in a complex urban network.

2.6. Summary of research needs

In this chapter, the literature review presented in previous sections have discussed different industrial ecology applied methods in existing UM studies and CE implementation (in Sections 2.2 and 2.3), together with a thermodynamic analogy to cities as open systems (in Section 2.4) and bringing these together (in Section 2.5) demonstrates the frontier of urban sustainability assessment in the current applications. **However, a framework that considers the differential in energy and material flows to evaluate the utilisation of resources imported into urban systems is absent from the existing assessments.** To fill this gap, the concept of exergy provides a medium for a universal indicator that is standardised based on thermodynamic principles to cover both energy and material flows in a multi-resource system, inclusive of both quantity and quality of the flow carriers, in order to perform a complete assessment on urban resource use.

UM is undeniably a powerful tool for complex system analysis and resource management planning to improve resource efficiency and accelerate the transition from a linear-to-circular economy. However, despite the sheer volumes of literature and methodologies developed on tracking and analysing resource flows, current understanding of the ecological behaviours of resource use in urban systems is still far from sufficient to move our cities and communities towards sustainable consumption.

Understanding the utilisation and conversion of exergy in urban processes would provide transparency to the transformation pathways of resource circulation among the components within the urban systems and the interactions between the systems and the external environment. In fact, one promising avenue is to use the open system network approach, which incorporates the ENA method and ecosystem theories into an urban network setting, providing an interface where cities can be managed as ecosystems to drive development in a more sustainable, liveable and resilient direction. The open system network approach shares similar principles with the practices of cross-sectors CE to retain and circulate resource flows within the urban systems for as long as possible in order to reduce the demand for new material intake, then gradually decouple urban development from resource consumption.

In summary, the following items highlight what needs to be done in the research fields to address the knowledge gaps in current understanding of resource use in an urban environment, and thereby to drive sustainable development in cities:

1. Development of an UM methodological workflow to construct an open system network framework for assessing the states of resource use in urban systems based on the total amount of resources imported into the cities - **will be addressed in Chapters 3 and 4**
2. Formulation and implementation of an exergy-based performance assessment tool for understanding resource utilisation and transformation in urban systems to evaluate the effectiveness of resource use through urban processes - **will be demonstrated in Chapters 4, 5 and 6**
3. Potential avenues and directions for future research and development of UM framework based the existing data as data availability remains the main constraint in many UM studies - **will be discussed in Chapter 7**

To address these, Chapter 3 will demonstrate the advantages and drawbacks of network analysis application in a case study to investigate the metabolism of urban systems and demystify the use of exergy-based accounting methods to describe the interdependencies and relationships within the socio-economic structure of cities. These will then lead to the development of an exergy-based assessment framework in Chapter 4 for evaluating the effectiveness of resource use in urban systems based on the data available for the timeframe of the case studies in Chapters 5 and 6. In addition, Chapter 7 will discuss the future prospects of UM concept to overcome the data constraints of the framework and extend the applications of the concept to promote urban sustainability.

Chapter 3

Intra-city metabolism of functional urban areas in England and Wales

The current chapter contains material that was previously prepared for the following articles:

Tan, L. M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.

3.1. Chapter introduction

This chapter presents an in-depth inspection on intra-city metabolism across an entire urban system by taking a network approach to construct a foundation for developing a novel open system network framework in Chapter 4. The ecological network analysis (ENA) outlined in Section 2.3.6 offers a practical and scientifically-supported method, incorporated with ecosystem theories, to analyse metabolic flows in complex ecological systems. In this chapter, ENA is applied in a case study to investigate the distribution of resources within 35 cities across the urban systems of England and Wales in 2011. Furthermore, to study the impacts of spatial distribution on the density of resource flows within a city, the urban flow networks are also supplemented with the geographical distance between the economic activities as a new feature added to the structural analysis of ENA. This provides a critical examination of the opportunities and obstacles in the application of network analysis for better understanding of resource demands and flow circulations within the local economy.

In the rest of this chapter, Section 3.2 explains the methodology adopted in the processes of data sourcing and preparation, followed by an explanation of the ENA methodologies implemented in this study. The results of metabolic relationships and network community structures are presented in Section 3.3. Finally, Sections 3.4 and 3.5 discusses the implications and limitations of this study.

3.2. Case study background and methodology

To understand the requirements on resource management and examine the metabolic characteristics of a city, ENA is applied on all 35 urban audit functional urban areas (FUAs) in England and Wales in this case study, as shown in Figure 3.1. ENA links the socio-economic sectors in an urban area to construct an inter-connected network and the analysis investigates the pairwise metabolic relationships through the intra-city monetary transactions to reflect the degree of urban sustainability in the ecological network in terms of its resource flows and consumption. The study is also extended with the estimated geographical distance between the economic sectors from their respective classification of workplace zones to address the spatial impact of the urban networks.

3.2.1. Data preparation

Input-Output Supply and Use Table for 2011 published by the Office for National Statistics (ONS) (2017c) is used in this study to give the estimates of UK national accounts of industry inputs and outputs as well as product supplies and demands. In order to examine the flows at a local scale, economic statistics such as gross value added (GVA) data (ONS, 2017b) of different sectors for each FUA are used to scale down the national flow data accordingly, assuming the same ratio for local production and consumption of goods and services compared to the national figures. This assumption is essential here due to the lack of inter-city flow data and may result in erroneous estimations of import and export values since international cross-boundary flows do not necessarily scale with the local GVA. Both import and export are treated with the same scaling method to minimise the error. For this analysis, the format of input-output data for all industrial sectors follows the structure of Leontief's (1986) model. The input-output monetary flows within the city are tabulated in the form of a balanced square matrix to construct an urban resource flow network from the adjacency matrix.

Table 3.1: List of 35 FUAs in England and Wales with population and GVA data for 2011.

Rank	Abbrev.	Functional Urban Areas	[1]Population	[2]GVA, £ millions (share %)
1	LO	London	12,142,021	413,048 (48.4%)
2	WM	West Midlands (Birmingham)	2,864,763	52,211 (6.1%)
3	MA	Greater Manchester	2,776,368	52,800 (6.2%)
4	LP	Liverpool	1,506,492	26,784(3.1%)
5	NE	Tyneside Conurbation (Newcastle)	1,199,547	25,672 (3.0%)
6	LD	Leeds	1,160,663	26,575 (3.1%)
7	SP	Sheffield	908,572	15,597 (1.8%)
8	BZ	Bristol	894,582	23,235 (2.7%)
9	CD	Cardiff	885,276	15,418 (1.8%)
10	NG	Greater Nottingham	870,408	16,528 (1.9%)
11	LC	Leicester	836,641	15,845 (1.9%)
12	KH	Kingston upon Hull	590,796	10,151 (1.2%)
13	CV	Coventry	542,820	10,004 (1.2%)
14	PO	Portsmouth	520,816	10,905 (1.3%)
15	BU	Bournemouth	511,926	10,399 (1.2%)
16	SJ	Stoke-on-Trent	469,806	7,579 (0.9%)
17	MB	Middlesbrough	465,356	7,906 (0.9%)
18	CH	Cheshire West and Chester	459,774	8,751 (1.0%)
19	NR	Norwich	381,393	8,024 (0.9%)
20	SS	Swansea	378,571	5,971 (0.7%)
21	BE	Brighton and Hove	370,536	7,287 (0.9%)
22	SO	Southampton	361,722	8,248 (1.0%)
23	PR	Preston	356,826	7,137 (0.8%)
24	DB	Derby	343,858	7,405 (0.9%)
25	EX	Exeter	328,271	6,664 (0.8%)
26	BP	Blackpool	325,870	5,359 (0.6%)
27	RG	Reading	310,282	10,773 (1.3%)
28	BB	Blackburn with Darwen	285,498	4,944 (0.6%)
29	CB	Cambridge	272,567	8,321 (1.0%)
30	IP	Ipswich	258,319	5,630 (0.7%)
31	NP	Newport	236,975	4,331 (0.5%)
32	LL	Lincoln	201,603	3,883 (0.5%)
33	GL	Cheltenham	197,914	5,006 (0.6%)
34	TN	Hastings	180,902	2,786 (0.3%)
35	BN	Burnley	176,608	2,651 (0.3%)
		Total	34,574,342	853,828 (100%)

1 Combined regional population data based on Local Authority in the UK for 2011 (ONS, 2017a)
2 Combined regional GVA data based on Local Authority in the UK for 2011, unit of £ millions (ONS, 2017b)

In this study, 35 FUAs are identified based on the urban audit boundary in England and Wales for 2011. Table 3.1 shows the abbreviations and names for all 35 FUAs, in a decreasing order of their total population. The urban audit boundary defines the scope of this case study for 35 FUAs in England and Wales, as shown in Figure 3.1, which includes the core central city of each FUA and its commuting zones (Eurostat, 2017). In this definition, the wider FUAs may consist of multiple local administrative units (LAUs, the lowest administrative level of local governing councils) as data collecting units. The resultant data of urban population and GVA of the urban areas are obtained by combining all the local authorities within the respective boundaries. In this case, agglomeration heterogeneity of UK industrial mix draws disparities across the FUAs contributing to varying demands and behaviours in terms of resource use in cities (N. Chen and Novy, 2011). See Appendix 1 for the breakdown of industries in all FUAs. Note that the usage of phrases 'FUA' and 'city' are not interchangeable as 'FUA' refers to a specific urban area in England or Wales while 'city' is used more generally and can apply to any urban area inside or outside the case study system.

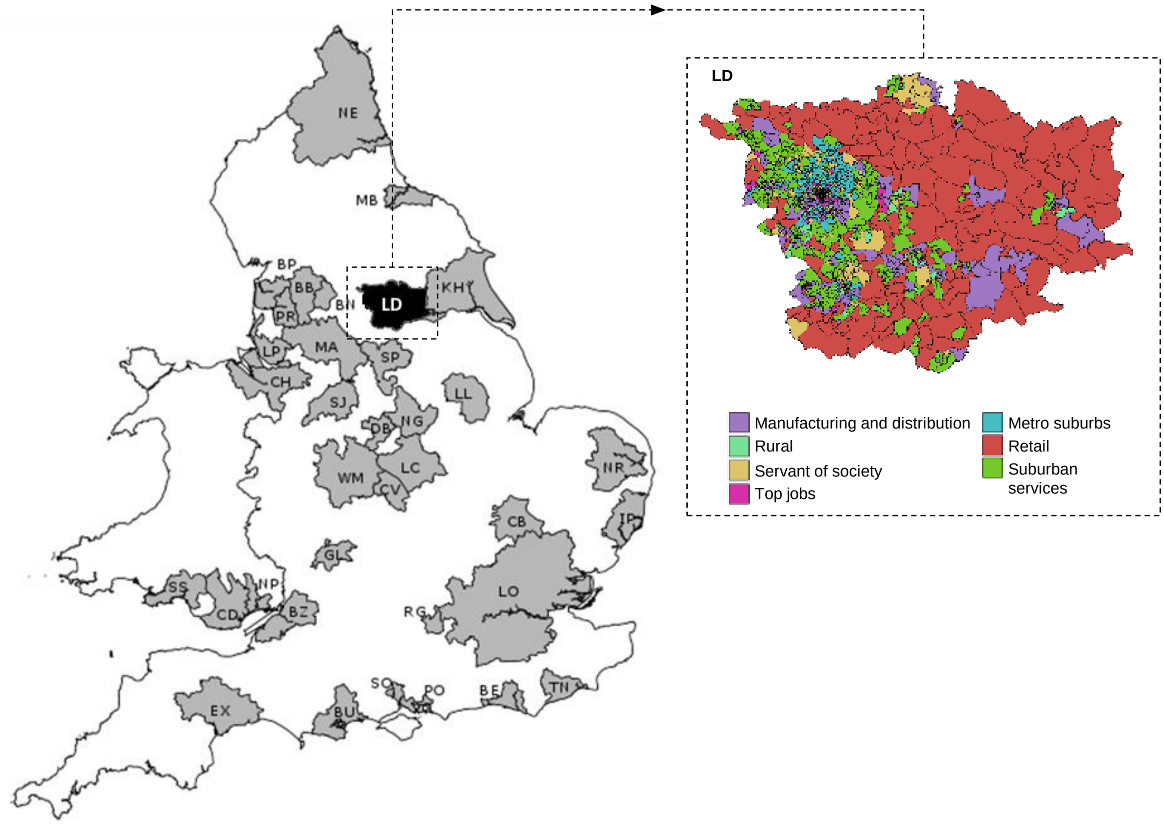

Figure 3.1: Map showing the geographical location of 35 FUAs and a detailed view of the workplace zones in Leeds (LD) with its respective classification based on industrial type, as an example of a FUA in the case study urban systems.

The sectors in the National Input-Output Supply and Use Table at the intermediate product level are categorised according to the UK Standard Industrial Classification of Economic Activities (SIC2007) (ONS, 2016) to reallocate 105 economic sectors in the table into the 11 categories of GVA data provided by the local authorities based on the types of economic activity, as described in Table 3.2. This is to reduce the resolution of economic activities in order to obtain the input-output flow data at the urban level through GVA scaling.

Table 3.2: Intra-sectoral economic sectors and description based on UK SIC 2007.

Sector and Abbreviation		Section	Description
P1	Production 1	A	Agriculture, forestry and fishing
P2	Production 2 *Production activities other than P1 and Manufacturing*	B	Mining and quarrying
		D	Electricity, gas, steam and air-conditioning supply
		E	Water supply; sewerage, waste management and remediation activities
M	Manufacturing	C	Manufacturing
C	Construction	F	Construction
D	Distribution	G	Wholesale and retail trade; repair of motor vehicles and motorcycles
		H	Transport and storage
		I	Accommodation and food service activities
IC	Information and Communication	J	Information and Communication
FI	Finance and Insurance	K	Finance and Insurance activities
RE	Real Estate	L	Real Estate activities
B	Business services	M	Professional, scientific and technical activities
		N	Administrative and support service activities
PA	Public administration services	O	Public administration and defence; compulsory social security
		P	Education
		Q	Human health and social work activities
OS	Other services	R	Arts, entertainment and recreation
		S	Other service activities
		T	Household activities for own use

As shown in Figure 3.1, the workplace zones classification data based on workforce populations statistics (Cockings *et al.*, 2015) are applied to investigate the spatial distribution of the local community structure and study the impact on local resource consumption. For workplace zones, sector allocations are carried out based on the employment data documented by ONS (2012) in each workplace zone and two sectors with the two highest workforce populations are selected. However, there are two exceptional cases of special condition in this part: first, if the employment number for multiple sectors are similar, the zone is allocated under multiple sectors simultaneously; second, if one sector only exists in a particular workplace zone, it is selected regardless of its population in that area. Geographic information system (GIS) is used to measure the spatial distance between the sectors within an urban area and to study the relationship between the spatial connection among the sectors and their monetary flows. The Spatial Join function combines the workplace zones with each urban audit output area of the 35 FUAs (ONS, 2017a) inspected in this case study. The centroid, or geometrical centre of each polygon in the workplace zone area is identified using GIS to represent the coordinate location of the respective allocated economic sector. As result, a distance matrix (11×11) is generated to tabulate the average pairwise distance between all 11 sectors for each FUA.

3.2.2. *Ecological network analysis*

The conceptual ecological network model in Figure 3.2 shows that each node represents a sector (as listed in Table 3.2), located at the centroid of each workplace zone on the map of an urban area and the arrow connection between the nodes represents a resource flow.

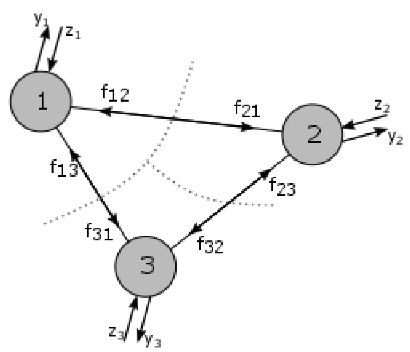

Figure 3.2: The conceptual schematic diagram of Leeds to demonstrate the network model with multiple sector nodes and connecting flows between them.

In this study, the network is connected with bi-directional flows of different weights, which correspond to the monetary value of the flows. For steady-state operation, the input-output system is assumed to be in equilibrium, where the sum of all aggregated inflows is equal to the sum of all outflows, $T_i^{(in)} = T_i^{(out)}$. Given that f_{ij} represents flows from node j to i and vice versa, hence, for a total m nodes in the network, formulae for calculating inflow and outflow at an arbitrary node i are:

$$T_i^{(in)} = T_i = \sum_{j=1}^{m} f_{ij} + z_i \tag{3.1}$$

$$T_i^{(out)} = T_j = \sum_{j=1}^{m} f_{ji} + y_i \tag{3.2}$$

where z_i represents cross-boundary inflow and y_i represents cross-boundary outflow.

However, the initial regional input-output table is usually nonequilibrium. Inter-city flows are not accounted when scaling down the input-output flows using the local GVA data. Only the national import and export are taken as cross-boundary flow moving in and out of the city. In this case, to balance the local intra-city input-output table, any computed difference between the initial $T_i^{(in)}$ and $T_i^{(out)}$ values is treated as addition to the total cross-boundary inflow (z_i if there is extra input) or outflow (y_i if there is extra output) around each FUA, regardless of inter-city or international flows. With the balanced input-output flow matrix, the ENA method (S. Chen *et al.*, 2010; Fath and Borrett, 2006; Jørgensen *et al.*, 1995) is applied to study the metabolic relationships between the sectors within the FUAs with each sector being treated as a node in the urban network connected to other nodes by weighted edges. The functional analysis methods of ENA are as demonstrated in Sections 3.2.3- 3.2.6.

3.2.3. Throughflow analysis

Throughflow Analysis (Y. Zhang *et al.*, 2010) transfers the initial direct and dimensional flow matrix into two dimensionless integral flow intensity matrices, in which $\mathbf{N}$ refers to the output-oriented flows while $\mathbf{N}'$ refers to the input-oriented flows. Firstly, the non-dimensional inter-compartment flow matrices, $\mathbf{G} = [g_{ij}]$ and $\mathbf{G}' = [g'_{ij}]$ are given as:

$$g_{ij} = \frac{f_{ij}}{T_j} \tag{3.3}$$

$$g'_{ij} = \frac{f_{ij}}{T_i} \tag{3.4}$$

The integral flow intensity matrices, $\mathbf{N}$ and $\mathbf{N}'$ can be calculated from $\mathbf{G}$ and $\mathbf{G}'$ as shown in the following equations:

$$\mathbf{N} = \mathbf{G}^0 + \mathbf{G}^1 + \mathbf{G}^2 + \mathbf{G}^3 + ... + \mathbf{G}^m = (I - \mathbf{G})^{-1} \tag{3.5}$$

$$\mathbf{N}' = (\mathbf{G}')^0 + (\mathbf{G}')^1 + (\mathbf{G}')^2 + (\mathbf{G}')^3 + ... + (\mathbf{G}')^m = (I - \mathbf{G}')^{-1} \tag{3.6}$$

The identity matrices, $\mathbf{G}^0$ and $(\mathbf{G}')^0$, represent self-flow at the nodes where $\mathbf{G}^1$ and $(\mathbf{G})'^1$ represent any one-step, direct flow between two nodes, G^2 and $(\mathbf{G}')^2$ represent any two-step, indirect flow between two nodes and $\mathbf{G}^m$ and $(\mathbf{G}')^m$ represents the m-step, indirect flow between two nodes in the network. This enables the integral throughflow across multiple path-lengths in the flow network to be considered in ENA.

3.2.4. Control analysis

A control analysis (S. Chen and Chen, 2015; Schramski *et al.*, 2006) is conducted to quantify control and dependency relationships between the nodes. Control Allocation ($\mathbf{CA}$) matrix reflects how the supplying sector controls the consumption-input of the receiving sector, while Dependence Allocation ($\mathbf{DA}$) matrix reflects how the receiving sector depends on the production-output of the supplying sector. The equations for $\mathbf{CA}$ and $\mathbf{DA}$ are:

$$\mathbf{CA} = [ca_{ij}] = \begin{cases} n_{ij} - n'_{ji} > 0, & ca_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{i=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leq 0, & ca_{ij} = 0 \end{cases} \tag{3.7}$$

$$\mathbf{DA} = [da_{ij}] = \begin{cases} n_{ij} - n'_{ji} > 0, & da_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{j=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leq 0, & da_{ij} = 0 \end{cases} \tag{3.8}$$

Note that $\mathbf{CA}$ is a consumption-based metric and $\mathbf{DA}$ is a production-based metric because the elements of $\mathbf{CA}$, ca_{ij}, are normalised based on the sum of flows supplied to all m nodes in the network from each j while the elements of **DA**, da_{ij}, are normalised based on the sum of flows received by each i from all m nodes in the network. The results of control and dependency relationships are expressed on a scale of 0 to 1 to indicate the extent of which the sectors are in control or dependent on one another.

3.2.5. Utility analysis

In utility analysis (Fath and Patten, 1998), the types of metabolic relationships between any two nodes can be characterised by using a dimensionless integral utility intensity matrix, **U**, which is formulated as:

$$\mathbf{U} = \mathbf{D}^0 + \mathbf{D}^1 + \mathbf{D}^2 + \mathbf{D}^3 + ... + \mathbf{D}^m = (I - \mathbf{D})^{-1} \tag{3.9}$$

where $\mathbf{D} = [d_{ij}]$ is the direct utility intensity matrix, in which the elements d_{ij} can be calculated as:

$$d_{ij} = \frac{f_{ij} - f_{ji}}{T_i} \tag{3.10}$$

As summarised in Table 3.3, the positive or negative sign notations of the paired elements (u_{ij}, u_{ji}) in the **U** matrix can be used to indicate the types of metabolic relationship between any two nodes, i and j, such that:

- If the signs of u_{ij} and u_{ji} are both positive (+, +), both sectors benefit from each other and hence have a mutual relationship.
- If both u_{ij} and u_{ji} are negative (−, −), it means both the sectors are negatively influenced by each other as they compete for a fixed amount of resource available in the network so there is a competitive relationship.
- If u_{ij} is positive while u_{ji} is negative, then node i receives positive benefits from node j while j receives negative impacts from i, in this case, j is the prey and is being exploited, while i is the predator and exploits j. Hence, it is an exploitation relationship when u_{ij} and u_{ji} have different signs as (+, −), or vice versa.

Table 3.3: Types of metabolic relationship between two nodes based on sign pairs (S. Li *et al.*, 2012) from the **U** matrix.

(u_{ij}, u_{ji})	+	−
+	Mutualism	Exploitation
−	Exploitation	Competition

To identify the overall metabolic performance of the network, two dimensionless quantities, namely, mutualism index, M, and synergism index, S, can be computed from **U**. M is defined as the ratio of the total number of utilities with positives signs (S_+) to the total number of utilities with negative signs (S_-) in the **U** matrix.

$$M = \frac{S_+}{S_-} = \frac{\sum max[sign(u_{ij}, 0)]}{-\sum min[sign(u_{ij}, 0)]} \tag{3.11}$$

If M is greater than 1, it implies that there are more beneficial relationships than non-beneficial cases in the system and hence the system can be considered mutualistic and healthy as the connections between these sectors bring benefits (positive utilities) to their economic activities. S is defined as the ratio of numerical sum of all positive utilities to numerical sum of all negative utilities in the overall **U** matrix. The value of S represents benefit-to-cost ratio of the system (Fath and Borrett, 2006).

$$S = \frac{\sum max(u_{ij}, 0)}{-\sum min(u_{ij}, 0)} \tag{3.12}$$

The overall benefit gained by a system is proportional to the value of S which depends on the signs of the utility elements, u_{ij}, computed from the weights of resource flows between the economic sectors. Hence, in other words, higher S value means gaining more benefits at a lower cost.

3.2.6. Network community structure

Analysing of the community structure of an urban ecological network provides a new dimension to the current scope of ENA studies to address the spatial component of the system. This can be done by computing network modularity using a community detection algorithm (Blondel *et al.*, 2008) to study the clustering properties of the nodes and classification of the community groups based on the flow weights. The algorithm unfolds the hierarchical community structure of the network to identify community groups in the network through optimising modularity. This simple and reliable algorithm can detect small communities by-passing the so-called resolution limit problem (Fortunato and Barthélemy, 2007) in short computing time.

Network visualisation and community classification are carried out based on two flow conditions: monetary-throughflow between all 11 sectors, and the throughflow densities (throughflow per unit distance) between two nodes. For comparison across all 35 FUAs under the two conditions, the flow values in the datasets are normalised over the total maximum flow across all the networks.

3.3. Case study results

Across all 35 FUAs in England and Wales listed in Table 3.1, Leeds, as one of the major cities in the UK, is used as an example to represent the common case observed in the results, unless stated otherwise. This is because Leeds shows an average performance and exhibited a similar urban structure commonly found in other FUAs.

3.3.1. Intra-city metabolism

From an ecological perspective, intra-city metabolism resembles a natural ecosystem consisting of multiple hierarchical levels. Individual units at different levels are connected through interactions with each other in the form of a pyramidal structure based on their ecological behaviours (producer or consumer), as shown in Figure 3.3. Those units represent different roles in the ecosystem to maintain proper functions of the system and promote organisational growth as a whole. Economic sectors in cities play different roles in the urban ecosystem based on their respective metabolic characteristics and functions in the network. From the lowest level, the producer supplies resources to the units at the upper levels to fulfil their needs or in other words, survival of the upper levels depends on sufficient inputs from the lower levels. These form unique paired relationships among these units at different hierarchical levels and the types of exhibited relationships can be explored through ENA.

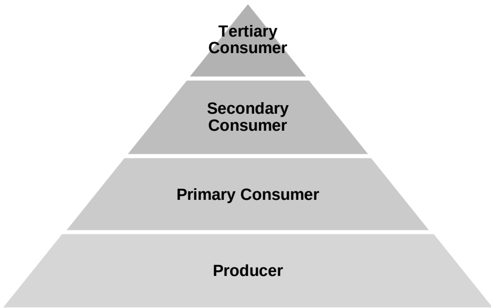

Figure 3.3: Pyramidal structure showing the different hierarchical of an ecosystem.

The control analysis identifies the degrees of control relationships based on consumption-input and the degrees of dependence relationships based on production-output between the 11 sectors. Figure 3.4 shows the results of network control (**CA**) and dependency (**DA**) relationships for the urban systems with a normalised scale from 0 to 1.

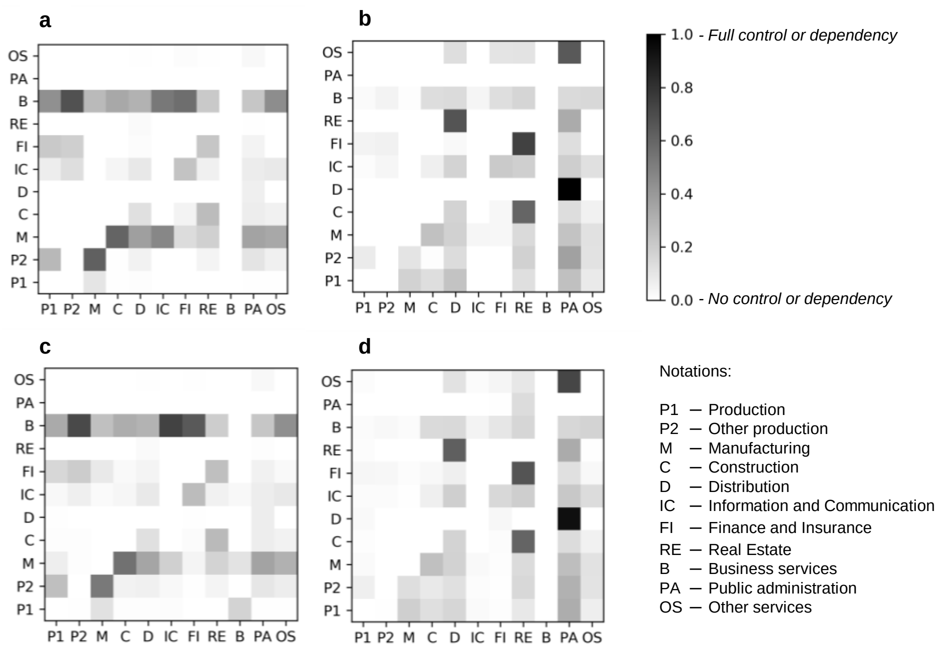

Figure 3.4: Results of (a) network control (sector number in column controlled by row sector) and (b) network dependency (sector in column depended on row sector) of Leeds, and the average results of (c) network control (sector in column controlled by row sector) and (d) network dependency (sector in column depended on row sector) of all 35 FUAs.

Network control results in Figure 3.4(a) show that the business sector is not controlled by any other sectors but it controls the consumption-input of all 10 other sectors in Leeds's resource flow network. The highest degree of control relationship is 74% over the other production sector (P2), followed by 68% control over the finance and insurance sector. From the network dependency results in Figure 3.4(b), the business sector is completely independent while the sector for public administration services is found to be dependent on the production-output of other sectors, in which it is highly dependent on the distribution sector and has not been depended on by any other economic sector in Leeds.

Furthermore, the average of **CA** and **DA** matrices across all 35 FUAs are computed to investigate the overall network control and dependency relationships in the whole urban systems. From the average network control results in Figure 3.4(c), the business sector remains as the key controlling sector of resource consumption-input in the urban economies. In this context, identifying the significant control relationship in the urban ecological network helps in understanding the key functions of the sectors in the ecosystem and their impacts on other sectors. For the case in Figure 3.4(c), the network control relationships between the business, other production (P2), manufacturing and construction sectors form a structured ecological pyramid to demonstrate the resource supply chains from the producer at the lowest level to consumer at the top level consumers, as shown in Figure 3.5(a). The chained relationships between these sectors form a control hierarchy as resource supplied through the lower level controls the consumption of the level above it, and affects all the subsequent levels above, under the same principle as the natural ecosystem pyramid shown in Figure 3.3. To connect producers to consumers in the ecosystem, the processes of material transformations at the intermediate levels are often controlled by the producers while it also has firm control over the consumers. However, due to the high population densities and intensive business activities in cities, the business sector remains in strong control over all other sectors, hence it is placed at the lowest level of the pyramid to show its dominance over the consumption of all the upper sectors despite of being a resource consumer in nature. This presents a challenge in urban governance to regulate the supplies and demands for resource flows in future development to ensure sustainable consumption with adequate outputs of production flows within the network.

From the average network dependency results shown in Figure 3.4(d), chained dependency relationships are identified between the finance and insurance, real estate, distribution and public administration services sectors. On the highest level of the pyramid shown in Figure 3.5(b), public administration activities such as education, social security and defence are found to be dependent on the production-output of the distribution sector, including the services provided by the local transportation system and goods delivery. On the second highest level, the distribution sector are dependent on the real estate sector on the lower level which in turn relies on the production-output of the finance and insurance sector on the lowest level of the pyramid.

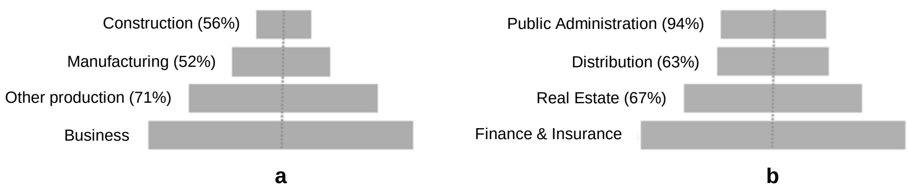

Figure 3.5: Pyramidal structure of urban ecosystem based on (a) **CA** and (b) **DA** results. The width (shown in percentage) of each level reflects the degree of control or dependency relationships between the sector and the sectors on the lower level.

Further analysis on stable metabolic relationships helps to identify the repetitive characteristics in the pairwise relationships which all the 35 FUAs have in common. This is done by intersecting 35 sets of relationship matrices of all FUAs to find the consistent patterns of their common relationships.

The results are tabulated in Figure 3.6 as a symmetrical square matrix along the diagonal based on the types of relationship. Exploitative relationship is directed to tell which sector is being exploited by another sector. See Appendix 2 for the tabulated relationship matrices of all 35 FUAs.

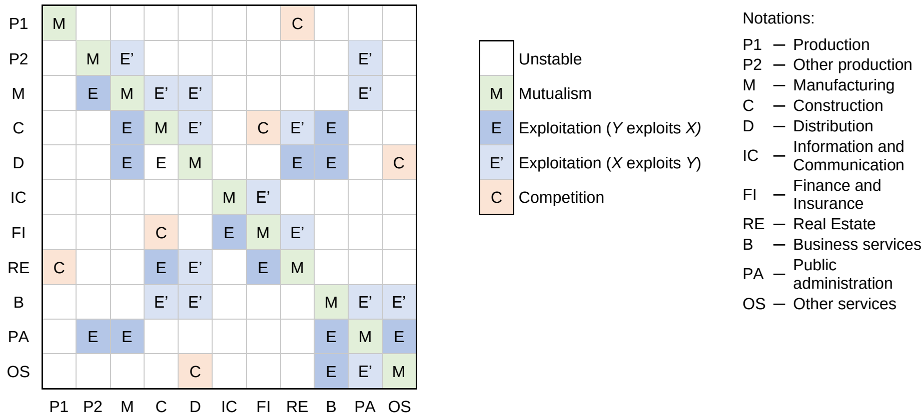

Figure 3.6: Stable relationships between the 11 economic sectors across all 35 FUAs.

Excluding self-flow at each sector for internal promotions (Patten, 1991), no stable mutualistic relationship is observed in all 35 FUAs. Three pairs of competitive relationships are found in six different sectors. Exploitative relationships dominate the overall network as 15 pairs are observed, with the highest occurrence at the distribution sector for exploiting others while the business sector is mostly exploited by others. For instances, the distribution sector exploits other production (P2), manufacturing, real estate and business sectors. On the other hand, the business sector is being exploited by other sectors such as construction, distribution, public administration services and other services activities.

Moreover, stable competition relationships are found between three sets of economic sectors: firstly, the production (from agriculture, forestry and fishing activities) sector (P1) competes with the real estate sector; secondly, the construction sector competes with the finance and insurance sectors; and lastly, the distribution sector competes with other services activities. These (paired) sectors are competing for resources from the same suppliers, mainly from the manufacturing and business sectors, in terms of monetary trades and investments. These observations suggest that flow connections between these competing sectors has no positive impact on the overall network supply chains to maintain the functions and operations of the economies. These provide an important insight for urban stakeholders to reconsider their connections in these sectors and restructure the supply chains in the network to improve their overall system performance.

Figure 3.7 shows the results of M and S indices from the utility analysis on all 35 FUAs, in a decreasing order of the index values from left to right on the horizontal axes. From Figure 3.7(a), only 10 cases, which corresponds to seven FUAs in the 10 highest populated areas (based on the ranking in Table 3.1) and in additions of Reading (Rank 27), Brighton and Hove (Rank 21), and Portsmouth (Rank 14), have a M value greater than 1, indicating a healthy urban metabolic system. The average M across all 35 FUAs equals to 0.93 which implies only 48% of all utilities are positive, in which London (Rank 1) has the highest M of 1.20 and Blackburn has the lowest, 0.70. It is worth noting that these areas have comparative S and are both above the average value. For the results of S, Leeds (Rank 6) lies on the average value of 3.56 with Derby (Rank 23) being the highest and Ipswich (Rank

30) is the lowest. With larger population in major cities, formation of a more diversified and matured economic structure strengthen the connections in the network to promote mutual benefits locally as the system grows.

From the formulations of M and S indices in Section 3.2.5, M measures the overall system mutuality quantitatively by the number of positive or negative utility count observed while S takes into account of the numerical magnitude so the results of S are affected by the quality of each count. From Figure 3.7(a), M changes gradually from the highest value on the left to the lowest value on the right compared to the changes in S which show a larger difference in the values between two consecutive readings illustrated in Figure 3.7(b). The gap between the highest and the second highest S values is seven times larger than the gap between the second and third highest S values. According to the distribution of S results shown in the box plot, the four lowest values are the outliers in this case. This is due to the large differences between the magnitudes of those positive utilities in the **U** matrix of these FUAs. The main contributor of those positive utilities is the self-flow of a sector for internal benefits and promotions, so these observations suggest that the inter-sectoral flows are less mutualistic than the internal flows and more prompted to exhibit an exploitative relationship with other sectors. This is supported by the domination of exploitative relationships (shown in Figure 3.6) which made up to 64% (Competitive 20%; Mutualistic 16%) of the overall urban metabolic system across all 35 FUAs.

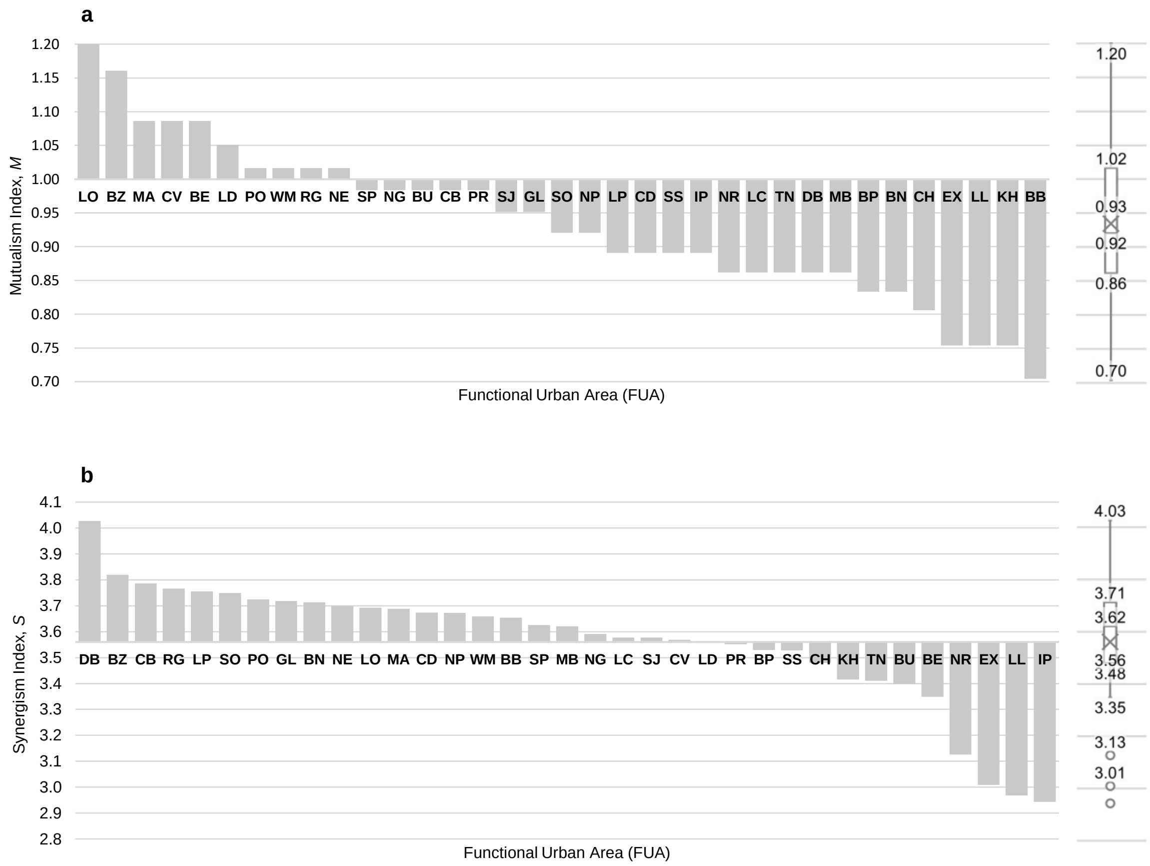

Figure 3.7: Column charts of (a) Mutualism index, M and (b) synergism index, S of the 35 FUAs and their respective box plots to show the data distribution across all cases.

Findings from the utility analysis agree with the pyramidal structure of the urban metabolic ecosystem constructed based on the network control and dependency results from the control analysis. The business sector is located at the lowest hierarchical level of the ecosystem (as shown in Figure 3.5(a)), acting as the limiting factor of the system's metabolism by controlling the consumption of other sectors and it is also mostly exploited by other sectors as a consumer.

3.3.2. Network community structure

Structural analysis of ENA studies the clustering of economic sectors within the urban ecological network based on the minimal nodal modularity to identify the classification of community groups formed among those sectors. In this study, throughflow network of 35 FUAs are constructed to investigate the clustering properties of the network community structure. A common structure is observed in the majority of these areas showing the similar community grouping classification except for four less-populated areas which exhibit a varied version in their throughflow network structure. These results are computed based on the total throughflow value calculated at each sector using an throughflow analysis to account for all direct and indirect flows across multiple path-lengths through other all sectors within the same network. The throughflow value represents the integrated flows across the full network. The clusters formed are known as community groups where the sectors belong to the same community group are more strongly attached to one another. Classification of network community groups considers the modularity at each node with one of the computing parameters being the resultant weighted throughflow value from all other nodes across the fully connected network after normalisation.

A visualisation software is used to demonstrate the classification of colour-coded community groups in all 35 FUAs in this case study. The results of community groups classification based on throughflow network are as shown in Figure 3.8.

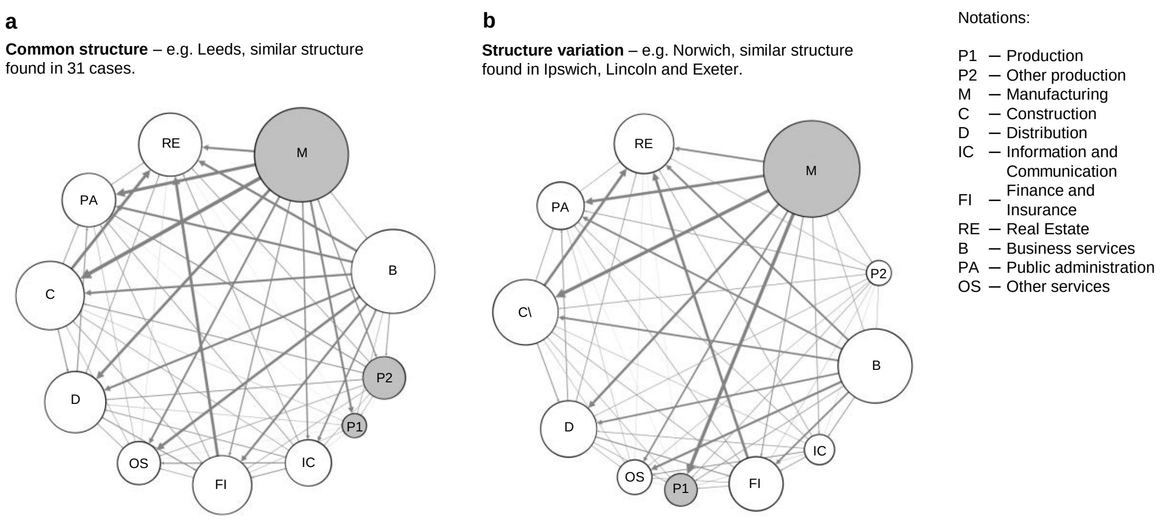

Figure 3.8: Classification of community groups into two clusters based on throughflow network (white nodes for the large cluster and grey nodes for the small cluster) showing (a) the common structure in Leeds and (b) the variation observed in Norwich and three other FUAs.

In Figure 3.8, the common network community structure is illustrated using the example of Leeds in 2011, which shares the similar clustering structure with 30 other FUAs including some of the highly populated areas such as London, Birmingham, Manchester, Liverpool, Newcastle as well as other areas with smaller population such as Burnley, Hastings and Cheltenham. Sizes of the nodes and edges are proportional to the overall degree and weight of the flow respectively. The placement of nodes is arranged in a circular layout with descending order of weighted in-degree to each node in counter-clockwise direction to show the consumption-input of resources by sector.

As shown in Figure 3.8(a), the manufacturing sector (the largest node) has the highest weighted overall degree as it plays an important role in the processes of energy transformation as an intermediate consumer, connecting the producing sectors to the final-users. However, according to the placement order of the nodes which are arranged in a counter-clockwise direction, the manufacturing sector also has the lowest weighted in-degree of resource consumption flows into the sector, followed by the business sector. This means the manufacturing and business sectors are the main producers in the network with high output contributions and low input consumptions. In richer areas with fast-growing business activities and higher GVA per capita, such as London and Reading, the business sector overtakes the manufacturing sector to be the largest node within the intra-city network. An exceptional case is Kingston upon Hull where the construction sector is larger than the business sector. On the other hand, the real estate sector, has a relatively high consumption as it is ranked as the lowest in terms of weighted in-degree among the 11 sectors although the production sector (P1) is the smallest node with the lowest weighted degree in all cases.

In terms of community grouping classifications, two clusters, which consist of eight and three sectors respectively, are formed:

- **Larger cluster**: Business (B), Information and Communication (IC), Finance and Insurance (FI), Other Services (OS), Distribution (D), Construction (C), Public Administration Services (PA) and Real Estate (RE)
- **Smaller cluster**: Manufacturing (M), Other production (P2) and Production (P1)

From the clustering structure, the producers and intermediate consumers in the smaller cluster have higher tendencies to cluster among those sectors with stronger economic connections. The larger cluster in the network consists of mostly the final consumers or end-use sectors in the urban ecosystem. The two largest nodes with the highest overall weighted degrees, the manufacturing and business sectors, belong to two different community groups. Hence, classification of the remaining nine sectors are influenced and determined by the weightage of flow connections between the remaining nodes and the two largest nodes, representing the two clusters. In Leeds, eight sectors in the larger cluster are mainly the consumer-type receivers from the business sector while the remaining three sectors in the smaller cluster act as the producer-type suppliers to support the resource-intensive business activities in the area.

A different type of community structure, as shown in Figure 3.8(b) is observed in Norwich, Ipswich, Lincoln and Exeter. In these areas, other production (P2) belongs to the larger cluster dominated by the business sector while the smaller cluster consists of only two sectors, the manufacturing and production sectors (P1). Comparing this result to the more common structure shown in Figure 3.8(a), the other production sector (P2) is more connected to the consumer-type receivers in the larger cluster with more connections and hence, increases the overall degree of the node. This is because of the overwhelming consumption of resources in the economy of these areas resulting in insufficient supplies of production-output to meet the high demand. Nonetheless, the types of economic activities (including mining, quarrying, electricity and water supplies) indicates the fundamental role the other production (P2) sector as a primary producer in the urban ecosystem. In this study, the analysis is limited to intra-city flows only hence, any inter-city supplies of resources such as export of local products to other regions is not considered. Further investigations on inter-city metabolism can be conducted to explore resource flows between different areas and their interactions with the external environment.

Investigations of the spatial impacts of geographical distance between the sectors on network community structure give the results of throughflow density networks, as shown in Figure 3.9.

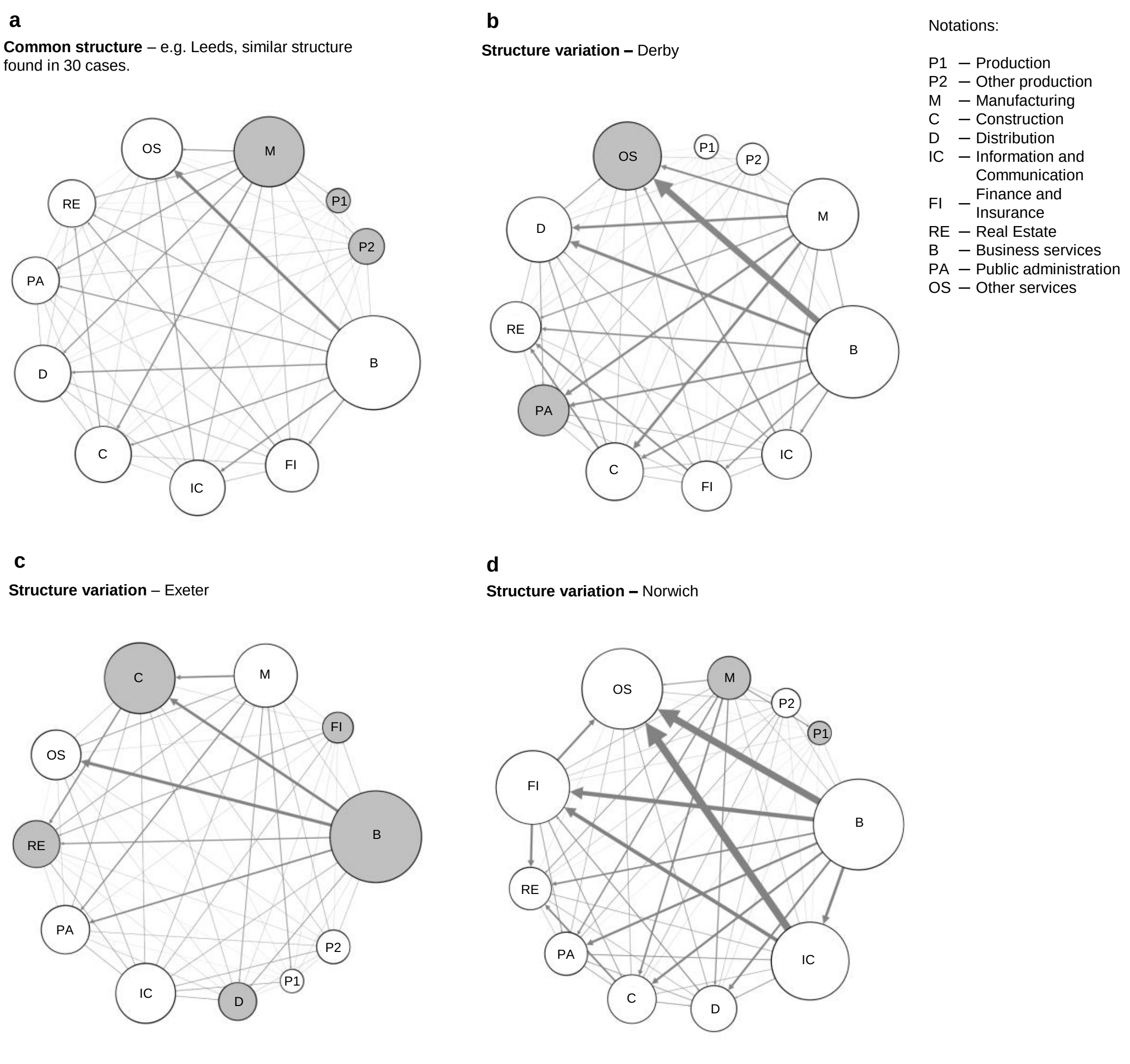

Figure 3.9: Classification of community groups into two clusters based on throughflow density network (white nodes for the large cluster and grey nodes for the smaller cluster) showing (a) the common structure in Leeds and the variations observed in (b) Derby, (c) Exeter and (d) Norwich.

Classification of community groups based on the throughflow density network in Figure 3.9(a) is similar to the throughflow network observed in most of the cases with the common structure shown in Figure 3.8(a). The clusters of sectors are identified based on their economic activities and functioning roles in the urban ecosystem, either as consumers in the larger cluster or as producer in the smaller cluster. However, sizes of the nodes are different in the throughflow density networks because of changes in nodal weighted-degree when taking into account of average spatial distance between the sectors and hence, resulted in different network community structures compared to the results in Figure 3.8. In the density networks, the business sector has higher weighted degree and denser edge connections than the manufacturing sector. Besides, the nodal size of the manufacturing sector decreases with lower density due to the larger distance between the industrial zone for manufacturing activities (which are located further away from the central) and the other consumers in the same area. In contrast, the business sector (the biggest node) has denser flows due to its proximity benefits from a closer location and higher accessibility to the consumers in other sectors, and this was undetected in the throughflow networks.

In some cases, the lower degree and reduced dominance of the manufacturing sector in the throughflow density network resulted in more complicated intra-sectoral interactions in the urban ecosystem when the impacts of spatial characteristics are considered. For example, the throughflow density network of Derby in Figure 3.9(b) shows both the producers and consumers are found in the larger cluster while the smaller cluster consists of the public administration services and other services activities only. This is because the producer and consumer sectors are spatially scattered and equally distributed across the whole area owing to the strategic geographical location of Derby in the Midlands, spanning the central region of England (Midlands Connect, 2017). Derby's highly connected network of resource flows contributes to its highest synergism index, with $S = 4.03$ from Figure 3.7(b), and benefit-to-cost ratio across all 35 FUAs.

Another variation in Figure 3.9(c) shows the different clustering properties in Exeter where the manufacturing sector is smaller than the business and construction sectors. In Norwich, classification of community groups based on throughflow density network shows a similar structure as its throughflow network except for the changes on the size of the nodes due to the spatial distribution of the sectors in the urban network, as shown in Figure 3.9(d).

The data available are not sufficient to provide spatial information of several sectors in Blackpool and Burnley, resulting in smaller sample sizes for the number of sectoral nodes in the network of these areas and therefore, results of structural analysis on the clustering properties of their throughflow density networks are excluded in this study.

3.4. Implications of the case study

The intra-city flow network, constructed with ENA which is also supplemented with the geographical distance between the workplace sectors, represents the inter-connected structure of an urban ecosystem. Resource flows between the sectors are projected as urban ecological networks to study the distribution of resources within the boundaries of the FUAs. Understanding the metabolic relationships between the sectors and classification of the community groups in the urban networks helps to identify the points of intervention for efficient policymaking with larger impact by targeting the dominating sector with the strongest influence on other sectors in the areas.

The results describe the metabolic characteristics of the urban systems in England and Wales as exploitative which suggests their metabolic systems are still in the developing phase and there are space for further improvements. The business sector is exploited by others but also in control of the consumptions in most of the other sectors because it suffers losses in the resultant throughflow due to higher outflows than inflows passing through the business node. As such, the sector also acts as the limiting node or the "gatekeeper" to control the amount of resource received and consumed by other sectors in the network. Highly concentrated business-related activities and tertiary services in urban areas have significant impacts on the metabolism of these cities. Mutualism and synergism indices results strongly suggest that London has the most matured system among those FUAs in England and Wales. Economic diversity in cities with larger population contributes to the development of healthy metabolic systems through balancing and regulating the distributions of resources among different sectors in the cities based on various types of activities and demands for different resources. This provides a foundation to build an effective resource network in urban areas for regulating the overall production and consumption of the sectors through the chained relationships in the intra-city ecosystem.

Community classification of sectors shows the importance of the inter-relationship within the organisation of each community class. In most of these areas, formation of the producer-type and consumer-type clusters separated the economic sectors based on their respective hierarchical roles in the ecosystem. The producer-type cluster maintains the foundation of resource supply chains to other sectors in the cities while the consumer-type cluster focuses on the distribution of resources received by the consumer sectors for final expenditure. The throughflow density network sheds light on the impact of spatial distance between the sectors within the city's boundary. The analysis considered the size of the city, proximity and accessibility of those sectors. In the case of Derby, the geographical location of a city can have an impact on the community structure of its ecological network. This result emphasises on the importance of addressing the impact of spatial distribution in planning and managing resource distribution in urban systems.

Understanding the relationships between economic activities and their spatial distribution will assist policymakers in the processes of decision-making and implementation of resource management strategies for sustainable urban development. This study has considered the intra-city networks of all FUAs across the entire urban system of England and Wales to investigate and characterise the patterns of resource exchanges and ecological behaviours of the economic sectors. The key implication here is to facilitate the development of urban policy levers for a system-wide change, rather than solutions isolated to a single city.

3.5. Limitations

In this study, portraying metabolism of an urban system as ecological network using the concept of urban metabolism (UM) provides a platform to inspect a city based on the internal flow connections within its socio-economic system. This is done by supplying ENA with economic data for the case study cities. Although the ENA framework provides transparent and important insights to analyse system diversity and interdependencies among the urban components through the functional analysis demonstrated in Section 3.3, the results and discussion still highlight a number of shortcomings in ENA including (1) the debated use of input-output monetary transactions as resource supply and use to account for the metabolic activities in cities and (2) insufficient spatial and temporal data, at the urban level, for a thorough investigation on the metabolism of economic activities in cities.

One of the main limitations of this study is the use of monetary flows as a proxy for material flows between the sectors within an urban area. In reality, monetary and material flows accounts are inequivalent. The transition of monetary flows reacts differently compared to material flows due to price fluctuations depending on supplies and demands for stocks in the market. To provide a more accurate measure to investigate resource use in cities, these can be substituted with an equivalent quantity of physical resource flows in the urban system. For this purpose, the concept of exergy provides a convenient tool for accounting the work extractable and material transformation across different urban processes in the economy based on the usefulness of resources available. This highlights the needs of developing an analytical tool in the current UM framework that links the concept of exergy and network analysis, which will be addressed in the next chapter.

Findings from the throughflow density networks contribute to a novel investigation into spatial properties of the urban flows networks with more structural variations in terms of network clustering and classification of community groups based on the flow densities. The current derivation of flow densities, however, should not go unqualified. As presented in this study, a census-based classification of workplace zones has been used to examine the spatial distance between the 11 sectors. This mostly identifies the predominant activity taking place within a workplace zone and not necessarily articulated in terms of the economic sectors under which the activities would fall. As such, the assignment of sectors to individual zones has been primarily based on the likelihood of the sectors activity matching the classification profile for a given zone. This has necessitated the use of average pairwise distance in this work by taking the average distance between all zones tagged under the same classification of workplace sector within an urban area. In strict terms, this would smooth out the pair-wise distance distribution between the sectors. Besides this, since the intensity of activity within each workplace zone is unknown, distances are treated equally and unweighted possibly biasing the mean distances used. Overcoming the effects of such aggregated approach requires a further consideration of sectoral employment surveys and travel-to-work modes in order to better identify the workplace zones associated with certain sectors and the intensity of activities take place in each zone so that the spatial profile can be weighted based on the prominence of economic sectors.

On intra-city level, granularity of data remains the main constraint since scaling to aggregated urban level from larger scales (eg. national and regional data) is required. Cross-boundary flows including imports, exports and inter-city flows are excluded from the analysis of network community structure due to limited data available. The steady-state assumption is made to compensate for any unbalanced flows with external import or export. In such, the downside of this is the negligence of differential between inter-city and international trade flows and this could be minimised if more detailed data become available to future researchers. In addition, this can also be improved with data input for a longer time period to learn about the temporal behaviours of an urban system and how the behaviour changes over time to inform decision making for planning resource management in cities and to achieve the long-term goals of sustainable development. To address these limitations, case studies of Singapore (in Chapter 5) and Great Britain (in Chapter 6) will demonstrate novel investigations of urban resource use in a timeseries.

Chapter 4

Development of an open system network effectiveness analysis

The current chapter contains materials that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.

Arbabi, H., Punzo, G., Meyers, G., **Tan, L. M.**, Li, Q., Densley Tingley, D. & Mayfield, M. (2020). On the Use of Random Graphs in Analysing Resource Utilisation in Urban Systems.*Royal Society Open Science*, *7*, 200087.

4.1. Chapter introduction

This chapter introduces the framework of open system network effectiveness analysis (OSNEA) as a novel ecological-thermodynamic approach to urban metabolism, including the development workflow and data requirements of this new method. OSNEA is a complementary addition to the ecological network analysis demonstrated in Chapter 3.

The following sections in this chapter will explain the pioneering work on the development of OSNEA inspired to provide an understanding of how cities can utilise the limited resources effectively. OSNEA is an exergy-based method that accounts for the use of resources through urban processes in an open system network. The methodology of OSNEA consists of four key steps: Acquisition of commodity mass flow data for exergy-based resource accounting (in Section 4.2); Formulation of the input-output exchanges of goods and services between the socio-economic sectors (in Section 4.3); Assembly of an exergy-based input-output adjacency matrix to construct an urban flows network (in Section 4.4); Network analysis to investigate the performance of the system by conducting OSNEA, including the introduction of a set of *effectiveness* indicators for examining the states of resource utilisation and conversion in the system (in Section 4.5). Section 4.6 explains the data requirements of the OSNEA method and Section 4.7 gives a short conclusion of this chapter. The workflow diagram in Figure 4.1 summarised the methodology development process of the framework.

4.2. Exergy-based resource accounting

The concept of exergy provides a standardised thermodynamic quantification tool to measure the maximum usefulness of resource flows entering the system. Within the spatial boundaries defined, the total exergy imported and exported in the form of physical goods can be estimated from the Comtrade database which contains annual record of traded commodity mass flows (United Nations Department of Economic and Social Affairs, 2018) based on the 4-digit Harmonised Commodity Description and Coding System (HS-4) codes and the specific exergetic content of materials. The Harmonised System is an international nomenclature to standardise classification of commodity types and has been adopted by most of the countries worldwide in goods trading. The classification codes consist of six digits in full, with the first two digits refer to the broader product range (e.g. *74. Copper and articles thereof*), and the next two digits refer to grouping within the same product range (e.g. *7411. Copper tubes and pipes*). The last two digits, which refer to more specific details of the product (e.g. alloy compositions), are omitted in this analysis due to the constraints in acquiring the detailed specifications for all product types.

Since the introduction of the Harmonised System in 1988, several revisions have been made to the nomenclature (due to several reasons such as technology advancement, changes in international trade patterns and introduction of new products) to ensure consistent trade practices among the countries. For this reason, for temporal data spanning the years with amendments made to the classification standards, recalling the older versions of the commodity codes used in the earliest year of study is required to ensure consistent reference to the material types through the study and to correct the quantity of resource imported.

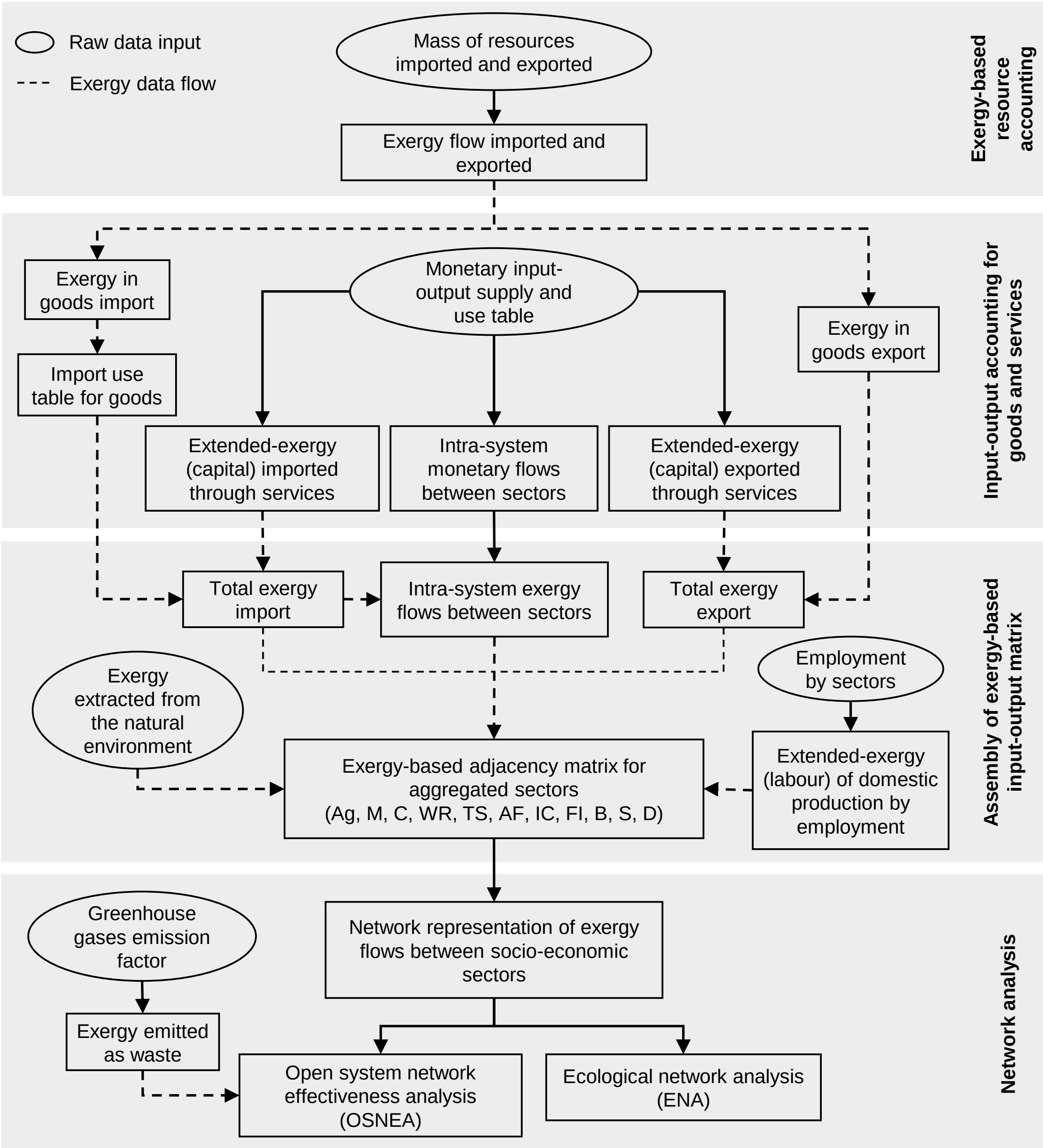

Figure 4.1: Workflow diagram showing the key steps and data required to develop the OSNEA framework.

The specific exergy values, measured in the unit of *kilojoule per kilogram*, are mainly taken from the previous works on evaluating the chemical exergies in elements (Szargut, 1989) and other compounds (Morris and Szargut, 1986), including the metal industries (Ayres *et al.*, 2006). For example, exergy accounting for sampled material types considered are as tabulated in Table 4.1. The specific exergy values of these commodities are compiled based on their respective HS-4 codes in the 2012 revision. The reference conditions of surrounding temperature and pressure are assumed to be at $25°C$ and 1 atm. The role of reference conditions is discussed by Rocco (2016b) in which thermodynamic characterisation of resource flows is subjected to fluctuations of the external factors and the real environment is indeed far from a steady system due to the constantly changing environment with varying seasons, climates and geographical locations of a case study. However, this assumption is needed to provide a definition to describe the reference conditions as current investigation is incapable of performing theoretical evaluation of exergy values for all materials due to time and data constraints. See Appendix 3 for more details of the commodity types and their specific exergy values.

Table 4.1: Specific exergy values for selected commodities based on their respective HS-4 code.

HS-4 Code	Commodity description	Specific exergy $[kJ/kg]$	Data source
2711	Petroleum gases	48.09	(Energy Statistics Division, 2005)
3923	Plastic articles	34.46	(Dewulf and Van Langenhove, 2004)
6810	Cement, concrete	1.97	(Koroneos and Kalemakis, 2012)
6903	Ceramic goods	0.14	(Szargut, 1989)
7411	Copper tubes and pipes	2.11	(Ayres *et al.*, 2006)

4.3. Exergy-based input-output analysis

Exergy-based input-output analysis (ExIO) is a joint application of input-output analysis and exergy analysis to study the input-output exchanges within an economic system based on the actual amount of exergetic flows (Rocco, 2016a). ExIO uses the equivalent exergy values of material flows to form a flow network connecting the flow transformation processes instead of using the monetary transactions in a typical input-output analysis as demonstrated in Chapter 3. This section will cover the methods of quantifying the equivalent exergy contents in goods and services, and also the formation of an exergy-based adjacency matrix for constructing the urban resource flow network.

4.3.1. Input-output accounting for goods

The network of intra-system resource flows between the economic sectors can be extracted from the monetary input-output supply and use table. Following Leontief's (1986) model, the table of input-output transactions between the sectors form a network as a balanced square matrix. The table also includes the economic data pertaining to annual capital flows such as gross value added (GVA), private expenditure consumption and gross fixed capital formation (GFCF) of the economy.

For an open economy, the total exergy import is comprised of goods and services. The amount of exergy contained in the form of goods can be calculated from the equivalent exergetic content of the resource intakes. Also, the information of the types and amounts of goods imported by each sector can be obtained from the import use table to determine the resource inflow to each component of the network. For exports, the goods are associated with the sectors handling the relevant products based on the mass of the exported goods recorded in the Comtrade database (United Nations Department of Economic and Social Affairs, 2018).

4.3.2. Input-output accounting for services

The extended-exergy of service, in the units of *Joule*, is defined as the embodied exergy of the monetary capital invested to deliver the service recorded in the input-output table. For a single monetary unit delivered, the *exergy equivalent of capital* (ee_K), can be computed as the ratio of the total incoming exergy flux (E_{in}) to the *cumulative monetary circulation* ($M2$) in the system for that year. With reference to the econometric factors used in Sciubba's (2011) extended-exergy accounting (EEA) method, ee_K is formulated as:

$$ee_K = \frac{\alpha\beta E_{in}}{M2} \tag{4.1}$$

where α is the first econometric factor representing the fraction of incoming exergy flux used to generate the cumulative labour work-hours of the whole population and β is the second econometric factor representing the amplification of wealth creation. Population (N_h), wages (S_w) and employment data, including the total number employed workers (N_w) and the average workload per worker (W_w) in the unit of *hours per year*, are required to determine α and β using the following equations:

$$\alpha = \frac{e_{surv} F N_h}{E_{in}} \tag{4.2}$$

$$\beta = \frac{M2}{S_w N_w W_w} \tag{4.3}$$

where e_{surv} ($\approx 10^7$ *Joule per person per day*) is the estimated *exergy consumption required for survival* (United Nations Development Programme, 1990). F is a dimensionless quantity defined as the *exergy consumption amplification factor* based on the Human Development Index (HDI) of an economy such that $F = HDI/HDI_0$ where $HDI_0 = 0.055$ was identified based on a correlation analysis between HDI and exergy consumption per capita (Sciubba, 2011).

Replacing α and β in Equation 4.1 with Equations 4.2 and 4.3 gives the resultant ee_K formula:

$$ee_K = \frac{e_{surv} F N_h}{S_w N_w W_w}. \tag{4.4}$$

The final extended-exergy of services, EE_K is the product of ee_K, which is measured in *Joule per monetary unit*, and the monetary costs of the services. The equivalent extended-exergy of services exported can also be calculated from ee_K in a similar manner to the imports.

4.4. Assembly of exergy-based input-output matrix

In open system networks, resource intakes are mainly supplied through cross-boundary imports from the external environment. The sum of all imports, combining the exergy in goods and extended-exergy in services, gives the total exergy imported by each of the sectors. Similarly, summing up the values of exergy exported, in the forms of goods and services, gives the total export exiting the system from those sectors. From the total exergy import entering the system, the resources are then distributed from the importing sector to other sectors according to the normalised input-output matrix, $\widehat{\mathbf{M}}_{ij}$, based on the total import received by each individual sector using the following equation:

$$\mathbf{M}_{ex} = diag(f_{import})\widehat{\mathbf{M}}_{ij}. \tag{4.5}$$

Distributing the vector of exergy import, f_{import}, based on $\widehat{\mathbf{M}}_{ij}$ creates an exergy-based adjacency matrix, $\mathbf{M}_{ex}$, for an open system network sustained by the incoming resources, resembling a dissipative urban system. The structure of the resultant assembled matrix is as shown in Figure 4.2.

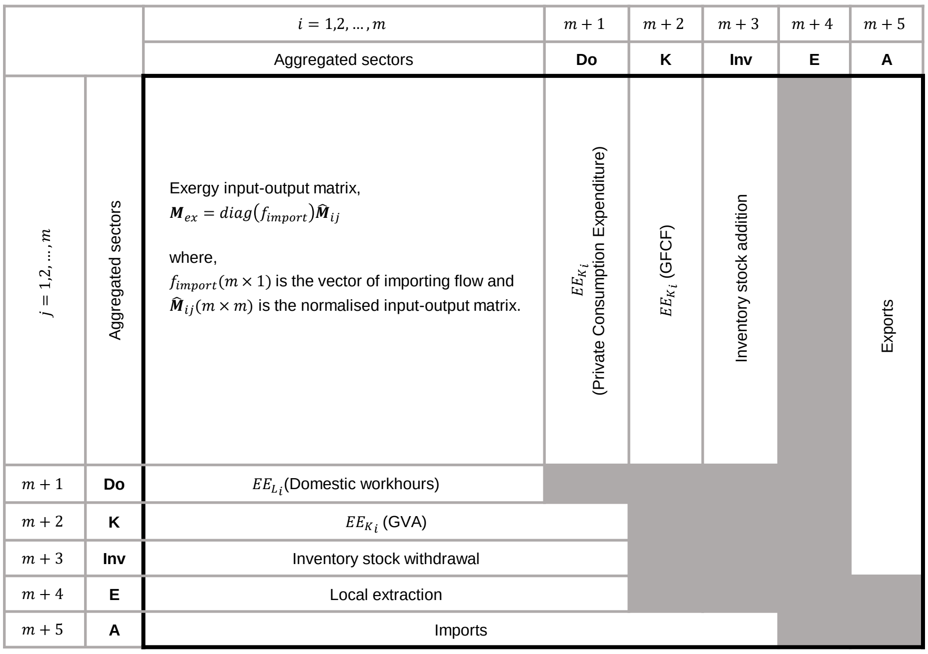

Figure 4.2: The assembly of an exergy-based input-output matrix, for m number of aggregated sectors.

The aggregated sectors are, in general, conveniently categorised as producer (agriculture, mining, forestry), primary consumer or transformer (manufacturing, construction, distribution, transportation) and consumer as end-user (services, domestic activities) based on the purposes and types of their activities. The number and range of sectors present in an urban system may vary across different cities. Besides the typical economic sectors, a domestic sector is additionally included in the matrix to take into account of household activities and contributions of the labour workforce supporting the economy through employment. Domestic production is estimated as the extended-exergy of labour by computing the total number of work-hours, N_{wh}. The exergy equivalent of labour output, ee_L, measured in the unit of $Joule\ per\ hour$, is defined as the amount of exergy required for the labour workforce to contribute one work-hour and can be calculated as:

$$ee_L = \frac{\alpha E_{in}}{N_{wh}} \tag{4.6}$$

and replacing α and β in this equation with Equation 4.2 and 4.3 gives:

$$ee_L = \frac{e_{surv} F N_h}{N_{wh}}. \tag{4.7}$$

The extended-exergy of domestic labour received by sector i can be expressed as $f_{i,domestic} = EE_{L_i}$ and calculated by multiplying ee_L by the total employed work-hours of the sector in a year. Resource consumed by the domestic sector, recorded as monetary private consumption expenditure of final demand in the input-output table, can be considered as the extended-exergy equivalent to the capital consumed calculated by multiplying ee_K and the monetary expenditure to obtain EE_K in Joule.

Furthermore, exergy production through local economic activities are treated as imports from the environment (represented by the node labelled as E in Figure 4.2) resulting from extraction of new resources. For example, agricultural, forestry and mining activities draw inflows of exergy into the system from the external environment to sustain local consumption.

In the development of OSNEA, the integration of thermodynamic and economic systems follows the principle of a hybrid input-output analysis where exergy serves as an extension vector to the normalised monetary input-output matrix. The monetary transactions in the input-output matrix can be used as proxies of resource flows. The resultant input-output matrix, as shown in Figure 4.2, is the adjacency matrix of the flow network which has the same number of rows and columns as the total number of nodes in the network where each node represents a sector. In addition to the aggregated sectors of economic activities, a domestic node, labelled as Do, is also included to account for household consumption and labour contributions to the local economy in terms of EE_{L_i}. Moreover, EE_{K_i} for services and monetary flows of GVA and GFCF, go through a capital node labelled as K and any addition or reduction in local stock inventories is handled by node labelled as Inv. Net flows at node K are treated as capital incomes of the economy. For external nodes outside the system, flows from node E represent resource extractions from the natural environment while node A represents the abroad environment that interacts with the system via imports and exports. Furthermore, each element of the matrix represents a directional weighted edge between two nodes such that f_{ij} indicates a flow from the sector in row j to the sector in column i.

4.5. Resource effectiveness indicators

OSNEA evaluates the ability of the system to utilise the resource imported through the *effectiveness of utilisation* indicator, ε_U, and the ability to convert the resource imported to useful products through the *effectiveness of conversion* indicator, ε_C. The *effectiveness* indicators, utilisation and conversion, represent the consumer and producer characteristics of the ecosystem respectively. The following sections demonstrate the formulations and implementation of the *effectiveness* indicators in the OSNEA framework.

4.5.1. Definition and formulation of effectiveness

From Carnot cycle, the theoretical maximum efficiency, η_{ideal}, for an energy transfer process is defined as:

$$\eta_{ideal} = (1 - \frac{T_l}{T_h}) \times 100\% \tag{4.8}$$

where the ratio of the temperature at the cold sink, T_l, to the temperature at hot source, T_h, acts as the limiting factor to the maximum achievable efficiency. Expressing Equation 4.8 in terms of the rate of work, $\dot{W}$, and the rate of heat energy input, $\dot{Q}_{in}$, gives:

$$\dot{W}_{ideal} = \dot{Q}_{in} \times \eta_{ideal}. \tag{4.9}$$

Applying the same principles on the metabolism of urban socio-economic activities, the maximum outputs from the sectors and their processes are limited by the capacity of infrastructure facilities, technology available and operational efficiencies. If all the sectors are operating under their ideal conditions, assuming zero waste emission, the net difference between the input and output exergies is assumed to be inevitably destroyed when the resource available is utilised in order to maintain the processes at their maximum efficiencies. Development of inter-connected pathways between the sectors allows longer circulations of resource flows in the network through cascading processes in the system which results in more exergy transformation and destruction as the system grows with increasing resource inflow (Kay *et al.*, 1989).

To examine the use of resources imported, exergy destruction serves as a measure of the exergy dissipation capability of a system in converting the energy available to produce useful work done. The conceptual diagram in Figure 4.3 shows the flow exchanges at a single node i.

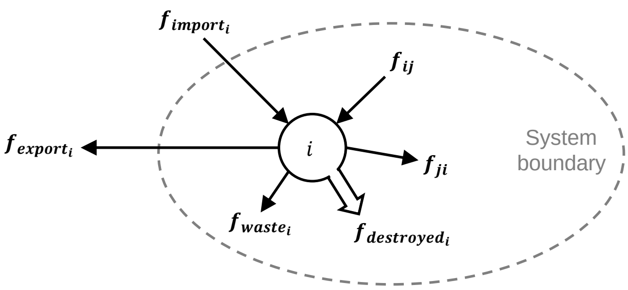

Figure 4.3: The conceptual diagram showing the flow balance at node i.

As shown in Figure 4.3, inputs to i, $\sum f_{input_i}$, are: import to i from the external environment, f_{import_i}, and any intra-system flow supplied from other nodes j, f_{ij}. The outputs from i, $\sum f_{output_i}$, are: export from i to the external environment, f_{export_i}, and any intra-system flow to other nodes j, f_{ji}, as well as the waste emitted, f_{waste_i}, from the system including the greenhouse gases (GHG) emission. From these, the net flow at i is the exergy destroyed at node i, $f_{destroyed_i}$, as resources are being utilised locally. Thus, the exergy balance at i is:

$$\sum f_{input_i} = \sum f_{output_i} + f_{destroyed_i} \tag{4.10}$$

$$f_{import_i} + f_{ij} = f_{export_i} + f_{ji} + f_{waste_i} + f_{destroyed_i}. \tag{4.11}$$

For all nodes in the whole network, the resultant sums of intra-system flows are equal such that $\sum f_{ij} = \sum f_{ji}$, so these terms are cancelled out. Thus, exergy balance for the whole network with a network size equal to m is:

$$\sum_{i=1}^{m} f_{import_i} = \sum_{i=1}^{m} f_{export_i} + \sum_{i=1}^{m} f_{waste_i} + \sum_{i=1}^{m} f_{destroyed_i} \tag{4.12}$$

$$\sum_{i=1}^{m} f_{import_i} = \sum_{i=1}^{m} f_{export_i} + \sum_{i=1}^{m} f_{waste_i} + \sum_{i=1}^{m} f_{input_i} - \sum_{i=1}^{m} f_{output_i}. \tag{4.13}$$

For an OSNEA implementation, Table 4.2 shows the metrics considered in the framework to examine the performance of an urban system in the contexts of resource use and environmental sustainability.

Table 4.2: Description and equations for the metrics used in the OSNEA framework.

Metric	Equation	Description
Exergy import $[J]$	f_{import_i}	The total exergetic content of cross-boundary resources entering the system at city's boundaries received by each sector, including local production and extraction of natural resources, calculated from mass flows.
Effectiveness of utilisation, ε_U	$\frac{\sum_{i=1}^{m} f_{destroyed_i}}{\sum_{i=1}^{m} f_{import_i}}$	A new dimensionless system-wide performance metric based on the ratio of exergy destruction to total exergy import, representing a fraction of the total resources imported that is utilised in the system to produce work done.
Effectiveness of conversion, ε_C	$\frac{\sum_{i=1}^{m} f_{export_i}}{\sum_{i=1}^{m} f_{import_i}}$	A new dimensionless system-wide performance metric based on the ratio of the total exergy export (including capital generation and output to inventory) to the total exergy import, representing a fraction of the total resources imported that is converted to useful products for exporting purposes.
Exergetic efficiency	$\frac{\sum_{i=1}^{m} f_{output_i} - \sum_{i=1}^{m} f_{waste_i}}{\sum_{i=1}^{m} f_{input_i}}$	A dimensionless ratio of the total aggregated useful output (except f_{waste_i}) to the total aggregated input of a sector, representing the useful work produced with a given resource intake.
Exergy intensity $[J/monetary\ unit]$	$\frac{f_{import_i}}{GVA_i}$	Exergy imported to generate per unit GVA of a sector.

It is worth clarifying that the new indicator introduced in Table 4.2, *effectiveness of utilisation* (ε_U), is different to the terminology of *utilisation efficiency* used in other analysing methods (Rosen, 2007, B. Zhang *et al.*, 2018). These often refer energy utilisation merely as reflection of resource consumption and evaluate the utilising efficiency based on the total resource input. In the current work, utilisation results from the energy transformation processes that cause quality degradation and exergy destruction. The metric of *effectiveness*, with a denominator of exergy import, refers to the ability of the system to utilise or convert the high-quality resources imported to achieve work done or create other useful products. In contrast to the description of *effectiveness of conversion* (ε_C) introduced in Table 4.2, Sciubba (2008) defined *conversion effectiveness* as the ratio of extended-exergy output to the equivalent exergy input. ε_C defined here is a system-wide indicator to measure how much of the resources imported is converted to products that are exported in exchange for monetary income or contributed to the local stock inventory.

The idea of OSNEA is to describe the producer and consumer behaviours of an urban ecosystem based on their *effectiveness* performances to indicate how much of the high-quality resources imported into the cities is effectively utilised and converted to useful work through local processes. The arguments are:

- For producing sectors, higher ε_C and efficiencies are preferred to improve the system transformation processes at minimal costs and waste emission;
- For consuming sectors, the meaningful measure of ε_U is the ability of the system to maximise the use of resources available and reduce the needs for new extraction or import.

From these arguments, the results provide new insights to assess system performance based on the ecological behaviours exhibited through the *effectiveness* indicators. In addition to the *effectiveness* indicators, measuring the exergetic efficiency and exergy intensity of a sector (as formulated in Table 4.2), or for the entire economy, gives an empirical comparison of different resource use metrics to perform a complete assessment of the system performances from all aspects of urban sustainability.

4.5.2. Overall resource effectiveness and balance from the effectiveness plot

Following the law of energy conservation, the frontier of system effectiveness is subjected to the thermodynamic limit bounded by the total amount of resource available in the system through exergy imports, $\sum_{i=1}^{m} f_{import_i}$. From Equations 4.12, assuming zero waste emission under the ideal operating conditions for all sectors ($f_{waste_i} = 0$) within the system, the maximum value of exergy import available in the system can be computed as:

$$\sum_{i=1}^{m} f_{import_i} = \sum_{i=1}^{m} f_{export_i} + \sum_{i=1}^{m} f_{destroyed_i}. \tag{4.14}$$

From the equations in Table 4.2 the thermodynamic limit of ε_U and ε_C can then be derived as:

$$\varepsilon_{U,limit} = 1 - \frac{\sum_{i=1}^{m} f_{export_i}}{\sum_{i=1}^{m} f_{import_i}} \tag{4.15}$$

$$\varepsilon_{C,limit} = \frac{\sum_{i=1}^{m} f_{export_i}}{\sum_{i=1}^{m} f_{import_i}}. \tag{4.16}$$

For open system network where the available resources are supplied through imports, it is assumed that $f_{import_i} > f_{export_i}$ and therefore, from the formulae of $\varepsilon_{U,limit}$ and $\varepsilon_{C,limit}$ in Equations 4.15

and 4.16, the ranges of ε_U and ε_C are as follows:

$$0 \leq \varepsilon_U < 1 \quad (4.17)$$

$$0 \leq \varepsilon_C < 1. \quad (4.18)$$

Although both ε_U and ε_C are expressed as a ratio to the exergy import and have an upper limit of 1 due to the thermodynamic limit of the overall system, the values of ε_U and ε_C does not necessarily sum to unity when taking into account of the non-energetic externalities such as capital flows and labour work in terms of extended-exergy. Another reason for the *effectiveness* values to exceed the limit of 1 is because of the potential withdrawal of goods from local stock inventories and generation of extended-exergy equivalent to GFCF and incomes from exports added to the capital reserve in the city, as recorded in the input-output table, in which case both are not counted as import and export of the system therefore would result in a sum greater than 1.

An effectiveness plot, as shown in Figure 4.4, is used to show the system performance by plotting the trajectory of ε_U against ε_C through time. Measuring the magnitude and angle from the horizontal axis of the effectiveness plot gives the *overall resource effectiveness* (R) and the *overall effectiveness balance* (θ) respectively on a polar coordinate system.

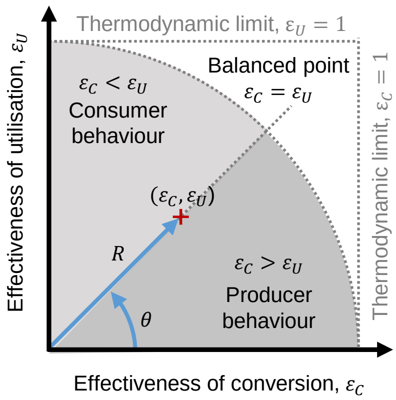

Figure 4.4: An effectiveness plot of ε_U against ε_C and the schematic frontier of the thermodynamic limit at magnitude equal to 1, as both axes are bounded by a maximum value of 1.

As shown in the effectiveness plot, R and θ can be calculated from the values of ε_U and ε_C:

$$R = \sqrt{\varepsilon_U{}^2 + \varepsilon_C{}^2} \quad (4.19)$$

$$\theta = tan^{-1}\left(\frac{\varepsilon_U}{\varepsilon_C}\right). \quad (4.20)$$

The values of R assess the *overall resource effectiveness* performance of the whole system in making use of the resources available for both utilisation and conversion purposes while θ gives a numerical quantifiable measure of the balance between production and consumption activities in the whole system such that:

- When $\varepsilon_C > \varepsilon_U$ and $\theta < 45°$, the system inclines towards producer behaviour.
- When $\varepsilon_C < \varepsilon_U$ and $\theta > 45°$, the system inclines towards consumer behaviour.

Plotting the results of *effectiveness* in a time series provides the trajectory of system behaviour which can then be interpreted as the system responses to the changes in the amount of resource supplied through imports. A system can have interchangeable producer-consumer behaviour through time in order to achieve a balance by regulating the distribution of resources available among the producing and consuming sectors to maintain the value of θ close to 45°. The thermodynamic limit of *effectiveness* (dashed-curve-line) shown in Figure 4.4 assumes the maximum magnitude, R_{limit}, is equal to 1, however, this requires further analytical work to estimate the theoretical limit of *effectiveness*.

4.6. Data requirements

The OSNEA framework is designed and developed to study the metabolism of urban economies as open systems. From the workflow illustrated in Figure 4.1 (raw data inputs are in circles), the types of data input required are:

- Mass data of cross-boundary resource imports and exports to compute the inflow and outflow of the system
- Monetary input-output supply and use table
- Resource extraction from the natural environment through local production activities
- Employment data (total work-hours, number of employees and wages) by sectors
- GHG emission factor of industrial and domestic energy use

Official statistics usually hold yearly records of the required data, though these may vary with different case study cities. In the OSNEA framework, the rates of resource flows and exergy destruction are calculated based on the annual figures. Therefore, for the sake of simplicity, the rate of resource flow, f is measured in the unit of $Joule\ per\ year$.

For accounting economy-wide GHG emissions, estimates can be calculated by using an emission factor as a coefficient to convert activity statistics to GHG emissions such that (National Atmospheric Emission Inventory, 2017):

$$Emission = Factor \times Activity \tag{4.21}$$

For example, emission factor for carbon dioxide, CO_2, measures the amount of CO_2 released to the atmosphere, in term of the equivalent mass of CO_2 produced by a unit of activity conducted such as energy combustion or electricity generation. In this study, GHG emissions based on the activities of exergy imports (measured in the unit of $Joule$) by the industries are calculated by using the emission factor data.

4.7. Chapter conclusion

This chapter demonstrated the development workflow of OSNEA as a novel assessment framework to investigate the effectiveness of resource utilisation and conversion in cities. As outcomes of the work demonstrated in this chapter, the derivation and formulation of ε_U and ε_C indicators offer two new exergy-based metrics to assess urban sustainability and promote better use of all resources available. The following chapters present two case studies for understanding urban metabolism of a single-city system in Singapore and a multi-city system for the cities in Great Britain using the new OSNEA methodology.

Chapter 5

An OSNEA case study of Singapore: A single-city system

The current chapter contains material that was previously prepared for the following articles:

Tan, L. M., Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.

5.1. Chapter introduction

To verify and validate the Open System Network Effectiveness Analysis (OSNEA) framework developed in Chapter 4, this chapter will demonstrate the application of OSNEA in a case study of Singapore representing a single-city model to account for the resource use based on the total aggregated imports and exports across system's boundary, over the time period of 2005-2014. OSNEA is adopted to investigate the city' behaviours based on the resource flow connections and evaluate the ability of the system to utilise the resource imported through *effectiveness of utilisation* (ε_U) and the ability to convert the resource imported to useful products through *effectiveness of conversion* (ε_C).

In this chapter, Section 5.2 provides a brief background of the case study location and the network representation of Singapore economy structure. Section 5.3 gives the accounting of total resources imported by Singapore throughout the years in the quantities of mass and exergy. Next, Section 5.4 compares the application of monetary and exergy-based ecological network analysis (ENA) to analyse the metabolic relationships within the urban economy as a comparison to the use of conventional monetary flows. Sectoral efficiencies and effectiveness results from OSNEA are included in Section 5.5. Next, Sections 5.6 and 5.7 discuss about the implications and limitations of the study and lastly, Section 5.8 concludes the chapter. See Appendix 4 for the Python script used to generate the results presented in this chapter.

5.2. Case study background

Singapore is an island city-state which has limited reserves of natural resources. As such, the inflow of resources is drawn into the city through foreign imports, resembling an open system. The maritime border of the city automatically draws a distinct and intuitive boundary distinguishing foreign imports from intra-system flows in the urban scale economy. For these reasons, Singapore is perfectly suitable as a case study with its own entry of input-output data. Earlier urban metabolism (UM) studies of Singapore have demonstrated a wide variety of methods performed to study this city, including the applications of material flow analysis to evaluate domestic material consumption (Schulz, 2007), life cycle assessment to investigate embodied emissions (Schulz, 2010) and a non-equilibrium thermodynamics framework to explore urban growth (Bristow and Kennedy, 2015).

In this case study, OSNEA is applied to the socio-economic system of Singapore to examine the functionality of the city and assess states of resource use in the economy over a time period. According to Singapore Standard Industrial Classification (SSIC), Table 5.1 shows the intra-sectoral classification based on the city's economic structure. The resultant classification has to comply with the aggregation format of official employment and economic data for extended-exergy accounting of labour work and capital flows. The datasets required are: economy and employment data from the Singapore Department Statistics (2018), resource use and greenhouse gases emission data from the Energy Market Authority (2018) and local production data from the Agri-Food and Veterinary Authority (2018). From the sources available, data for 2005, 2007, 2010, 2012, 2013 and 2014 are extracted in this case study. For an OSNEA application, network representation of the urban system, including the sectors (nodes) and flow connections (edges) within the city, is as illustrated in Figure 5.1.

Table 5.1: Intra-sectoral economic activities and description based on SSIC 2015.

Sector and Abbreviation		Section	Description
P	Production	A	Agriculture and fishing
		B	Mining and quarrying
		D	Electricity, gas, steam and air-conditioning supply
		E	Water supply; sewerage, waste management and remediation activities
M	Manufacturing	C	Manufacturing
C	Construction	F	Construction
WR	Wholesale and Retail	G	Wholesale and retail trade
TS	Transportation and Storage	H	Transportation and storage
AF	Accommodation and Food	I	Accommodation and food service activities
IC	Information and Communication	J	Information and communication
FI	Financial and Insurance	K	Financial and insurance activities
B	Business	L	Real estate activities
		M	Professional, scientific and technical activities
		N	Administrative and support service activities
S	Other services	O	Public administration and defence
		P	Education
		Q	Health and social services

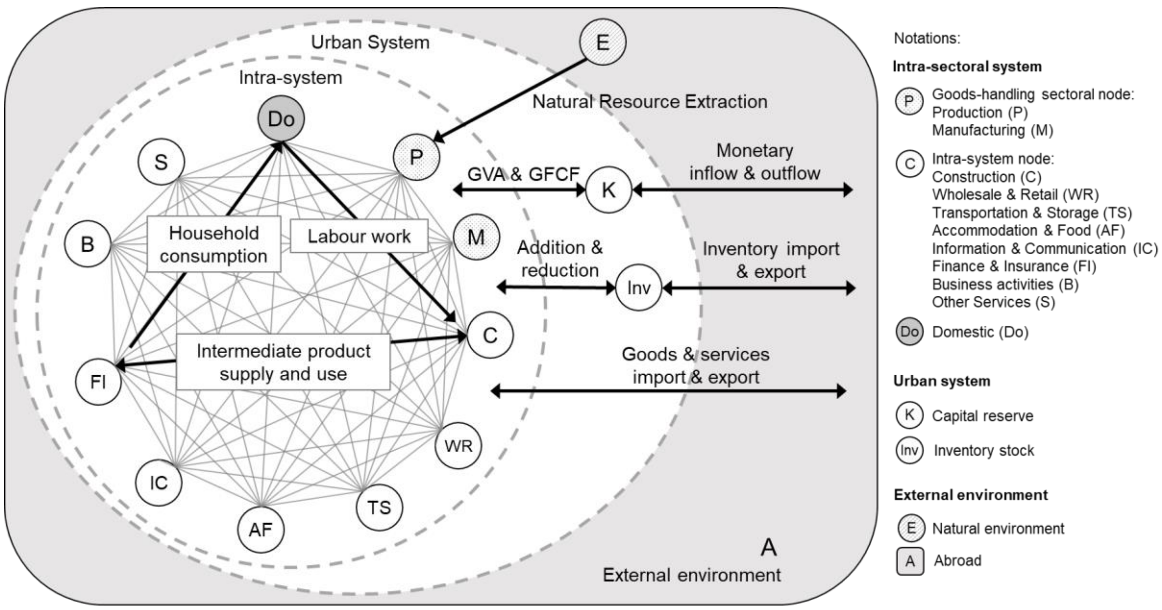

Figure 5.1: Network representation of open system network for the case study of Singapore.

5.3. Mass and exergy imports

The city's import use data shows the quantities and types of goods and services imported by each sector. The accounted goods imported are obtained from the Comtrade database (United Nations Department of Economic and Social Affairs, 2018), following the 4-digit Harmonised Commodity Description and Coding System, correspondence to the 2007 revision. The aggregated sectors in the classification and description of economic activities follows the national input-output table for all imports and exports. Figure 5.2 shows the mass of goods and the total exergy flows (equal to the sum of exergetic content of the goods and the extended-exergy of services) imported by the sectors in 2005, 2007, 2010, 2012, 2013 and 2014.

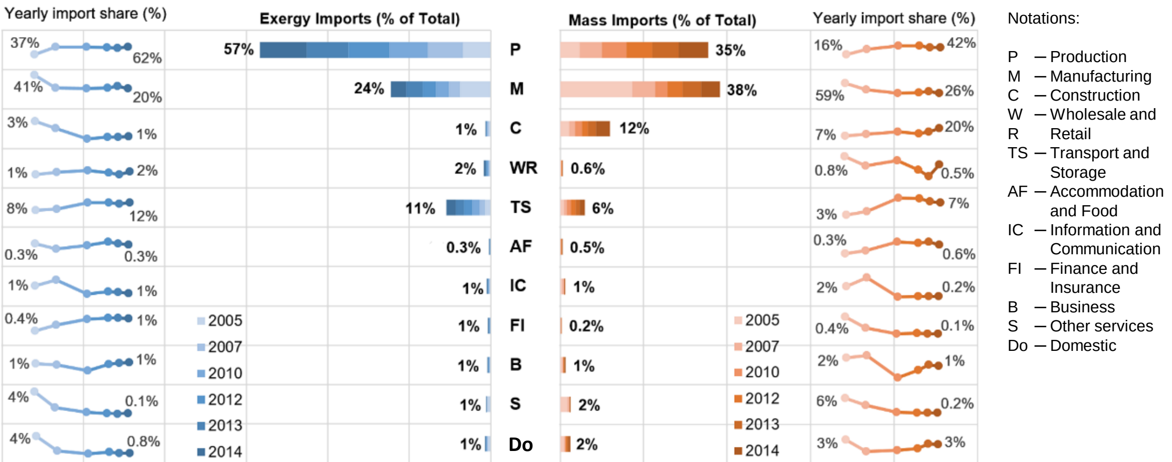

Figure 5.2: The comparison between the sum of exergy (left) and mass (right) imported by each sector, as a percentage of total resource imported by all the sectors in all six years. The trends of yearly import share by each sector are shown as a percentage of resource import by each sector in that year.

The results in Figure 5.2 show the highest mass import (36%) by the manufacturing sector due to a large quantity of resources imported to be used as the raw materials for local manufacturing activities. The production sector has the highest exergy import (55%) because the sector largely imports high-quality energy carriers such as coal, natural gas and petroleum to power local utility services in the city. It is expected that the construction and manufacturing sectors would have higher mass import due to the large quantity and weight of building materials, while the transportation and storage sector would have high exergy import due to high fossil fuel consumption. From the exergy import data, the trends of exergy and monetary intensities of Singapore's economy based on their annual Gross Domestic Product (GDP), in relative to the year 2005, are shown in Figure 5.3.

Although the exergy and monetary intensities of all sectors (including the domestic sector with no GDP contribution) have changed steadily since 2005 (shown as the solid-black-line in Figure 5.3), a wide variation is observed across the different sectors (represented by coloured-lines). For instances, the transportation and storage sector and the business sector have lower exergy intensity in the early years but eventually require more exergy imports for further GDP generation in the later years. Comparing the monetary intensities among these sectors, the importing cost per unit GDP has increased enormously (up to 6 times) from 2005 in all sectors except for the services sector with declining monetary intensities. It is worth noting that the manufacturing sector is one of the high-income sectors and managed to maintain low intensities throughout the years.

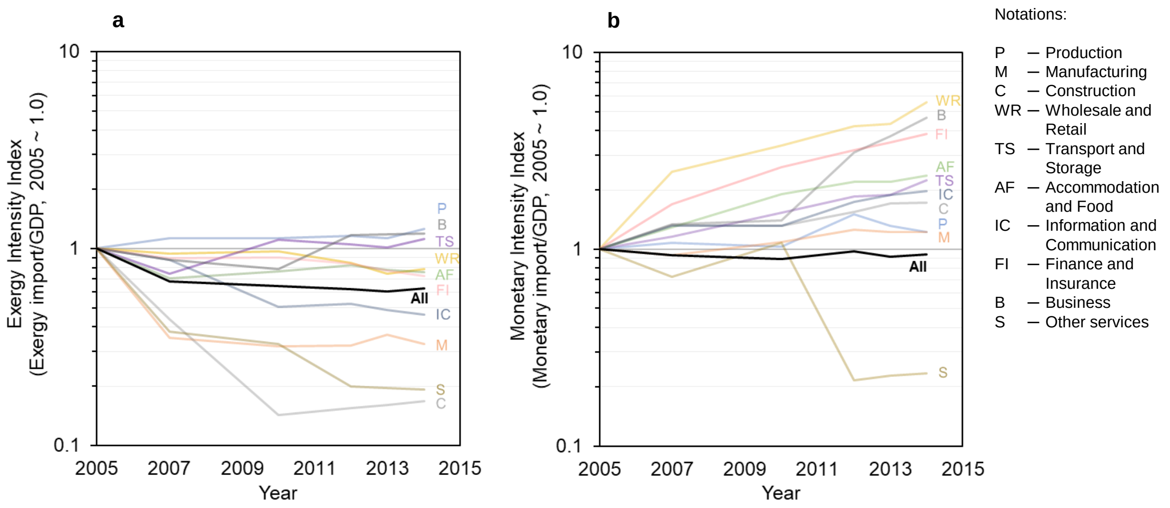

Figure 5.3: Change in (a) exergy intensity (exergy import per unit GDP generated), (b) monetary intensity (monetary equivalence to the import per unit GDP) relative to the year 2005 (2005~1.0).

The exergy import and intensity results give an overall account of the resource intake by an open system network through a wide range of economic activities in the city over the years and compare multiple units (e.g. exergy, mass, monetary units) used to quantify the amount of resource imported. The comparison between exergy and monetary intensities shows that exergy is a better representation of the flows to describe the resource exchanges between the sectors.

5.4. Exergy-based ecological network analysis

ENA is also applied to both monetary and exergy-based input-output flow matrices to study the metabolism of Singapore based on the exchanges between sectors. Figure 5.4 shows the ENA results of control, dependency and metabolic relationships between the sectors, for the year 2010 with both exergy and monetary flows. See Appendix 5 for the supplementary plots of all ENA results.

The plots in Figure 5.4(a) reveal the differences between the controlling sectors when comparing the analyses of monetary values and exergy resources. With monetary flows, the tertiary sectors (such as the finance and insurance sector and the information and communication sector) are in stronger control whereas in the case of exergy flows, the transportation and storage sector if of substantially higher control over the amount of resource consumed by most of the other sectors. This highlights the role of the transportation and storage systems as a resource distributor. In Figure 5.4(b), for exergy flows, a pattern for concentrated dependencies is observed at the domestic sector as one would expect for the domestic households to be the main consumers in the ecosystem. Therefore, household consumption is heavily dependent on the production of other sectors to deliver the products or services required by the end-users in the domestic sector. The relationships mapped in Figure 5.4(c) shows consistent mutualism across the diagonal due to the benefits of self-promotion within the same industries. However, competition relationships are observed between the accommodation and food sector and other tertiary sectors (such as the finance and insurance sector, the business sector, the services sector) as they compete for the same resources and cause negative impacts on both parties. For exergy flows, the side above the diagonal is mainly dominated by light-grey patches (X exploits Y) while the side below the diagonal has more dark-grey patches (Y exploits X) because the importers (i.e. the production sector, the manufacturing sector and the transportation and storage sector) are exploited. This means they are losing resources to support others' benefits through imports from abroad. In contrast, results from monetary flows show an inverted pattern across the diagonal due to higher monetary flows at the consuming sectors which also have lower energetic values. Although the use of monetary evaluation is common for assessing economic performance of cities, the quantity of exergy is a better suited unit to describe the resource use behaviour of an urban ecosystem in the study of UM.

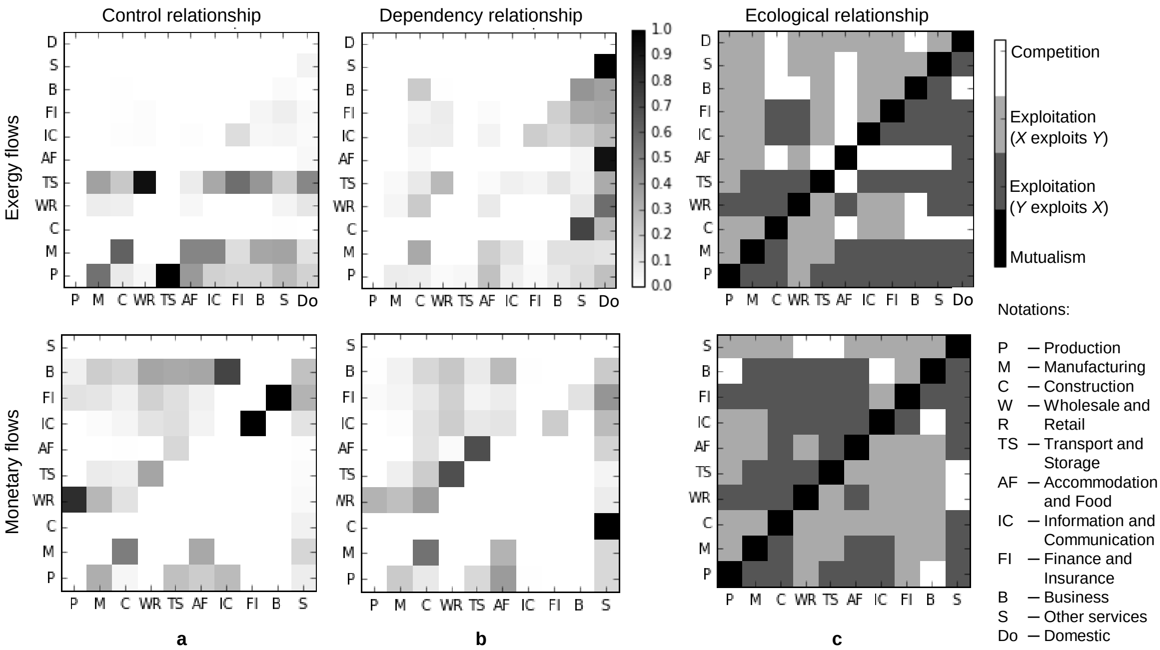

Figure 5.4: ENA results for the year 2010, showing (a) control relationship, (b) dependency relationship and (c) ecological relationships, mutualism, exploitation and competition, between the sectors based on exergy (top row) and monetary (bottom row) flows. Noted the continuous colourbar applies to the plots in both (a) and (b) to show the control and dependency relationships for the urban systems with a normalised scale from 0 to 1, while the discrete colourbar applies to the plots in (c) to describe the types of pairwise relationships between the sectors.

From Figure 5.4, the individual sectors fit well within their respective ecological roles based on the types of economic activities. Following the hierarchical structure of an ecosystem, the producing sector on the lowest level is the main supplier to support the upper-level consumers hence, the production sector is being exploited by others. On the intermediate level, the distributing sector acts as the primary consumer that connects the resource supply chains between the lower and upper levels hence, the transportation and storage sector controls the consumption of other sectors in the ecosystem. The final consumer at the highest level relies on the lower-level suppliers hence, the domestic sector is highly dependent on the production of other sectors. Therefore, comparing to the results in Figure 5.4, it can be deduced that the ecosystem of Singapore is balanced and supported mainly by the resources imported to maintain the city's metabolism. For a balanced system, targeted policy interventions to regulate consumption activities along the resource supply chains in the urban economy will help to reduce the imports and material extractions for sustainable urban development.

5.5. Sectoral efficiencies and system effectiveness

For a thermodynamic system, efficiency reflects the productivity of each sector based on the aggregated inputs from all sources regardless of the flow destination or the source. At the optimum processing efficiency, resource intakes through local supplies helps to increase flow circulations within the system and reduce the demands for importing new resources. Figure 5.5 shows the scatter plot of efficiencies against exergy imports for each individual sectors.

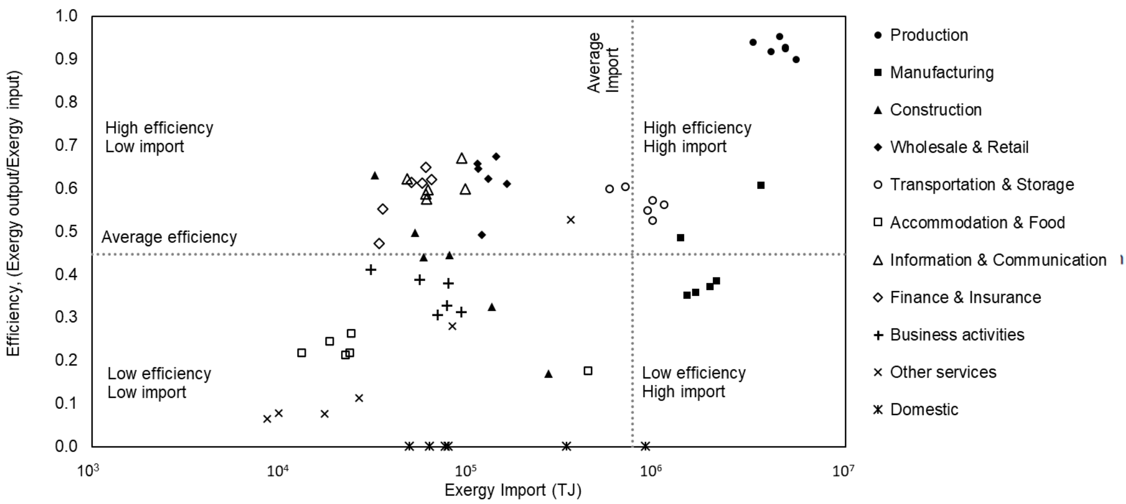

Figure 5.5: The efficiency and exergy import (log-scale) of each sector distributed over four quadrants bounded by the system-wide average values (each point represents a year).

As shown in Figure 5.5, the sectors fitted within the range of high efficiency and low import (in the top-left quadrant) are the finance and insurance sector, the information and communication sector and the wholesale and retail sector. The finance and insurance sector and the information and communication sector belong to the group of tertiary sectors which only require minimal resource import (mainly services) to sustain their activities. The wholesale and retail sector manages the flow distribution among the sectors to deliver goods and services from the producers or importers to the consumers, which helps to retain local resources in order to maintain high efficiency performances and low imports. Among the sectors with high imports, the production sector has the highest efficiencies as the main importer of primary energy acting the role of producer in the ecosystem. Although the manufacturing sector is regarded as inefficient and has high imports in Figure 5.5, the sector also has low exergy intensities with high GDP contribution for economic benefits as shown in Figure 5.3. Furthermore, as the essential consumers, the domestic sector, has the lowest efficiency because labour work is the only output from household activities. These observations reinforce the balanced ecosystem deduced from the ENA results at the end of Section 5.4.

OSNEA evaluates the effectiveness of resource use through urban processes based on the imported resources available in the city. Figure 5.6 shows the effectiveness trajectory of Singapore through time (2005-2014). As demonstrated in Section 4.5, the axes of an effectiveness plot each represent an OSNEA indicator: on the vertical axis, *effectiveness of utilisation* (ε_U) measures the ratio of exergy destruction to the total exergy import, representing the fraction of the total resources imported that is utilised in the system to produce work done whereas on the horizontal axis, *effectiveness of conversion* (ε_C) measures the ratio of exergy export (including capital generation and output to inventory) to the total exergy import, representing the fraction of total resources imported that is converted to useful products for exporting purposes, in exchange for capital inflow. These are designed based on the hierarchy of urban ecosystem, so that for the producing sectors (on the lower hierarchical levels), higher ε_C and efficiencies are preferred to improve the system transformation processes for minimal costs and waste. For the consuming sectors (on the higher hierarchical levels), ε_U measures the ability of the system to maximise the use of all resources available and reduce the need for new extraction or import.

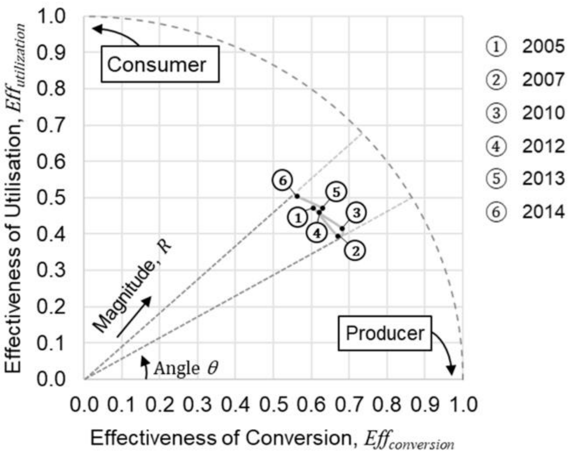

Figure 5.6: The trajectory of ε_U and ε_C (in the ascending order from ① to ⑥) and the schematic frontier of the thermodynamic limit at magnitude equal to 1, as both axes are bounded by a maximum value of 1.

The results show that the system has utilised 39% (2007) to 50% (2014) of the total usefulness equivalent to the total resources imported ($0.39 < \varepsilon_U < 0.50$) through exergy destruction. The conversion outputs have a total usefulness equivalent to 56% (2014) to 68% (2010) of the import ($0.56 < \varepsilon_C < 0.68$) to generate capital inflows for economic growth. The increase in the radius magnitude, which represents the overall resource effectiveness of the system, R, from 0.75 (2014) to 0.80 (2010), indicates an overall improved performance. The system shifted towards higher ε_U and lower ε_C in after a significant change in trajectory direction between 2007-2010, showing an increasing resource utilisation by the system. The back-and-forth trajectory, with fluctuating polar angle θ representing the overall effectiveness balance varies from 30° (2007) to 42° (2014), suggests a trade-off between ε_U and ε_C . From Figure 5.6, between 2005-2007, the ε_C increases but the ε_U decreases and an opposite behaviour between 2010-2012 and 2013-2014. These movements can be interpreted as the system organises internally and compromises to achieve a balance (assumed 45°from the axes) between the producing and consuming sectors, although the results for the recent years are more inclined towards a consumer-like behaviour owing to the growing services and domestic sectors. The thermodynamic limit (dashed-curve-line) shown in Figure 5.6 assumes the maximum magnitude is equal to 1, however, this requires further analytical work to estimate the theoretical limit of effectiveness as discussed in Section 4.5.2.

5.6. Insights and implications from the case study

In this study, OSNEA investigates the ecological behaviours of Singapore socio-economic system, through a time period, to provide novel insights of the system performance using a pair of new *effectiveness* indicators (ε_U and ε_C) to assess urban sustainability. The indicators quantify the ability of an urban system to extract the maximum usefulness from resources available. Comparing to other UM methods which merely focus on cities' consumption and emissions, OSNEA addresses an often-overlooked criterion of resource utilisation in cities that should be understood in the global development agenda. Measuring resource utilisation based on the rate of exergy destruction to the total imports of the city shapes a new dimension to understand UM with a novel method of evaluating resource use through the new performance metrics. This requires a call for attention and incentives from global researchers and policymakers to redefine urban sustainability and promote effective use of high-quality city resources.

Introduction of the OSNEA framework sheds light on the issues concerning the state of resource utilisation in urban systems. The ε_U indicator measures how much of the resources imported into the city have been utilised based on the rate of exergy destruction; the model indicates operations at higher utilisation rates are more resource-effective. Furthermore, the ε_C indicator complements the assessment framework by considering the conversion rate for generating useful resource outputs based on the imports. The *effectiveness* indicators in OSNEA differ from the conventional measurements of process efficiency from the output-to-input ratio by assessing system performance based on the total resources imported. High *effectiveness* indicates longer resource circulations within the flow network to achieve the states of maximum resource use and complete degradation through cascading processes. From a circular economy (CE) perspective, *effectiveness* serves as a measure of system circularity and flows transmission within the network to promote higher *effectiveness* through higher connectivity and longer use cycles. The *effectiveness* indicators can also be used to measure circularity of flows in an urban network by assessing the rate of resource utilisation when the work done is extracted from the available resources (causing exergy destruction) through socio-economic processes in cities. Following the principles of CE, retaining resource flows in use within the urban network increases the connectivity, circulations and utilisation of resources which is reflected as higher effectiveness using the OSNEA indicators. From the *effectiveness* results in Figure 5.6, Singapore has, on average, utilised 45% of the maximum extractable usefulness from the resources imported over the years, showing a significant potential to achieve higher *effectiveness* by lowering the imports and wastes. The system has, on average, converted 63% of the imports to local stock additions and capital incomes through exports.

Exergy analysis is a convenient tool for accounting the work extractable and transformations of resource flows across different urban processes and economic activities in different sectors. In Figure 5.4, the exergy-based ENA has captured the inter-dependencies between the sectors and revealed a spectrum of ecological roles within the economic structure. Furthermore, another advantage of exergy over monetary-based ENA is the expansion of the network beyond intra-sectoral system, meaning labour and capital flows are included.

The essence of OSNEA is the establishment of *effectiveness* indicators to describe the ecological behaviours of the system. In Section 4.5, the arguments relate *effectiveness* to the ecological roles of different sectors in the socio-economic system. The results in Figure 5.6 suggest a trade-off relationship between the producing and consuming sectors in the city, while the results in Figure 5.3 show that the intensities of all sectors remained steady since 2007 compared to the changes in individual sectors. From the perspective of urban industrial ecology, maintaining the ecological balance between the producers and consumers in an ecosystem is important to ensure the coexistence of different sectors within the same environment and long-lasting organisational stability. Thus, the work on OSNEA is closely related to the urban ecosystem analogy and has similarities with Kay's discussion on self-organising behaviours in dissipative open systems for better understanding of cities (Kay *et al.*, 1999).

Confining the frontier limit of the trajectory would assist urban planners and resource managers to focus on the more practical objectives in their development agenda. This helps in optimisation of system performance by identifying the areas for potential improvements of resource use in the system. For instance, introducing trade tariffs that regulate the imports and exports to manage the distribution of resources among the producing and consuming sectors in the city helps to maintain the balance by closing the development gaps between sectors. From a broader perspective, this also applies to the relationship with the external environment as unregulated patterns such as consumption beyond planetary limits could disrupt the ecological balance and lead to system collapse, causing irreversible damage to the natural ecosystem and the environment.

The findings can inform decision makers of the potential leverage points for policy interventions as OSNEA provides insights integrated across the social, economic and environmental aspects. This case study adds to the ongoing debate on decarbonising urban activities through the quantification of the performance of resource-intensive sectors such as utilities provision, manufacturing and transportation due to high exergy imports, as shown in Figure 5.2. Switching to renewable energy sources or low-carbon alternatives can help to relieve the high concentration of energy footprint in cities and reduce the demands for high exergy imports, improving the overall effectiveness performance with larger radius magnitude, R. New interventions should also consider the impacts on the socio-economic system concerning local businesses, labour employment and consumer prices. For example, employing advanced technologies can increase the efficiencies of the manufacturing sector which was found to have high imports but low processing efficiency in Figure 5.5, however, this may cause unemployment due to automation and result in rising living costs. The framework provides decision-makers with a tool to assess the system requirements and contemplate the necessities of compromising resource intakes and economic incomes for long-term environmental sustainability in future development.

5.7. Limitations

The key limitation of this case study is the lack of spatial characterisation in the OSNEA framework to describe the distribution of metabolic performance across the city. This study demonstrated a sector-based approach as a vital first step to address the challenges to urban sustainable development providing insights of the resource needs of the sectors based on Singapore's economic structure and industrial mix. This can be integrated with a spatial analysis to inform decision making for planning resource allocation and distribution across the economic sectors based on their geotagged locations when the data becomes available.

The shortcomings of data available, at the urban level, could be due to syntactic incompatibilities between different data sources with varying resolutions and timescales when the data were collected. The input data of resource flows, either in mass or their equivalent exergetic contents, are assumed to share the same chemical and exergetic properties as homogenous materials and hence, are also subject to accounting errors when the variations in quality between the individual commodities are neglected. In some cases, the consistency and continuity of temporal data are not guaranteed. In this case study, the time series data consist of only six non-consecutive years (2005, 2007, 2010, 2012, 2013 and 2014) because the input-output data for the intermediate years are unavailable.

To improve the overall validity of the results, a sensitivity analysis is conducted based on the uncertainties of the input data to determine the degree to which the accuracy of material data would impact the final outcomes of the study. The variations are calculated as a relative change in the original values of ε_U and ε_C (at ±0% uncertainty) according to the percentage uncertainty of exergy conversion values using the formula below:

$$Variation\ in\ \varepsilon\ at\ \pm x\% = \frac{\varepsilon_{\pm 0\%} - \varepsilon_{\pm x\%}}{\varepsilon_{\pm 0\%}} \tag{5.1}$$

Preliminary observations from the sensitivity analysis, as shown in Figure 5.7, for different resource types suggest the results of ε_U and ε_C are more sensitive towards the uncertainties in fossil fuel products in case (b), compared to other products in cases (a) and (c). The exergy contents of fossil fuels are estimated from the calorific values (Energy Statistics Division, 2005; Morris and Szargut, 1986) because accurate fossil fuel data is of higher significance to mitigate the loss in data accuracy for other materials.

For uncertainties range from 0% to ±50%, the results, in all cases, vary by less than 15% ($0.85 <$ variation in $\varepsilon_U < 1.10$) with the highest variation observed in case (b) for fossil fuel products only. This is acceptable because the uncertainties induced do not affect the conclusion of the study as the back and forth trade-off relationship between the producing and consuming sectors observed from the effectiveness trajectory plot over the time period studied remains the same as the original pattern. Comparing the results for different years in all cases, variation in 2014 is found to be the highest for both ε_U and ε_C results although the exergy imports in 2005 and 2014 are very similar. This is because of the higher imports by the production sectors in 2014 where the products are of higher exergetic contents so the results are more sensitive towards the uncertainties. Furthermore, an interesting pattern is also observed when comparing the results in cases (b) and (c) as increasing the uncertainties of exergy values and imports leads to higher ε_U and lower ε_C in (b) but case (c) shows the opposite trends with lower ε_U and higher ε_C. These observations shows a significant advantage of using an exergy accounting method than the conventional monetary evaluation and traditional energy accounting methods to consider the differential of quantity and quality in the resource mix comprises of different product types and material contents.

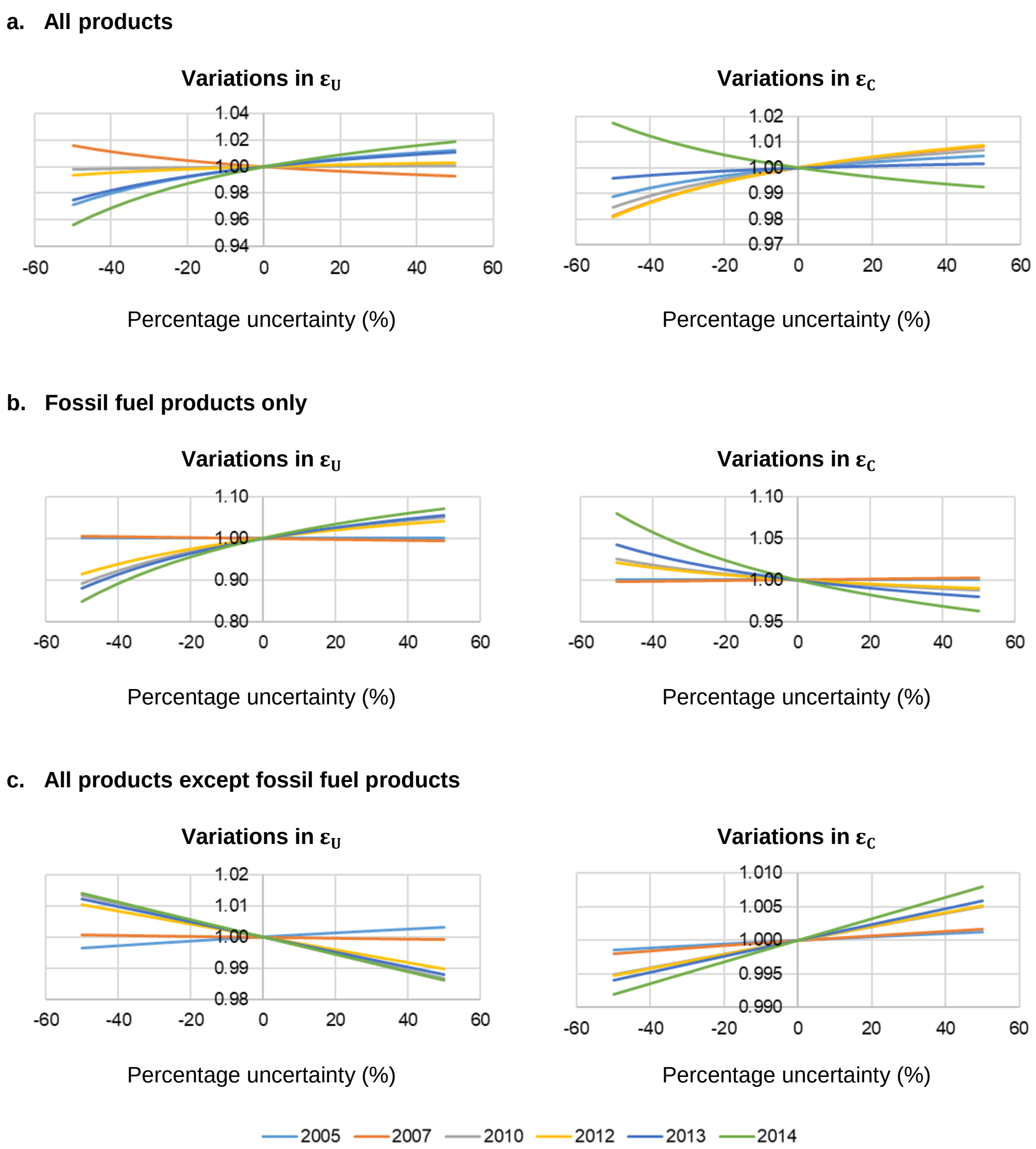

Figure 5.7: Sensitivity analysis for the effectiveness results (ε_U and ε_C) based on the percentage uncertainties (max. ±50%, at 10% intervals) of the exergetic values of (a) all products, (b) fossil fuel products only and (c) all products except fossil fuel products, compared to the original results with no uncertainty (±0%).

5.8. Chapter conclusion

This chapter shows how the OSNEA framework can be applied as a novel assessment tool to evaluate urban sustainability. In this case study, OSNEA is applied to study the effectiveness of resource use in Singapore and provide new insights of the metabolic relationship between the producers and consumers in the urban ecosystem. From the effectiveness results shown in Figure 5.6, the trajectory suggests a trade-off relationship between resource utilisation and conversion activities as the system organised and compromised to achieve a balance between the consuming and producing sectors.

Chapter 6

An OSNEA case study of the Great Britain: A multi-city system

The current chapter contains material that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectiveness across urban systems.

Arbabi, H., Punzo, G., Meyers, G., **Tan, L. M.**, Li, Q., Densley Tingley, D. & Mayfield, M. (2020). On the Use of Random Graphs in Analysing Resource Utilisation in Urban Systems. *Royal Society Open Science*, *7*, 200087.

6.1. Chapter introduction

This chapter presents a significant conceptual and empirical advance in understanding sustainable cities in terms of resource effectiveness by evaluating the effectiveness of resource use in cities and exploring their roles in the wider interconnected urban systems. The Open System Network Effectiveness Analysis (OSNEA) is used to conduct an in-depth investigation of resource effectiveness in a whole network of urban systems to identify their resource-use behaviours and clustering characteristics. Such analysis on a multi-city system can inform resource allocation strategies by identifying the hotspots of imports in the wider networks and redirecting resource flows to where they are most needed based on their effectiveness performances for better utilisation.

This study will also address the issues related to urban resource supply chains within a complex system of cities, as discussed in Chapter 3. Applying the OSNEA framework on a multi-city system will help to investigate the inter-dependencies within the wider urban systems by quantifying and mapping resource effectiveness across the whole systems. The advantages and practicalities of this method are validated through the Singapore case study presented in Chapter 5 using the *effectiveness* indicators introduced in Chapter 4.

In the rest of this chapter, Section 6.2 provides an overview of the structure of Great Britain's urban systems to introduce the case study background and explain the methods of data preparation to adopt the OSNEA framework. The findings of this case study, along with the interpretation and discussion of the results, are presented as follows: firstly, the results of resource effectiveness and balance in Section 6.3, followed by a clustering taxonomy for the whole urban systems in Section 6.4 and thirdly, a comparison of sectoral efficiencies in Section 6.5. Next, Section 6.6 discusses the insights and limitations of this case study, and lastly, Section 6.7 concludes the chapter. See Appendix 6 for the Python script used to generate the results presented in this chapter.

6.2. Great Britain urban systems

This section will provide an overview of the case study background, including the network representation and economic structure of the Great Britain (GB) urban systems, as well as the adaptations made on the OSNEA framework developed in Chapter 4 to acquire of the intra- and inter-city input-output data in order to extend the application of OSNEA to study a multi-city system.

6.2.1. Case study background

The GB urban systems contain 38 urban audit functional urban areas (FUAs) across England, Wales and Scotland (Office for National Statistics, 2017a), as shown in Figure 6.1. The urban systems interact with the external surroundings by importing resources from the inter-city system and abroad. The systems also export goods and services in exchange for capital incomes. At the intra-city level, connecting economic sectors via input-output transactions, together with the extended-exergy accounting (EEA) method to include domestic labour and capital contributions to the economy, form an intra-sectoral resource flows network within each FUA. Inter-city flows are added to the total imports and exports for each FUA within the urban system. Note that the usage of phrases 'FUA' and 'city' are not interchangeable as 'FUA' refers to a specific urban area in GB while 'city' is used more generally and can apply to any urban area inside or outside the case study system.

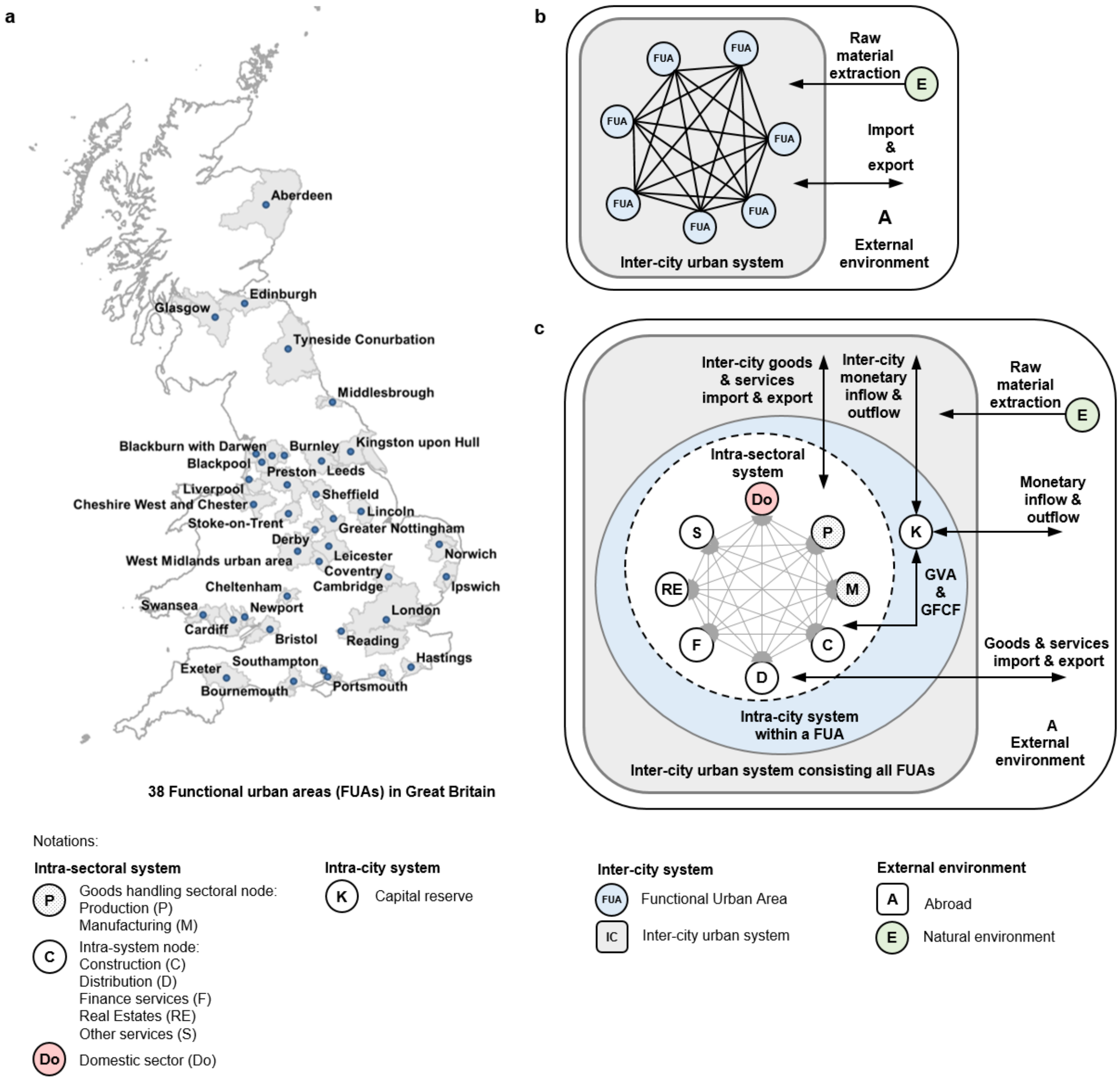

Figure 6.1: Schematic network representing the urban system of GB. (a) All 38 FUAs in GB are included in this case study. (b) The FUAs are connected by inter-city input-output flows to form a network of urban systems. (c) Within each FUA, the intra-sectoral system consists of all sectors in the cities including the domestic sector (Do) and the capital node (K).

In this chapter, a different time period is used, compared to the intra-city case study in Chapter 3 because the annual dataset used in this case study is only available over the time period from 2000 to 2010. This allows an extensive application of OSNEA to inspect the temporal trajectory of cities' effectiveness performances and to describe the behavioural changes of their resource use patterns. The scope of this study is also expanded to include three FUAs in Scotland in addition to the 35 FUAs in England and Wales. Industrial Workplace Zones dataset (Cockings *et al.*, 2015) used in Chapter 3 are produced according to the boundaries of output areas recorded in Census 2011 (of England and Wales) (Office for National Statistics, 2012) but these data are not available in Scotland's census and hence, Glasgow, Edinburgh and Aberdeen are omitted in the study in Chapter 3, but included in here.

6.2.2. Data preparation

The input-output data for intra-city, inter-city, inter-regional and international resource flows of the urban systems can be acquired from the EUREGIO database, a global input-output database with multi-regional details for European regions for 2000-2010. The regional details are based on the Eurostat Nomenclature of Territorial Units for Statistics (NUTS) Level 2 classification system (Thissen *et al.*, 2018; Netherlands Environmental Assessment Agency, 2018). The NUTS classification is a hierarchical system for dividing up the economic territory of the European Union and the UK, into multiple spatial levels, for collection and development of regional statistics (Eurostat, 2020). The construction of EUREGIO database allows flow analysis at a regional level by merging data from the World Input-Output Database (WIOD) (Timmer *et al.*, 2015) with regional economic accounts, including the inter-regional trade estimates developed by Netherlands Environmental Assessment Agency and some survey-based regional data. The input-output tables of resource exchanges between the sectors, together with the final demand and cross-boundary imports and exports, for all NUTS 2 regions in GB are extracted from EUREGIO table for all years (between 2000-2010) in this study.

Goods import and export data, mainly in the quantity of mass, with some exceptions such as traded electricity in the unit of *kilowatt-hour*, can be acquired from the Comtrade database for international trade flows (United Nations Department of Economic and Social Affairs, 2018). Commodity flows crossing the boundary of the UK, accounted in the unit of *kilogram*, for 2000 to 2010 are considered in this study. The mass of imported and exported goods can be converted to acquire the equivalent amount of exergy from their respective specific exergy values as demonstrated in Section 4.2. For commodities trade data, the 4-digit Harmonised Commodity Description and Coding System (HS-4) is used to match the goods with their corresponding product classification code documented in the statistical classification of products by activity (CPA) which is linked to the classification standards used by the EUREGIO database (Eurostat, 1998) and the Office for National Statistics (ONS) (2016). To derive the total exergy values of the imported resources, the HS-4 codes correspondence to all later years are converted and mapped onto the 1996 revision. The older version usually has a more general and broader definition of the product groups hence resulting in reduced sensitivity to the types of products imported, but this is essential in this case study to conserve the correct allocation of the general product groups in the resource mix.

Classification of industrial sectors is crucial in this study to ensure consistent data compliance and granularity throughout the whole case study duration because the data required to conduct this study are obtained from different data sources with various versions of sector classification. For example, industrial activities listed in the EUREGIO table follow the CPA standard used by Eurostat and WIOD while the economic data for all FUAs in the GB must follow the UK Standard Industrial Classification (SIC) of Economic Activities that is available from ONS. As economies are continually changing and evolving, these standards are being reviewed and updated regularly so a series of revisions have been published between 2000 and 2010. In this study, the earliest version (prior to 2000) is used to ensure a consistent sector aggregation and data format throughout the whole case study duration. The resulted industrial classification and the correspondence of economic activities comparing the different standards are summarised in Table 6.1. UK SIC 2007 is also included as a reference to the sector classification in Table 3.2 for the case study of England and Wales in Chapter 3.

Table 6.1: Industrial classification of intra-sectoral activities and the correspondence of economic activities from different standards.

Sector and Abbrev.		CPA 1996		UK SIC 2007		EUREGIO Sector	
P	Production	A	Agriculture, hunting and forestry	A	Agriculture, forestry and fishing	1	Agriculture
		B	Fishing	B	Mining and quarrying	2	Mining, quarrying and energy supply
		C	Mining and quarrying	D	Electricity, gas, steam and air conditioning supply		
		E	Electrical energy, gas, steam and hot water services	E	Water supply; sewerage, waste management and remediation		
M	Manufacturing	D	Manufacturing	C	Manufacturing	3	Food, beverages and tobacco
						4	Textiles and leather
						5	Coke, refined petroleum, nuclear fuel and chemicals etc.
						6&7	Electrical, optical and transport equipment
						8	Other manufacturing
C	Construction	F	Construction	F	Construction	9	Construction
D	Distribution	G	Wholesale and retail	G	Wholesale and retail	10	Distribution
		H	Hotels and restaurants	H	Transportation and storage	11	Hotels and restaurants
		I	Transport, storage and communications	I	Accommodation and food	12	Transport, storage and communications
				J	Information and communication		
F	Finance services	J	Financial intermediation services	K	Financial and insurance activities	13	Financial intermediation services

Table 6.1: (Cont'd) Industrial classification of intra-sectoral activities and the correspondence of economic activities from different standards.

Sector and Abbrev.		CPA 1996		UK SIC 2007		EUREGIO Sector	
RE	Real Estates	K	Real estate, renting and business services	L	Real estate activities	14	Real estate, renting and business services
S	Other services	L	Public administration and defence services	M	Professional, scientific and technical activities	15	Non-market services
		M	Education	N	Administrative and support services		
		N	Health and social work services	O	Public administration and defence		
		O	Other community, social and personal services	P	Education		
		P	Private households with employed persons	Q	Health and social work services		
		Q	Services of extra-territorial organisations and bodies	R	Arts, entertainment and recreation		
				S	Other services		
				T	Activities of households		

6.2.3. Data processing

To account for the exergy imported from abroad into a GB region, the total exergy import into the whole UK $\left(f^{UK}_{import_i}\right)$ is first distributed across all NUTS 2 regions in the UK according to the proportions of regional import values compared to the national import values. This is done by normalising the total exergy import by the monetary import values recorded in the input-output table to acquire a normalising factor $\left(£^{NUTS2}_{import\ i}/£^{UK}_{import_i}\right)$ which represents the equivalent exergy per unit monetary transaction for importing the resources into a region. For goods import, the commodities are supplied into the system from a foreign supplying (either production or manufacturing) sector and the local receiving sector can be identified from the input-output table. Hence, exergy imports from the production sector $\left(f^{UK}_{import_{i,P}}\right)$ and the manufacturing sector $\left(f^{UK}_{import_{i,M}}\right)$ are normalised separately for different product groups. Furthermore, extended-exergy imported via services $\left(f^{NUTS2}_{import\ \ i,K}\right)$ can also be computed using ee_K.

To obtain the amount of inflow for each FUA, the total exergy import, comprising goods and services imported from both the inter-city system (including the hinterlands outside the urban areas) and abroad, is then scaled down from the regional-level to the city-level based on the gross value added (GVA) ratio of the importing sector in each urban area to the GVA of their respective NUTS 2 region (ONS, 2017b). More precisely, for each FUA, the total exergy import of a sector i, $\left(f^{FUA}_{import_i}\right)$, can be computed as a fraction of the total exergy import of the whole NUTS 2 region, $\left(f^{NUTS2}_{import\ \ i}\right)$, and the whole UK, $\left(f^{UK}_{import_i}\right)$, as demonstrated in the following equations:

$$f^{NUTS2}_{import\ \ i} = f^{NUTS2}_{import\ \ i,P} + f^{NUTS2}_{import\ \ i,M} + f^{NUTS2}_{import\ \ i,K} , \tag{6.1}$$

where the import from production sector $\left(f^{NUTS2}_{import\ \ i,P}\right)$ is formulated as:

$$f^{NUTS2}_{import\ \ i,P} = f^{UK}_{import_{i,P}} \times \frac{£^{NUTS2}_{import\ \ i,P}}{£^{UK}_{import_{i,P}}} , \tag{6.2}$$

the import from manufacturing sector $\left(f^{NUTS2}_{import\ \ i,M}\right)$ is formulated as:

$$f^{NUTS2}_{import\ \ i,M} = f^{UK}_{import_{i,M}} \times \frac{£^{NUTS2}_{import\ \ i,M}}{£^{UK}_{import_{i,M}}} . \tag{6.3}$$

The city's import is also inclusive of the services imported as $\left(f^{NUTS2}_{import\ \ i,K}\right)$ which can be calculated in a similar manner as demonstrated in Equation 4.4 using ee_K as follows:

$$f^{NUTS2}_{import\ \ i,K} = £^{NUTS2}_{import\ \ i,K} \times ee_K . \tag{6.4}$$

Hence, for each FUA in each of the NUTS 2 region, the resultant import to sector i is:

$$f^{FUA}_{import_i} = f^{NUTS2}_{import\ \ i} \times \frac{GVA^{FUA}_i}{GVA^{NUTS2}_i} . \tag{6.5}$$

The aggregated GVA of the FUAs accounted in this case study are acquired by summing up the GVA of the individual Local Administrative Units (LAUs) published by ONS at the local authority level (ONS, 2017b). If a FUA is shared by more than one region (a, b, ..., N regions), the importing flow is scaled down using the GVA of the sector in the LAUs and then combined to form a FUA as the resulting sum of the individual LAUs:

$$f^{FUA}_{import_i} = f^{NUTS2}_{import\ \ i} \times \left(\frac{GVA^{LAU_a}_i}{GVA^{NUTS2_a}_i} + \frac{GVA^{LAU_b}_i}{GVA^{NUTS2_b}_i} + ... + \frac{GVA^{LAU_N}_i}{GVA^{NUTS2_N}_i} \right) . \tag{6.6}$$

The total incoming resource flows into each FUA is the sum of the inter-city supplies (I-C) from other areas in the same system and imports from abroad (A) such that:

$$f^{FUA}_{import_i} = f^{FUA}_{import_i}(I - C) + f^{FUA}_{import_i}(A) . \tag{6.7}$$

Therefore, operations in Equations 6.1-6.6 are conducted repeatedly to compute both $f^{FUA}_{import_i}(I - C)$ and $f^{FUA}_{import_i}(A)$ for each FUA in the case study. Due to the lack of data for accounting the actual commodity flows between cities at the time of study, the same normalising factors (for the respective products imported from the production or manufacturing sectors abroad) are used for accounting the inter-city imports and exports. This essentially assumes that the goods imported from other cities have the same exergetic content per unit monetary flow as the import from abroad. In addition, exergy flow from the natural environment through local production within the FUA is assumed to be negligible in this study because the main extraction activities, such as agriculture, mining and forestry activities, are conducted in the hinterlands outside the urban areas and the extracted materials are being supplied to the city through inter-city imports.

Similar accounting method as for the imports in Equations 6.1-6.7 is repeated for computing the total exergy exports from each FUA. As the system is bounded by the thermodynamic limits following the law of energy conservation, the outflow exergy is always lower than the inflow exergy due to resource utilisation and waste emissions from the transformation processes within the urban systems. Otherwise, it is assumed that the fossil fuel products documented in Chapter 27 of the HS-4 coding system for international trade flows (World Customs Organization, 2017) can be excluded from the exports to ensure the thermodynamic flows in the system are conserved. For the same reason, fossil fuels products are excluded from the inter-city exports to other areas because the production of such products is often performed outside the urban areas. For other products, exports of goods supplied from the production and manufacturing sectors are calculated in a similar manner as the imports using the mass export data obtained from the Comtrade database (United Nations Department of Economic and Social Affairs, 2018) and the specific exergy value of the commodities. Services exported from the FUAs are calculated in terms of extended-exergy outflows using ee_K.

For household activities, the exergy equivalent of labour output contribution from the domestic sector via employment can be calculated from ee_L. Employment data, such as the number of employees and the average work hours by sector (in the unit of *hours per year*), can be obtained from ONS (2019). However, these data are only available for regional statistics hence, the figures are scaled down to FUA and LAU levels using the GVA ratios. In some exceptional cases where the regional employment data is unavailable for a specific sector, the national median values are used. Moreover, to account for the waste exergy, f_{waste_i}, greenhouse gases (GHG) intensity data for UK energy use in 2000-2010 is used in this case study (The World Bank, 2020).

To construct the network of intra-system resource flows, the network can be expressed as an adjacency matrix with the same size as the number of sectors in the system. The final form of the assembled exergy-based input-output matrix, $\mathbf{M}_{ex}$, tabulates all resource exchanges within the system, and between the systems of cities, in a combination of exergy and extended-exergy flows. The values of total exergy import entering the system (through the importing sectors) form a flow vector, f^{FUA}_{import}, which is then distributed from the importing sectors to other sectors accordingly to the import supply ratio stated in the normalised input-output matrix, $\widehat{\mathbf{M}}_{ij}$, based on the sum of all monetary imports received by each sector from the inter-city system and abroad. Hence, the formula for $\mathbf{M}_{ex}$ is:

$$\mathbf{M}_{ex} = diag(f^{FUA}_{import})\, \widehat{\mathbf{M}}_{ij} \,. \tag{6.8}$$

6.2.4. Clustering classification

The OSNEA framework is developed to evaluate the abilities of an urban system to utilise and convert the resources available in urban systems using the *effectiveness of utilisation*, ε_U, and the *effectiveness of conversion*, ε_C, indicators as previously defined in Table 4.2. Using an effectiveness plot (ε_U against ε_C), the framework assesses the overall resource effectiveness, R, by measuring the radial distance on a polar coordinate system to evaluate the overall performance of the system in making use of the resources available for both utilisation and conversion purposes. The overall effectiveness balance, θ, can be obtained by measuring the angular coordinate to give a quantifiable measure of the balance between the production and consumption activities in the whole system.

A clustering analysis is used to describe the common behaviours exhibited among the FUAs of the same clusters and enable a targeted investigation on each cluster to identify the leverage points for policy interventions based on the unique characteristics of the clusters. The clustering patterns can be identified by comparing the clustering hierarchy of the pairwise Euclidean distances between any two FUAs in each year, treating the R and θ results for 2000-2010 as individual vectors of size equals to the number of years in the timeseries data. The distance between the two clusters is calculated using an average-linkage clustering method in each iteration, then the results are plotted in dendrograms to show the hierarchy relationships among the FUAs and clusters (Müllner, 2011).

6.3. Resource effectiveness and balance

The effectiveness plot of GB is shown in Figure 6.2 to analyse performance of the urban systems through time. The results compare a multi-city system generated in this case study, which also considers the inter-city flows within the wider urban systems in GB, to a single-city system of Singapore by including the case study results in Figure 5.6 generated in Chapter 5.

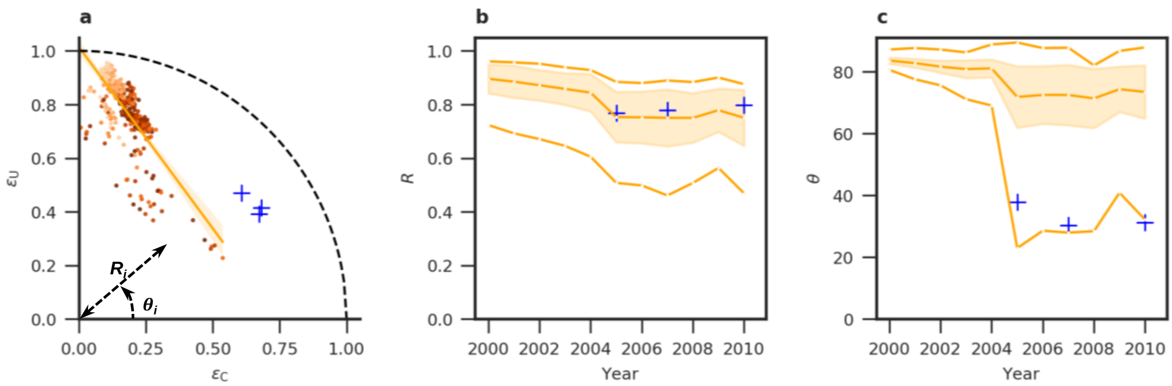

Figure 6.2: Overall R and θ results for urban systems in GB and Singapore for 2000-2010. (a) Plot of ε_U and ε_C through time. Orange dots represent the FUAs in GB while blue crosses represent Singapore. The colour saturation indicates the temporal transition of the case study period from 2000 (lightest saturation) to 2010 (darkest saturation). A regression line is fitted for the GB data to show the trends over years. (b-c) Temporal variations of R and θ showing the mean, standard deviation (shaded area), minimum, and maximum values.

The effectiveness plots in Figure 6.2(b) and (c) show a trend of decreasing ε_U and increasing ε_C over the years from 2000-2010. By taking the mean values of R and θ for all the FUAs in the system, the values decrease steadily throughout the period with a slight spike in the mean values in 2009. This means R has decreased from 2000, but in overall, the system has become marginally more balanced (θ = 45°) in 2010. This suggests a compromise between the producing and consuming sectors to optimise system effectiveness with lower utilisation (lower ε_U) for higher capital inflows into the cities (higher ε_C) to promote economic growth. Comparing the urban systems in GB to a smaller and denser urban system like Singapore for 2005-2010, both systems have a similar magnitude of R (which lie within the range 75% - 80%), but Singapore has a more consistent and balanced system as it lies on the minimum line of θ for the whole urban system of GB, which corresponds to the results for Aberdeen. The drop in θ between 2003 and 2004 is due to declined imports of oil and gas products, recorded in the Oil and Gas Authority (2020) open data, in Aberdeen from the extraction activities in the region. This observation indicates that GB exhibits a more consumer-like behaviour as tertiary sectors such as finance and services are concentrated in urban areas and producing sectors located outside the urban conurbations.

Figure 6.3 shows the spatial variations between the cities by mapping the import, export, the overall resource effectiveness (R) and overall effectiveness balance (θ) across the GB urban systems.

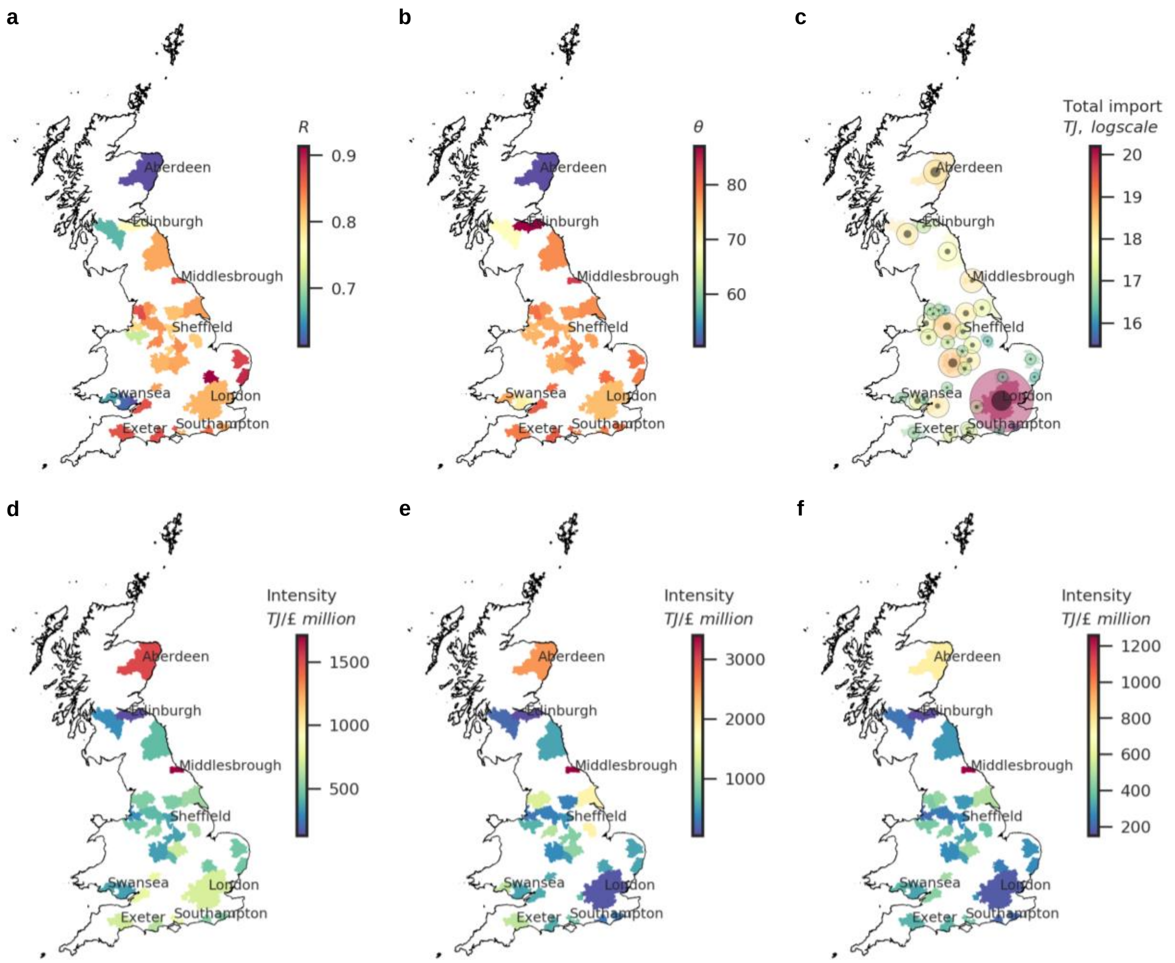

Figure 6.3: Mapping (a) average R over 2000-2010, (b) Average θ over 2000-2010, (c) cumulative imports (colour and size of outer circle) and exports (size of inner circle) for 2000-2010, (d) average exergy intensity of manufacturing sector over 2000-2010, (e) average exergy intensity of finance services sector over 2000-2010, (f) average exergy intensity of all sectors over 2000-2010, across the whole urban system.

Mapping the spatial variations highlights differences between cities in terms of their resource use behaviours and trade patterns across the whole system. Figure 6.3(a) and (b) show the distribution of average R and θ across GB. In general, the FUAs in England are more effective consumers with higher R and θ than those FUAs in Wales and Scotland. In Scotland, Aberdeen has the lowest average R and θ in the system. As one would expect given the size of the city, London has the largest import and export but it is also less effective than some of the nearby areas as shown in Figure 6.3(c). Moreover, some areas are highly effective, such as Middlesbrough, Cambridge and Ipswich, but do not have a good balance due to extremely high utilisation and strong consumer traits. Aberdeen, however, demonstrates a good balance between the production and consumption activities due to high exports and capital flows associated with the oil and gas industries in the area.

Comparing the exergy intensity of economic activities in different cities gives a better benchmarking criterion for evaluating states of resource consumption with respect to the economic productivity by measuring the amount of exergy imported by a city (or a sector) to generate a unit of GVA rather than referring to the gross exergy import. From Figures 6.3(d) and (e), exergy intensities of the manufacturing and finance sectors across all FUAs in the system expose the disparities of industrial specialisation between the northern and southern regions in England. This highlights the north-south divide in the UK due to the regional social and economic inequalities contributing to the development of productivity and income gaps (McCann, 2016). This can also be seen as the impact of having a more diversified economic structure in the south compared to the north with a larger income share associated with the manufacturing industries. Although manufacturing activities should have higher exergy intensity than financial activities, the scale of colourbar for finance intensity has a higher maximum intensity than the manufacturing intensity. This is because of the imbalance in the financial development levels among these cities causing high exergy intensity in financially underperforming areas such as Middlesbrough, Aberdeen and Lincoln with lower GVAs from the finance sectors. This suggests the areas with lower economic productivity do not necessarily have lower resource intakes and may still be exergy-intensive because of a lack of economic diversity, especially in the tertiary sectors, to fulfil the utilisation and conversion of all resources available. In Figure 6.3(f), the total exergy intensity includes any import by the domestic sector which does not contribute to the GVA. Comparing the distribution of exergy intensities for all sectors to the sector-specific intensities shows the system consists of diverse specialisations and economic focuses causing the cities to exhibit unique characteristics and resource use behaviours where cities with similar behaviours tend to cluster in the network and also have stronger influence on one another.

6.4. A clustering taxonomy of resource use behaviours

Further investigation on the cities' behaviours based on their clustering patterns helps to categorise the cities and identify their common interests and priorities for planning resource allocation across the whole system. This section demonstrates the development of a taxonomy of urban consumption describing the common characteristics for the areas within the same clusters. Using the clustering method outlined in Section 6.2.4, the clustering groups are first identified based on the θ results which show that Aberdeen's behaviour is substantially different (due to much smaller θ) compared to other FUAs and hence, Aberdeen is set apart from the rest of the clusters. Applying the same method on the *R* results for all FUAs gives the clustering classification shown in Figure 6.4. See Appendix 7 for the clustermap and the dendrogram for the clustering hierarchy.

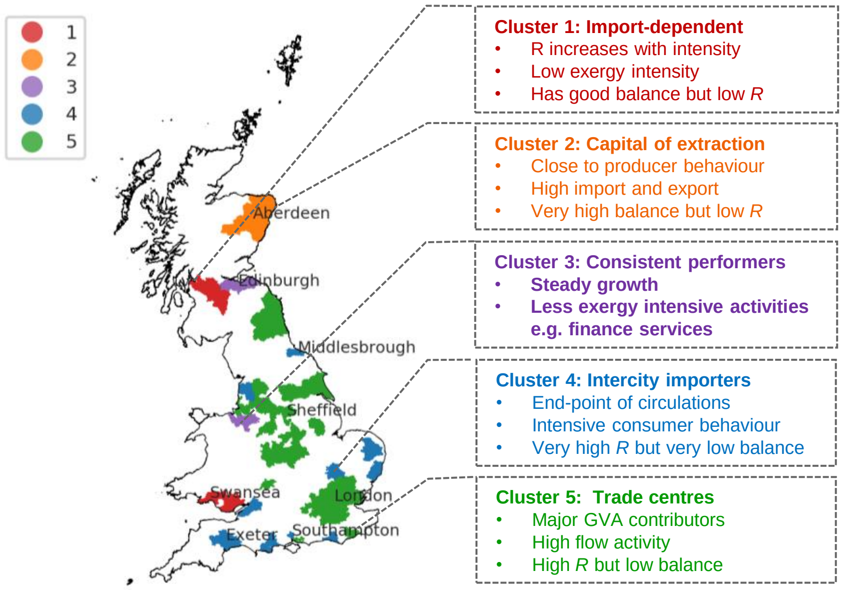

Figure 6.4: Mapping the cluster types in the urban system of GB showing the five clusters (colour-coded from cluster 1-5). The characteristics of the FUAs in a common cluster are as described in the callout boxes.

From the clustering classification, five clusters of different resource use taxonomies are observed among the FUAs within the GB urban systems. Further investigations of the clusters properties and their key characteristics help to optimise and improve their resource effectiveness and bring benefits to the whole urban system. Figures 6.5 and 6.6 show the clustering characteristics of the FUAs based on their exergy imports and the relative changes in OSNEA indicators through the years to provide novel insights for understanding how the cities are related in terms of the states of resource-use over time. In Figure 6.5(b), intercity import share represents the ratio of the import supplied through the inter-city system over the total resource import entering a FUA and in Figure 6.6(c), the import share represents the fraction of the total import by all the FUAs in the cluster divided by the total import of all 38 FUAs in the whole system. Furthermore, Figure 6.7(a) shows the intensity gaps of each FUA throughout years (2000-2010), which are obtained by computing the difference between the national and individual FUA intensities in each year. The exergy intensity gaps provide a yearly reference to the exergy import intensity of the FUAs compared to the intensity of the whole system and helps to identify areas with high intensities due to excessive imports or low economic productivity. In Figure 6.7(a), the size of exergy intensity gap is presented as a percentage difference between the exergy intensity of the FUAs and the national intensity. In Figure 6.7(b), a regression line is fitted for each cluster to show the relationships between *R* and exergy import intensity by cluster type. This shows that the cluster 1 (in red) has the highest gradient and hence, higher dependency on the exergy import to increase the effectiveness of the FUAs in the same cluster. For all clusters, *R* decreases with import intensity, which suggests that the cities are less effective when less resources are available for utilisation due to reduced imports. This means the system has utilisation capacity for the imported resources but lacks the ability to circulate the flows and make use of the remaining resources instead of bringing more imports into the system. Among all the five clusters, cluster 4 (in blue) has the highest average intensity and cluster 1 (in red) has the largest range.

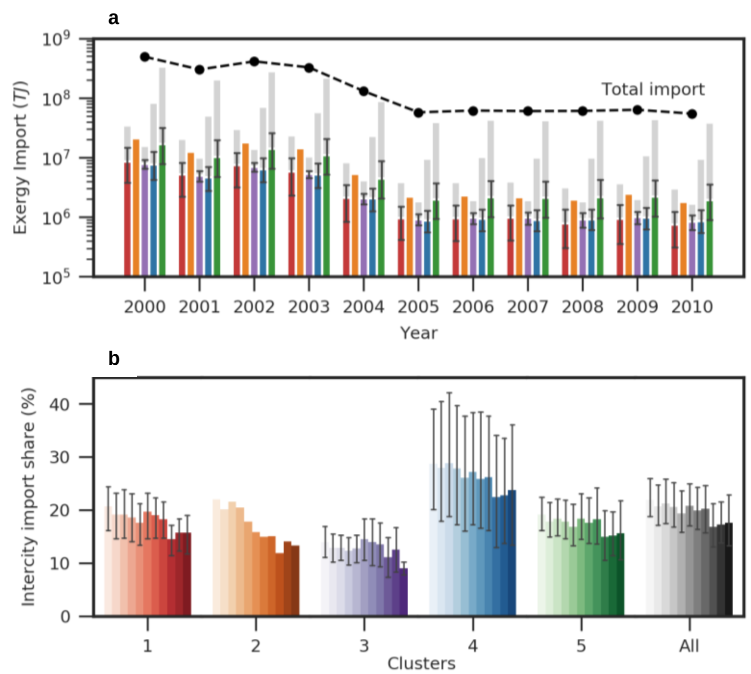

Figure 6.5: Properties of the clusters showing (a) the average annual resource import by a FUA with the error bars representing the standard deviation. The sums of import by all FUAs in each cluster are shown using the grey bars at the back of the coloured-coded bars and (b) the yearly intercity import share, colour-coded based on clusters, with the standard deviation shown using the error bars. The colour saturation indicates the temporal transition of the case study period from 2000 (lightest saturation) to 2010 (darkest saturation).

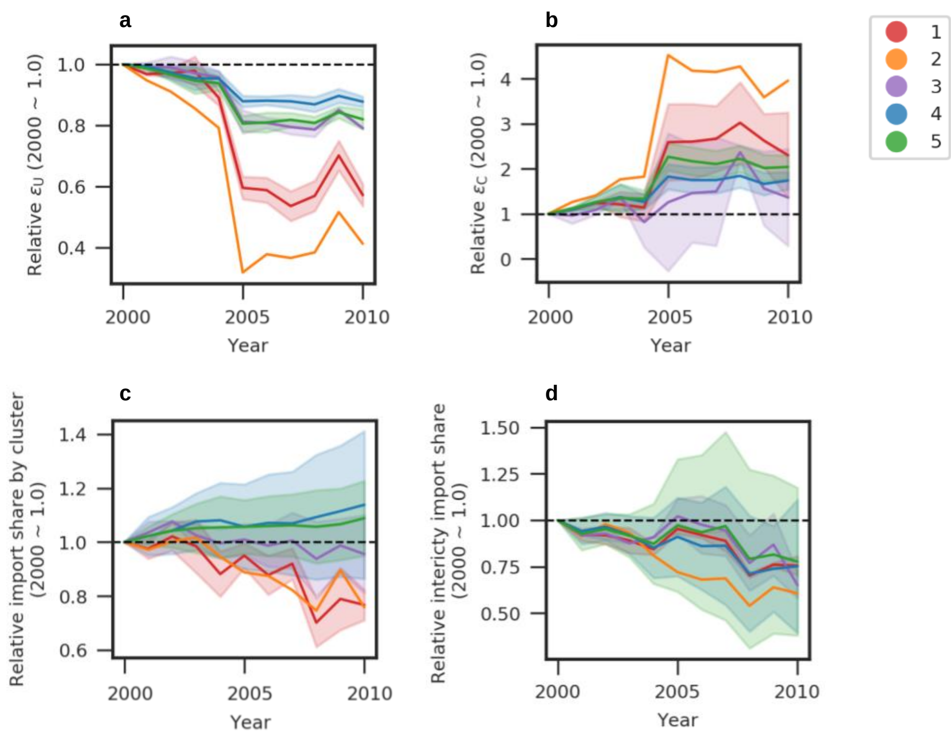

Figure 6.6: The relative changes of a selected range of cluster properties shown in the following plots: (a) ε_U, (b) ε_C, (c) import share, (d) intercity import share, are measured by comparing the resulted values to the initial values in 2000 in terms of average ratios over all FUAs in the same cluster (2000∼1.0), including the standard deviation within each cluster.

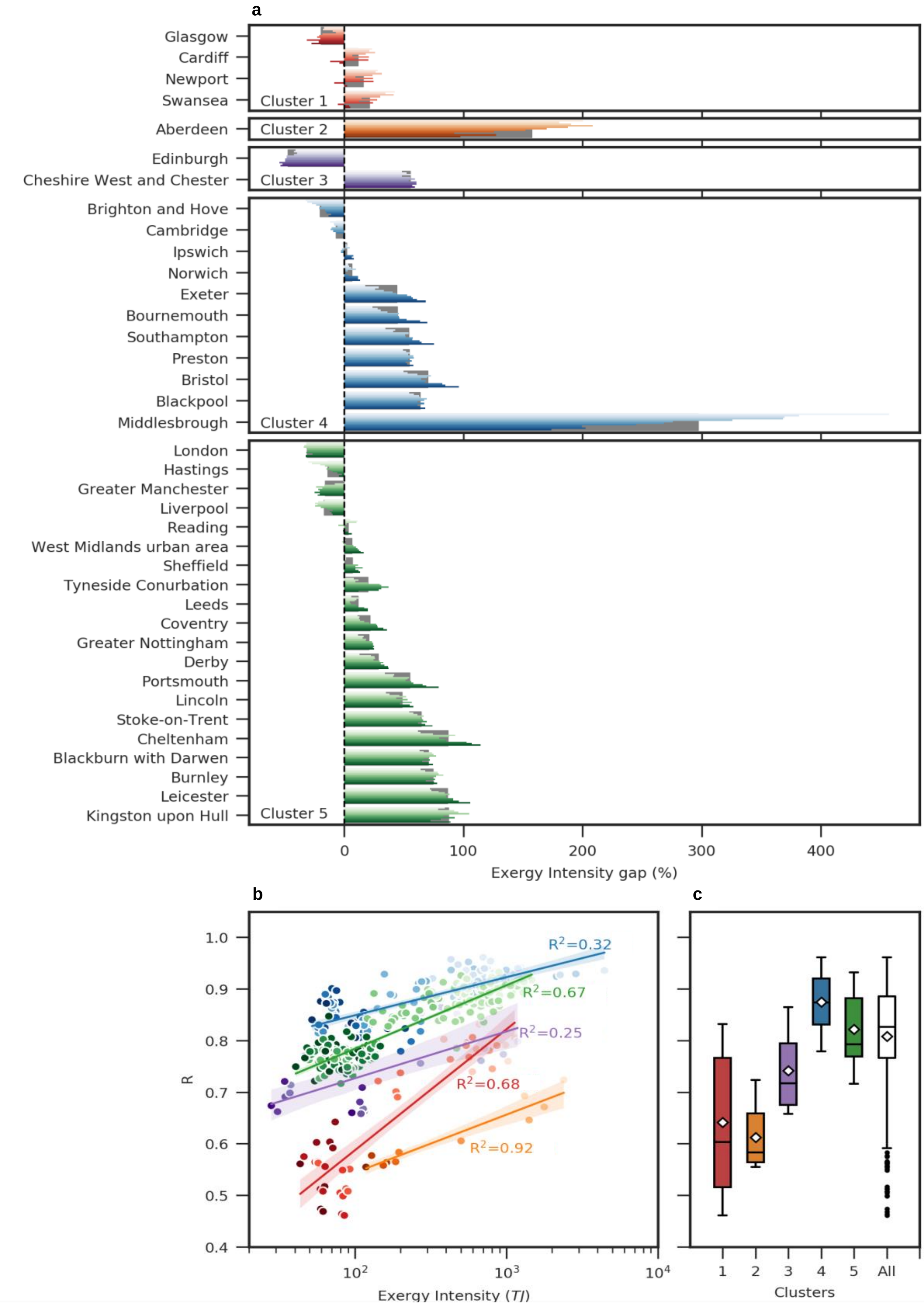

Figure 6.7: Exergy import intensity, colour-coded by cluster. The colour saturation indicates the temporal transition of the case study period from 2000 (lightest saturation) to 2010 (darkest saturation). (a) Exergy intensity gap and the average values indicated using the dark grey bar in the background. (b) Plot of *R* against the exergy intensities for all FUAs. Each scatter point represents a FUA in a year between 2000-2010. A regression line is fitted for each cluster. (c) Box plots showing the distribution of *R* by cluster type including the combined of all FUAs in the system.

Cities in **cluster 1**, are located in Wales and Scotland and identified to be import-dependent with the lowest import shares and exergy intensities among all the cities. Their effectiveness performances suggest the economic growth is limited by the amount of resource available. This raises a concern regarding the dilemma of balancing economic growth and resource sustainability if the demand for import increases. Hence, from a wider perspective of the whole urban system, more resources should be reallocated to these areas from the high-intake-areas to prolong circulation within the urban systems, provided that they have the capacity to maintain the effectiveness balance and utilise available resources effectively as the cities grow.

Aberdeen in **cluster 2** has been identified as the outlier compared to the effectiveness performance of other FUAs in the system. This is due to the geographical location of the city being strategically important to provide infrastructure services to the oil extraction industries near the North Sea (BP, 2019). Although the reported oil production in the region has declined over the years, Aberdeen still possesses very high exergy intensities throughout the period, as shown in Figure 6.7(a), because it serves as the capital of resource extraction in the region for handling high volumes of inflow and outflow of oil and petroleum products. Despite the high flow activity within and beyond the city's boundaries, the GVA income generated is too low and incomparable to the resource intensive activities in the extraction industries. The natural reserve of resources available for extraction is limited and oil production would have to be cut in order to meet zero-carbon targets, thus the city must diversify their economic activities away from oil extraction industries. The location of the city presents an opportunity for local planners to invest in infrastructure development and research facilities that facilitate the decoupling of economic growth from natural resource consumption through less resource intensive but high-income activities.

Cluster 3 consists of two FUAs, Edinburgh and Cheshire West and Chester, which are found to perform consistently throughout the years of this case study. Although the two areas are located in two different regions, and have a considerable difference in exergy intensities and their overall resource effectiveness, both areas have experienced a steady growth and minimal changes in performance over the years, as shown in Figure 6.6. This suggests their economic outputs are mainly generated from less resource-intensive activities that are less dependent on the resource imports (ONS, 2017b). This justifies the consistent effectiveness performance observed in those areas despite the change in overall import and varying intensities across the whole system. In this case, strategies to promote more effective ways of resource utilisation to reduce total resource imports and exergy intensities in these areas would be helpful in lowering the demand for resource extraction. For example, for Cheshire West and Chester, which has higher exergy intensity and lower effectiveness, performance can be improved by having longer flow cycles through a cross-sector circular economy (CE) to increase utilisation and recirculation of flows within the system. It is also worth noting although London has a similar economic focus on services-related industries, the city is subjected to a large degree of externalities and uncertainties due to high economic complexity and diversity so its performance fluctuates more than the two FUAs in this cluster.

Although **clusters 4 and 5** have very similar effectiveness trajectories and exergy intensities, a substantial difference is observed when comparing the sources of imports into the cities. The FUAs in cluster 4 have higher intercity import ratios than cluster 5 as well as any other clusters, as shown in Figure 6.5(b). On average, cluster 4 has the highest R and exergy intensities among all the clusters.

This suggests that these areas are the major importers of inter-city flows with intensive consumer traits and a very low effectiveness balance. These cities can be portrayed as the end-points of resource circulation and should be targeted for policy interventions to promote incentives to re-supply unused or reprocessed materials to other cities in the system in order to regulate the intake of resources by these areas. This will help to accelerate a system-wide shift to a CE by retaining the resources within the network for as long as possible, maximising the use of available resources. These arguments are justified by inspecting the freight traffic data at major seaports in England where the ports with the highest outwards flows are Tees and Hartlepool (Middlesbrough) and Southampton, which also have higher exergy intensities than the national benchmark (Department for Transport, 2018) as shown in Figure 6.7(a). In the opposite direction, high inwards traffic can be observed at Grimsby and Immingham (Kingston upon Hull) and London where both of these are important trade centres. These cities have high inwards and outwards flow activities and are also the major contributors of GVA in the areas. However, as the cities continue to expand, increasing population densities and consumer incomes present an inevitable sustainability challenge to minimise carbon footprints and waste emissions in the cities (Pichler *et al.*, 2017; Wiedmann and Lenzen, 2018).

The findings reveal that most cities in GB are open system consumers relying on imports where effectiveness decreases with declining intensities, while the population and GVA increase steadily over the years. This means the cities lack producer traits to sustain the resource-intensive activities and maintain the capacity to deliver proper services to the consumers. As such, a transition to CE is imperative to maximise the use of existing resources available and reduce the import of new materials into the urban systems when the existing resource flows are not fully utilised.

6.5. Sector-level efficiencies

In thermodynamic systems, evaluation of resource efficiency is often expressed as a ratio of total outputs to the total inputs of a process. The OSNEA framework is designed to look beyond this conventional definition of efficiency to redefine system metabolic performance by distinguishing resources intake from the external environment and resources circulated from local suppliers within the city's boundary. As a comparison, the *effectiveness* indicators are different from efficiency as *effectiveness* is a system-wide performance metric to assess the portion of the total import (from outside the system) that is utilised to deliver a service or product whereas efficiency at sector-level reflects the productivity of an economic activity in terms of the ratio of total output produced to the aggregated inputs from all sources.

In all sectors including the domestic sectors, the overall imports by the cities have decreased and the mean efficiency has increased over the years owing to advancements in operational technologies, increased labour productivity and renewable energy harvesting. However, the results in Figure 6.8 further confirmed the need for creating more effective urban systems. For all sectors, the efficiencies are relatively stable and import-independent, demonstrated by the nearly zero R-squared values in all cases. The saturated efficiencies can be understood as high potential for larger work done through more effective processes to fully utilise the existing resources and reduce the demands for raw material extraction and import.

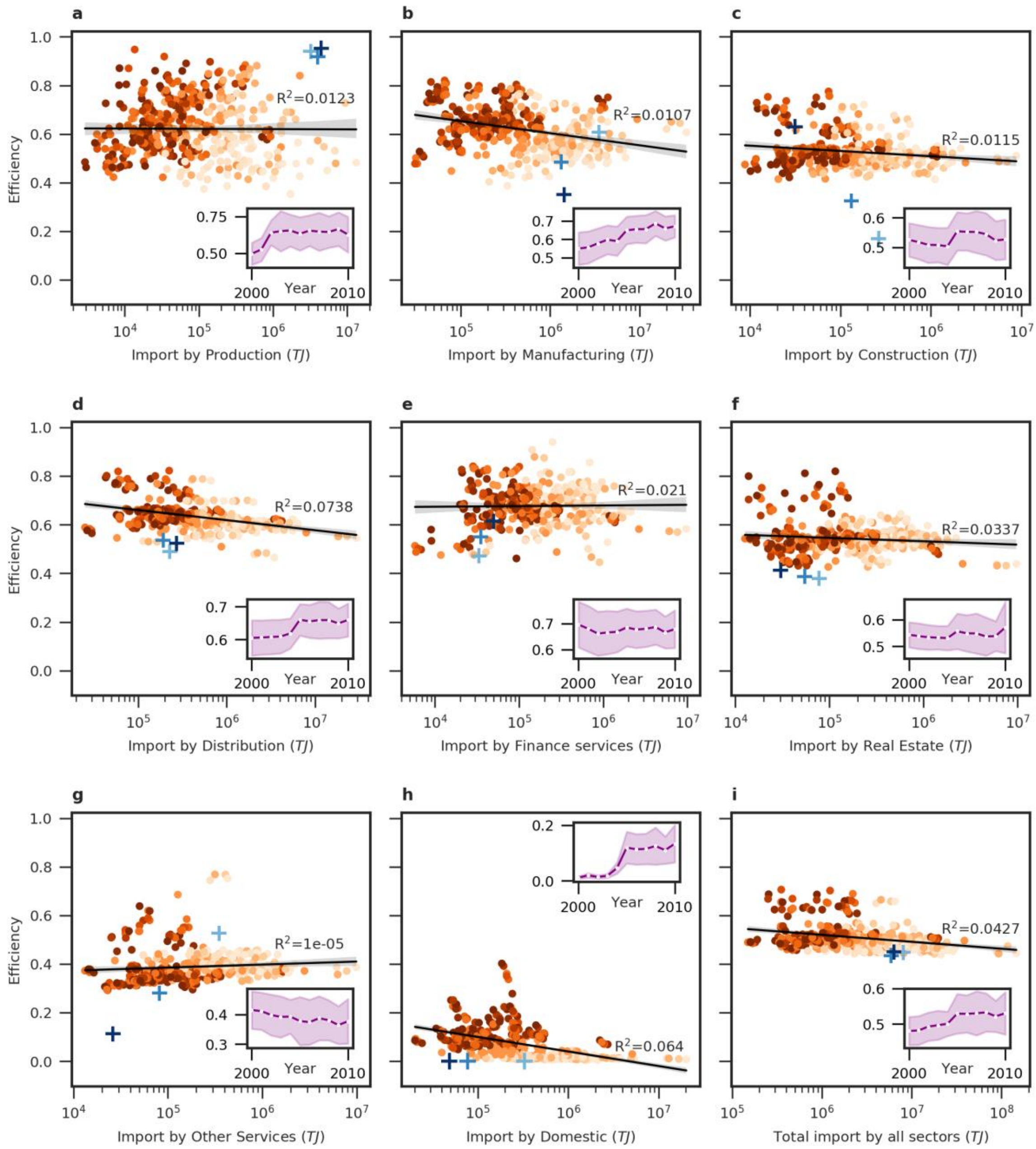

Figure 6.8: Exergy import intensity, colour-coded by cluster. The colour saturation indicates the temporal transition of the case study period from 2000 (lightest saturation) to 2010 (darkest saturation). (a) Exergy intensity gap and the average values indicated using the dark grey bar in the background. (b) Plot of *R* against the exergy intensities for all FUAs. Each scatter point represents a FUA in a year between 2000-2010. A regression line is fitted for each cluster. (c) Box plots showing the distribution of *R* by cluster including the combined of all FUAs in the system.

6.6. Insights and limitations of the case study

This case study demonstrates an application of OSNEA as a useful tool to assess the states of resource use in the system by measuring the differential in terms of both quantity and quality of the resources. Applying the framework on studying urban systems of different types of ecological behaviours and functions allows comparison between the systems as shown in Figure 6.2. The results show the distinctions between the urban systems where Singapore, which is a city-state, has higher export due to trading activities at the ports and electricity generation at local power stations, whereas the GB has a higher concentration of consumer activities in the urban areas that mainly rely on the resources imported into the cities. For the multi-city system in GB, it was found that cities can be more resource-effective with a more diversified industrial structure. From an ecological perspective, in the absence of producers in the system, the consumers will have to rely on resources imported, stressing the importance of promoting internal linkages between producers and consumers in the same urban system to maintain the ecological balance and flow circulation between cities when the availabilities of resources are limited. As such, policy interventions should prioritise strategies to improve effectiveness by creating an ecological balanced and diversified economic structure which offers higher chances of forming matching demands and supplies of resource flows locally. This approach promotes longer flow circulations by connecting the local producers and consumers among the economic sectors as a lever for transition to CE at the cross-sector level, helping the cities to maximise the use of all resources available.

Secondly, this work also highlights problems of system imbalances to draw attention to areas which would benefit from an intervention of redirecting unused resources imported elsewhere for better utilisation to reduce imports into the overall system. In other words, linking the consumer cities with high imports and utilisation to producer cities with high conversion capacities provides a pathway for sharing local resources. The study also highlights the natural geographical constraints or advantages of the cities. For instances, cities like Middlesbrough, Hull and Southampton are strategically located near the coastline causing high commodity flows in these seaport areas. Another example is Aberdeen where the behaviour of the city is hugely dependent on the abundant reserve of fossil resources in the region, hence the economy is heavily affected by the fluctuations in the oil market (Smith, 2016). The effectiveness results suggest that Aberdeen possesses a good balance but low effectiveness meaning the resources available are not fully utilised through the local economic activities and yet more resources are being imported into the city. Insights from OSNEA evaluate how well the urban system performed in terms of resource effectiveness and assist city planners to explore the ways to achieve better resource use and relieving their economic reliance on imports.

Monitoring urban metabolism is crucial to enable the shift from a linear-to-circular economy for decoupling economic growth from resource consumption. From a broader perspective, this study shows how the framework can be applied to assess and monitor resource use across urban systems of various sizes and economic structures, and potentially acts as a universal tool to connect global cities to analyse the patterns of resource flows across wider regions or continents. This tool will be useful to tackle the global resource problem. For sustainable urban development, creating a balanced system and effective operations help to limit the resource intakes and consumption-related emissions from global cities. This work also aligns with the C40's efforts on accounting the sector-based GHG emission from activities inside the cities to categorise consumer cities (C40, 2018). Their work shows that, among the 79 member cities studied, 83% of the cities (representing 63 member cities) are classified as consumer cities where their GHG emissions associated with the supply chains of resource flows are significantly higher than the producer cities. Besides this, a case study of carbon accounts in the UK cities shows the consumption-based emissions have exceeded the production-based emissions in most urban areas (Barrett *et al.*, 2013; Sudmant *et al.*, 2018). This agrees with the observations of effectiveness balance in Figure 6.3(b) where a majority of cities have higher effectiveness in resource utilisation than conversion ($\theta > 45°$). These findings support the implementation of the 2030 Agenda for Sustainable Development accelerating the transition to CE by closing the circularity gaps in resource flows (United Nations, 2018) to accomplish the Sustainable Development Goals (SDGs) for sustainable cities and communities (SDG 11) and responsible consumption and production (SDG 12).

On the other hand, similar to many other UM studies, the main limitation of this study is the lack of data to expand the application for more advanced investigations. In this case, the implications of the study would be amplified if the data for more recent years is available to advise the policymakers in planning their cities and resource management strategies. This study is also limited by the lack of commodity data at the inter-city level as discussed in Section 6.2.3. The acquisition and collection of such datasets would require initiatives and investments from the local governing bodies to track and record the full movements of goods between cities. Besides this, another limitation of this study is the absence of stock properties in the model due to insufficient data on local inventory for all FUAs in the system hence neglecting resource accumulations and storage units (such as the built environment) in the system. Thus, the row and column for the Inventory node, labelled as Inv as shown in Figure 4.2, are omitted from the matrix assembly in this case study. Further improvement should integrate storage characteristics in the model to simulate temporal variations of resource stocks and flows of an urban system when the required data become available.

6.7. Chapter conclusion

This chapter presents an OSNEA case study of multi-city system considering the networks of resource flows across the interconnected urban systems in the Great Britain. In conclusion, the results of resource effectiveness and balance emphasise that the absence of producers in the system due to high concentration of consumption activities in cities cause the economy to rely on imported resources for growth. The clustering taxonomy of resource use behaviour helps to identify the hotspots of imports in cities to redirect resources to where they are most needed and enable targeted policy interventions based on the metabolic characteristics of each cluster.

Chapter 7

Synthesis: Applicability, practicality and versatility of OSNEA

The current chapter contains materials that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.

Tan, L. M., Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.

Arbabi, H., Punzo, G., Meyers, G., **Tan, L. M.**, Li, Q., Densley Tingley, D. & Mayfield, M. (2020). On the Use of Random Graphs in Analysing Resource Utilisation in Urban Systems. *Royal Society Open Science*, *7*, 200087.

Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectiveness across urban systems.

7.1. Chapter introduction

In this work, the development of a novel ecological-thermodynamic approach to urban metabolism (UM) is presented by introducing the open system network effectiveness analysis (OSNEA) framework through the methodological workflow presented in Chapter 4. The applications of OSNEA are as demonstrated in the case studies for the urban systems of Singapore in Chapter 5 and Great Britain (GB) in Chapter 6, together with a brief discussion of the results obtained from each case study at the end of each chapter. This chapter will elaborate on earlier discussions by bringing together all findings generated and insights provided to consider the importance and challenges of such approach in the UM framework to promote urban sustainability.

In the rest of this chapter, Section 7.2 first provides a comprehensive review of the practicality of the OSNEA framework as an ecological-thermodynamic approach to UM whether the framework developed is suitable for the designated purpose of this work. Secondly, this is followed by a critical appraisal of the applicability of the methodology in Section 7.3 focusing on the limitations of the method for extending its application to other case studies. The third section of this chapter, Section 7.4, discusses the versatility of the OSNEA method to be used as a universal tool for urban sustainability assessment in the way forward. Lastly, Section 7.5 gives a chapter conclusion based on the synthesis of applicability, practicality and versatility of the OSNEA framework.

7.2. An ecological-thermodynamic approach: A review of the purpose and practicality

OSNEA represents a novel ecological-thermodynamic approach to redefine resource use behaviours in cities and shed light on the underlying problems of UM due to the resource-intensive relationships between the producers and consumers, highlighting the importance of balancing resource distribution in urban development. The concept of UM is based on the analogy between cities and natural biological systems while the ecological-thermodynamic approach lies on the interface of cities and natural ecosystems to investigate the effectiveness of urban economies. In essence, the idea of OSNEA revolves around the topic of UM to investigate the health and sustainability of urban ecosystems based on their sectoral networks of resource flows and the overall effectiveness balance between the producing and consuming sectors in the cities. A balanced ecosystem is beneficial to the delivery of proper functions of the systems to sustain a long-term economic growth.

The purpose of OSNEA is to assess the states of resource use in urban systems through resource exchanges among the economic sectors and to promote effective use of resources available by maximising the work done extracted from the existing materials through prolonged use cycles and continuous flow circulation among cascading urban processes in the open system networks. The work demonstrated in Chapter 4 is a pioneering development of the OSNEA methodology as the first in its area to examine the effectiveness of resource use through flows circulation and commodities distribution between various industrial sectors across the system of cities, addressing the differential of quality and energy degradation in urban processes. The OSNEA indicators provide a practical assessment to account for the change in both quantity and quality of the resource flows through transformation processes in the urban network based on the total imports using the exergy-based performance metrics, fulfilling the **objective 3** stated in Section 1.3.

The method is also validated and verified through a case study of Singapore in Chapter 5 to show how OSNEA can be used to analyse resource use in a city and inspect resource sustainability of the urban system for the first time. In this case study, the OSNEA framework is used to evaluate the effectiveness of resource use in the urban system of Singapore representing a single-city system and the results suggests a trade-off relationships between the producing and consuming sectors as the sectors compromised to balance the metabolic activities in the ecosystem. In Chapter 6 for another case study of the systems of cities in GB which represents a multi-city system, consumers traits dominate the systems due to concentrated consumption activities in urban areas since resources are supplied through producers located outside the urban boundaries. In these case studies, OSNEA is applied to study the input-output exchanges of resource flows between the sectors across the whole systems (in terms of exergy flows) and construct the open system networks representing the socio-economic structures of the cities. These fulfil the **objective 4** stated in Section 1.3 and provide a comparison to show the variations of urban economic structures and their resource use behaviours across urban systems.

The findings of overall effectiveness balance, expressed in θ values, of the system explore the ecological roles of the producing and consuming sectors in the cities based on their resource use performances to facilitate resource utilisation while maintaining high processing efficiencies and output conversion rate to sustain economic growth. From the case studies of UK cities in Chapters 3 and 6, the results highlights that London, a more compact city with a larger population size than the others, has better performances in terms of system mutualism and synergism indices, as well as the overall resource effectiveness and balance results generated from OSNEA. These show that industrial diversity in the economy is important to provide pathways for facilitating flow circulations and resource exchanges between the economic sectors and closing the circularity loops within the urban networks. Economic diversification is, however, a double-edge-sword that could accelerate population growth and resource consumption in cities without careful management as it requires a larger workforce to operate. Hence, it is crucial to ensure the configuration of sector mix in the economic structure of the city balances the production and consumption activities for the cities to enjoy the benefits of diversity and sustainability in the long-term. This is consistent with the targets prescribed in The Paris Agreement to accelerate global actions on "*building the resilience of socio-economic and ecological systems, including through economic diversification and sustainable management of natural resources*" (United Nations, 2015b, p.11).

Comparing the results obtained from the case studies of a single-city system (Singapore) and a multi-city system (GB), although the magnitudes of the overall resource effectiveness (R) of both systems are very similar, the main difference is the degree of their overall effectiveness balance (θ) where the single-city system has a better balance than the multi-city system. In a single-city system, internal production is a key component in the network of resource supply chains to process the resources imported for local use and in contrast, the multi-city system tends to exhibit a consumer behaviour due to the concentrated consumption activities in the urban areas which causes high resource intakes into the cities from the producers located outside the urban boundaries. This shed light on how more developed and bigger cities act as the sinks in the urban networks by drawing in resource flows from the rural areas or the developing regions to support their resource-intensive economic activities, resulting in high concentrations of carbon footprints in urban areas. This raises a question on how the origins of resource imports, whether it is imported from the cities' hinterlands including the rural areas, inter-city imports or international trades, affect the effectiveness of resource use. To explore this, development of a multi-scale model is required to analyse a complex economy-wide system and study the spatial impacts of the supply chains on the wider urban networks for understanding the dynamics of urban-rural resource linkages and the effects on overall system sustainability. From a future perspective, the current behaviour of urban resource use will gradually expand the development gaps between the developed and developing cities in a multi-city system due to income inequalities, and between the developed and developing countries on the global level, because the production and extraction of raw materials often occurred in the less developed areas with a lower GDP, who are usually net exporters (Moran *et al.*, 2018). With reference to the Sustainable Development Goals (SDGs), this is an alarming pattern of resource supplies and use in urban economies that needs to be countered through building resource-effective and self-sufficient cities to promote sustainable economic growth for all (SDG 8) and to reduce inequality within and among countries (SDG 10).

In summary, the development and application of OSNEA, as an ecological-thermodynamic approach to study the use of resources in UM, have two ultimate purposes: firstly, to use resources effectively and secondly, to reduce demand. Effective use implies maximising the work done extracted (or outputs delivered) from the existing resources in the cities, then leads to reductions in the demands for new material imports as the same amount of work can now be done with less resource inputs through more effective utilisation and conversion processes. Making better use of all resources available, including the by-products from the urban metabolic functions, also means retaining and recirculating waste outputs from urban processes and turning the waste streams into supplies of recovered materials in a circular economy (CE) to deliver new products or services, helping to eliminate waste emissions from cities. OSNEA adds a new dimension of effective resource use to the existing assessment tools to tackle cities' contribution to carbon footprint and climate change. The purposes of OSNEA are in parallel to the objectives of Carbon Neutral Cities - to achieve net-zero greenhouse gas emissions from all sectors within the cities' boundaries through sustainable consumption and production (C40, 2019).

7.3. Open system network effectiveness analysis: A critical appraisal of the limitations

This section constitutes a critical appraisal of the OSNEA framework based on the limitations and applicability of the method in different cases. From the literature review presented in Chapter 2 and the case studies demonstrated in Chapters 5 and 6, it has been established that the availability of data remains the main constraint in the applications of UM approaches. The following of this section discusses the limitations to the applicability of OSNEA focusing on (1) inadequate continuous timeseries data for temporal analysis, (2) incompatibilities between data formats and sources, (3) uncertainties of resource flow conversion for exergy accounting and (4) the lack of spatial data in the model.

From the work demonstrated in Chapter 4, the development and derivation of the OSNEA methodology is performed rigorously following the workflow illustrated in Figure 4.1 to develop a novel urban sustainability assessment framework based on data acquired from open sources. The case studies for both Singapore and GB are conducted using public available data only. The shortcomings of both of these studies are discussed in Sections 5.7 and 6.6 where data inadequacy is the main limiting factor for extending the investigation to observe the temporal changes in resource use behaviours of urban systems through a longer period to better describe the relationships within the intra-sectoral socio-economic system of the cities, and between the cities and their external environment over time.

The concept of UM is indeed a data-intensive application to analyse complex urban systems and to understand their resource needs. In the case of OSNEA, data requirement for conducting the study is considerably demanding as the analysis requires inputs of data from various aspects of the cities such as trade flow data, economic data, employment data and emission data (as listed in Section 4.6). These form a barrier restricting the applicability of the OSNEA method in other cities as it requires a collection of datasets that is unique for each case study city, especially for developing cities where data collection at the intra-city and inter-city levels can be time consuming and expensive to maintain. Nonetheless, assuming resource flows are correlated to the monetary flows through an economy, scaling the data from the national or regional level to the urban level with the sector-specific economic data of the city is plausible if the economy-wide data (of a country) is available. This is demonstrated in the case studies in Chapters 3 and 6 where the city-level data are obtained by scaling down from the national data with gross value added of the industrial activities in the cities to derive the amount of resources imported by the sectors. Besides this, since the data required are often obtained from various databases with different data management standards and practices, assumptions and adjustments made to reaggregate material types and economic activities are deemed necessary to perform such analysis. In this context, converting the datasets to the corresponding format for the earliest recorded year is required (as demonstrated in the GB case study in Chapter 6) due to variations in the description of traded commodities registered on the Comtrade database using the Harmonised System and the sector classification standards used in the local statistics to describe economy structure in the input-output data, see Table 6.1 for examples. Because of these, overcoming syntactic incompatibilities between these datasets presents an obstacle and a challenge to conduct an extensive application of OSNEA in global cities .

Moreover, the concept of exergy is integrated in the OSNEA framework for accounting of resource flows in urban systems. Resource intakes by the cities are accounted in the quantity of exergy import based on the specific exergy values of the materials under the assumption of steady reference conditions. A sensitivity analysis is also presented in Section 5.7 showing that the uncertainties of the specific exergy values for resource conversion have negligible impacts on the accuracy of the results (lower than 15% for a 50% uncertainty from Figure 5.7) as the errors are cancelled out when considering both imports and exports crossing the system boundary except for the exergy values of fossil fuel products. Nonetheless, for further improvement of the overall accuracy of the method, the role of reference conditions in exergy accounting should be considered in the OSNEA framework as discussed in Section 4.2 to derive the equivalent exergy values of materials with respect to the real surrounding environment with fluctuating conditions.

Furthermore, another shortcoming of the OSNEA framework is the lack of spatial characterisation in the analysis to describe the distribution of resource flows within an urban system. This is due to limited access to data at urban level compared to the regional and national levels. As such, the applicability of this method can be enhanced by considering spatial variation of the economic intensities across the urban systems to identify the pathways of resource flows within the system and highlight the hotspots of resource producers and consumers in the cities. However, in the current OSNEA methodology, regional or national data are scaled with economic statistics such as gross value added of the cities to estimate the portions of resource allocated to the cities based on their economic performances, assuming resource intensities of the cities are correlated to their economic growth. In brief, to further extend the applicability of OSNEA, addressing the spatial components of cities by incorporating a spatial analysis in the framework will enable a thorough investigation of urban resource use through a multi-scale system to assist policymakers in planning resource allocation and market regulations.

Besides these, the thermodynamic analogy of cities as open systems provides an interface for integration of thermodynamic and economic systems, in the form of open system networks, to understand the effectiveness and behaviours of resource use through urban metabolic processes. However, the real implication of OSNEA application is limited because the use of thermodynamic principles to model the resemblance between resource use in urban systems and transformation in energy systems is regarded as metaphorical (Hammond and Winnett, 2009). The use of exergy and extended-exergy in this study provide a descriptor to evaluate the theoretical maximum work extractable from the resources available, often expressed in terms of work availability or value of monetary benefits, to monitor the effectiveness and overall resource efficiency of the system, but the method does not reflect work done in reality. Hence, this should be taken into consideration when applying the framework in real-world situations.

In summary, discussion on the applicability of the OSNEA methodology in this section is intended to identify the limitations in current analysis and explore the areas for further improvements (in addition to those listed in Section 8.2) that will contribute to the establishment of OSNEA as a universal tool for urban sustainability assessment.

7.4. A universal tool for urban sustainability assessment: Versatility is the way forward

This section discusses the versatility of the OSNEA framework to be considered as an urban sustainability assessment tool. From OSNEA, the *effectiveness* indicators comprise a set of system-wide performance metrics representing the fraction of the total resources imported by an urban system that is utilised by the system to produce work done or converted to resource outputs. In an urban context, *effectiveness* measures the ability of the city to utilise (ε_U) or convert (ε_C) the resources available through cascading processes within the network cycles. In other words, the OSNEA framework is a new assessment method of urban sustainability concerning the states of resource utilisation and conversion based on the resources available in cities. In this aspect, the idea of OSNEA echoes the principles of implementing a CE in urban systems by taking an ecological-thermodynamic approach to account resource flows in UM. OSNEA evaluates the effectiveness of resource circulation within the systems to achieve a cross-sector circular metabolism across the entire urban economies. From a whole-system perspective, OSNEA offers a new way of accounting UM, reflecting resource sustainability in cities and assessing the system progress towards the implementation and industrial transition to CE.

The concept of CE is increasingly recognised and adopted by business managers and policymakers as a resource planning tool to foster sustainable growth through CE processes. For example, CE initiatives outlined in the European Commission's CE Action Plan (2020) focus on the sectors and products that consume most resources and of high circularity potential such as electronics, plastics, packaging, construction materials, food and water. For strategies targeted on specific material streams or the associated production lines, it is difficult to compare and assess the combined impacts of the adopted CE strategies across all hierarchies of resource use. Implementation of CE strategies in a complex urban system should consider the dynamics of all resource types in the cities. By converting resource flows to their equivalent exergy values, the application of OSNEA enables the formation and examination of a unified CE system at the urban level, including all economic sectors and taking account of all hierarchies of CE strategies, to reorganise the processes in the urban economies and promote a circular metabolism to improve resource efficiency of the whole system.

Furthermore, OSNEA can also be used in conjunction with the other methods in the UM framework to compare the effectiveness results to other UM indicators or environmental indicators for assessing the overall performance of the systems. For instance, the case study in Chapter 5 not only presents the effectiveness results, but also the control and dependency relationships among the economic sectors, based on both of the monetary and exergy flows, as a joint-application of OSNEA and the ecological network analysis to study the metabolism of Singapore city. In this case study, findings from the exergy-based analysis highlights the dependencies of the domestic sector as the main consumer within the urban economy (as shown in Figure 5.4) and reveals the trade-off trajectory between the producers and consumers to maintain an ecological balance for a long-term system stability (as shown in Figure 5.6). These results show the merits of OSNEA as a complementary exergy-based assessment to evaluate resource sustainability in urban systems from an ecological-thermodynamic perspective that is absent in the existing urban sustainability assessment methods and the UM framework. This is important for learning how cities can maximise the use of the limited resources available and reduce the extraction of new resources, helping the cities to become self-sufficient.

Moreover, the results for exergy intensities, as shown in Figure 5.3(a), are computed by comparing the exergy-based measurements to secondary data such as economic data to indicate the amount of exergy imported per unit economic income (gross value added) generated by a sector or the economy. Low exergy intensity means a lower price or cost of converting exergy into economic benefit and less resource import required by the system. For a greater impact, raising an awareness of limiting cities' imports through effective use of existing resources is important in all urban stakeholders from policymakers, business owners to the domestic consumers to lower the demands for new material intakes at local level. With decreased demands for import and international trade flows, carbon footprint of the global network of resource supply chains can be greatly reduced, relieving the pressure on the global sustainability challenges due to resource scarcity and greenhouse effects.

A global indicator framework (UN Statistical Commission, 2017) was developed for tracking the global progress towards the SDGs. There are 231 unique indicators across all 17 SDGs in the framework, in which 27 indicators are dedicated to monitor the targets of SDG 11 for sustainable cities and communities, and SDG 12 for responsible consumption and production. These include a number of indicators focusing on the rate of urbanisation, such as the ratio of land consumption rate to population growth rate (Indicator 11.3.1) and the average share of the built-up area of cities that is open space for public use for all (Indicator 11.7.1). For accounting material consumption and waste management, the indicator framework measures the proportion of municipal solid waste collected and managed in controlled facilities out of total municipal waste generated (SDG 11.6.1), material footprint (SDG 12.2.1), domestic material consumption (SDG 12.2.2) and the national recycling rate (SDG 12.5.1). However, none of these is conceived to address the emerging problems related to the effectiveness of resource use and circularity of resource flows in urban systems that threatens the sustainability of our cities and societies. Likewise, to achieve the vision of One Planet Living framework where human can live happily within the Earth's resources, the framework has incorporated the SDG indicators to propose level-specific indicators and predicted outcomes for monitoring cities' performances and inform the actions taken by the local governments (Gerhards, 2019). The framework considers indicators that are appropriate to local contexts, suitable for organisation-level actions and area-wide communities, based on data available. Taking a future perspective, the OSNEA indicators can be developed and adapted to act as a universal framework for assessing urban sustainability and bringing new dimension to global movement towards sustainable development. The *effectiveness* indicators (ε_U and ε_C) can be mapped onto other SDG indicators that is currently in use, such as domestic material consumption, material footprint and recycling rate (which are aligned with the objectives of SDGs 11 and 12), to account for the total resource intakes and reflect the states of resource use in cities.

The evidence discussed above (and all the results of the case studies demonstrated in Chapters 5 and 6) emphasise that the application of OSNEA is highly versatile and has great transferable value to deliver useful insights of the system's overall resource effectiveness and assist policymakers in urban resource management to promote sustainability. From a planning perspective, in the way forward, policy intervention is needed to support such an initiative to escalate the potential implications of OSNEA on shaping the blueprint for developing sustainable cities. In this respect, the indicators of resource effectiveness can be added to the existing monitoring framework of urban sustainability performances as an import regulation benchmark to limit the resource intakes by cities. The goal to achieve this is, however, a challenge for all including the researchers, policymakers and practitioners. As discussed in Section 7.3, mainstreaming OSNEA to create a universal tool for evaluating urban sustainability requires a data-rich environment in order to meet the data requirements for such analysis. To overcome this, the vital first step is to call for more attention and actions from the governing bodies to support data collection initiatives. For instance, tracking and recording the data for the movements of resource flows, including the mass and types of products, within and across the local boundaries, should be done not only at the regional and national levels but also at the urban or lower administrative levels.

7.5. Chapter conclusion

In this chapter, a synthesis of the discussion is brought together by combining all findings and the overall insights obtained from this work. This highlights the purpose and practicality of the OSNEA framework and addresses the limitations of its application while exploring the potential areas for further improvement. The key message from this chapter is to call for attention to the need for supporting and promoting urban metabolism data collection for better understanding of sustainable resource use behaviours in cities.

Chapter 8

Conclusion and Recommendations

The current chapter contains materials that were previously prepared for the following articles:

Tan, L. M., Arbabi, H., Li, Q., Sheng, Y., Densley Tingley, D., Mayfield, M. & Coca, D. (2018). Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales. *Resources, Conservation and Recycling*, *138*, 172–182.

Tan, L. M., Arbabi, H., Brockway, P. E., Densley Tingley, D. & Mayfield, M. (2019). An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis. *Applied Energy*, *254*, 113618.

Tan, L. M., Arbabi, H., Densley Tingley, D., Brockway, P. E. & Mayfield, M. (Under review). Mapping resource effectiveness across urban systems.

8.1. Conclusion

This section provides a snapshot of the knowledge contributions and conclusion of the work entailed in this thesis. This work presents the development and application of a novel approach to tackle the global resource problem, a real-world challenge facing the whole population that is yet to be fully understood. As stated in the research aim, by taking an ecological-thermodynamic approach, the open system network effectiveness analysis (OSNEA) is developed as a novel urban sustainability assessment framework to investigate resource utilisation in cities by evaluating the ability of the system to extract maximum work done from the resources available in cities. The methodology of OSNEA essentially utilises the techniques of ecological network analysis and input-output analysis to provide new insights into urban sustainability beyond the existing applied method in industrial ecology in accounting of urban metabolism (UM).

The study shows how the metabolic flows in cities, in the form of resource exchanges between sectors, affect the effectiveness performance of the urban networks. The *effectiveness* indicators measure the abilities of the systems to utilise and convert the resources available based on the imports of the systems. Formations of resource flow connections between sectors provide pathways to enable resource utilisation through consumer activities and conversion to outputs through producer activities. Combining the effectiveness of utilisation and conversion describes the resource use behaviours of the systems and gives an indication to the overall resource effectiveness of the systems.

To address the research question of "*how much of the resources available in cities is effectively consumed due to thermodynamic utilisation and energy degradation as the results of metabolic flow exchanges in the urban ecological networks?*", this work establishes a novel ecological-thermodynamic approach to measure the effectiveness of resource utilisation and conversion through economic sectors in the urban ecosystems using an open system network model. Recalling the research scopes outlined in Section 1.3, the development of such approach supports the aim of this work and contributes to the formulation of the OSNEA framework for accounting resource flows in cities and introduction of the *effectiveness* indicators, namely the *effectiveness of utilisation* and the *effectiveness of conversion*, as system-wide performance metrics to measure the ability of the system to extract the maximum work done from the resources available. In the OSNEA framework, higher effectiveness can be achieved by retaining materials in use and prolonging the circulation of resource flows within the local urban networks to extract higher work done from limited resources available in cities. As such, accomplishment of the same targets with less resource inputs will decrease the cities' demands for imports, and ultimately reduce the needs for resource extractions.

8.1.1. Summary of findings and knowledge contributions

Throughout this study, the key contributions and knowledges gained from the main body of this thesis, are summarised as follows, followed by a final section for concluding remarks.

i. The prominent producer and consumer behaviours in the urban systems can be derived based on the metabolic relationships between the economic sectors and resource supply chains within the urban ecological network.

In Chapter 3, ecological network analysis is applied to study the intra-city flows between economic sectors of 35 cities in England and Wales to investigate their respective metabolic relationships. In addition to the functional analysis of the urban ecological network, the intra-city flows network of each area is also supplemented with the geographical distance between the workplace zones to study the impacts of spatial distribution on the density of resource flows. From the results presented in Section 3.3.1, the consumption-control and production-dependency relationships reveal the hierarchical orders among the sectors resembling the pyramidal structure of an urban ecosystem. From the results in Section 3.3.2, the structures of network community classification emphasise the importance of inter-relationship within the internal organisation of each community class. The producer-type and consumer-type communities shows the tendencies of those sectors to cluster based on their respective hierarchical roles in the ecosystem which also helps to identify the ecological behaviours exhibited by the system.

Through this study, the intra-city case study highlights the drawbacks of existing UM accounting methods to investigate the metabolic transformations in material flows through resource utilisation and conversion processes in cities. This is also tied to **Objective 2** defined in Section 1.3 to inspect the application of existing methods and identify spaces for potential improvements of the UM concept. Adding a thermodynamic descriptor to evaluate the metabolic properties of material flows will provide a new dimension that allows an integrated quantitative and qualitative account of resource utilisation through urban processes.

ii. A novel open system network effectiveness analysis is developed by integrating the thermodynamic and economic systems of urban activities to study the behaviours of resource use in an urban system using the *effectiveness* indicators of resource utilisation and conversion.

In Chapter 4, OSNEA is developed as a novel assessment framework to investigate the cities' producer and consumer behaviours by studying the resource flow connections and the interactions between the socio-economic sectors. The framework incorporates an exergy analysis with an economic input-output analysis to explore the quantitative and qualitative transformation of resources through urban processes. Through the development of OSNEA, the workflow conceptualises the method as a novel ecological-thermodynamic approach to study the metabolism of cities as open system networks for better understanding of resource use in urban processes based on their imports, this is in line with the **objective 1** of this work.

The development of OSNEA includes the introduction of a pair of exergy-based indicators to evaluate the ability of the system to utilise the resource imported through the *effectiveness of utilisation* indicator (ε_U) and the ability to convert the resource imported to useful products through the *effectiveness of conversion* indicator (ε_C), as described in Table 4.2. This is also in line with the **objective 3** to formulate new assessment metrics for urban sustainability performances based on the effectiveness resource use in cities. The *effectiveness* indicators, utilisation and conversion, represent the consumption and production characteristics of the system respectively.

Chapter 4 represents the accomplishment of an important milestone in this work and in the related research fields - development the OSNEA methodology and formulation of the *effectiveness* indicators.

These have successfully addressed the research needs (items 1 and 2) identified in Section 2.6 based on the literature review.

iii. The trajectory of effectiveness results through time suggests a trade-off relationship between the producers and consumers to balance the production and consumption of resources in the city.

In Chapter 5, the application of OSNEA is tested through a case study conducted for Singapore city over the time period 2005-2014 as a single-city system (to deliver the **objective 4**). This study shows how the OSNEA framework can be applied as a novel assessment tool to evaluate urban sustainability based on the effectiveness of resource use in urban systems.

The effectiveness results show that the city-state, on average, has utilised 45% of the maximum extractable usefulness from the resources imported throughout the years, with the lowest effectiveness, 39%, and the highest effectiveness, 50%, in the years 2007 and 2014 respectively. From the effectiveness plot shown in Figure 5.6, the back-and-forth trajectory of the effectiveness results, with varying overall effectiveness balance of the system throughout the years, suggests a trade-off relationship between the producers and consumers in the urban ecosystem as the intra-sectoral system organises and compromises to balance their resource production and consumption when the system grows. In later years of the case study duration (2010-2014), there is an emergence of consumer traits in the urban system due to advancing tertiary industries to meet the increasing demands of consumer services and higher economic contributions for continuous growth.

These results show the traits of consumer and producer behaviours associated with the activities of the system and provide new insights as a complementary measure in examining urban development and the necessities of balancing resource intakes and economic incomes for long-term sustainability. For urban planners, OSNEA provides a useful tool to inform decision making across the social, economic and environmental aspects of the urban activities, including greenhouse gas emissions, domestic household consumption and workforce employment, for a thorough investigation of the city's metabolism.

iv. Analysing the effectiveness of resource use across the whole multi-city system enables clustering of cities based on their similar resource behaviours which reveals the absence of producers in the urban systems to close the circularity gaps of resource flows in interconnected urban networks.

Chapter 6 examines the interdependencies within the Great Britain urban systems by quantifying and mapping resource effectiveness across all 38 functional urban areas in the inter-connected urban networks, representing a multi-city system (to deliver the **objective 4**). The findings in Section 6.3 show higher tendencies of consumer-like behaviour in a multi-city system than a single-city system because the service-based tertiary sectors are concentrated in urban areas while the producing sectors are mainly located outside and hence, results in high utilisation and low conversion. In Section 6.4, the clustering taxonomy emphasises the absence of producers in the system causing the cities to rely on the imported resources for sustaining their metabolic activities and economic growth.

Observations from this work strongly suggest that cities can be resource-effective by having a more diversified industrial structure to extend the pathways of resource flows, closing the circularity gap between the suppliers and consumers. A possible avenue for regulating urban consumption and improving the cities' resource use performances is building compact circular cities to promote resource circulations within the urban systems through more connected networks and shorter distances between the urban units to cut emissions (Ellen Macarthur Foundation, 2019). Longer and denser flow circulations promote higher effectiveness locally which in turn reduce the system's reliance on international imports and drive the system towards sustainable development.

v. A crucial need for promoting global initiatives and collaboration in collecting and constructing databases for urban flow activity data should be addressed in the UM framework, supported through policy interventions providing incentives for learning and using the data to understand urban sustainability.

Chapter 7 discusses the practicality, applicability and versatility of the OSNEA framework as a tool for urban sustainability assessment. Section 7.4 provides a foresight of the challenges and potential adaptations on the framework for broader applications and addresses the research need of resolving the limitations of the framework due to data inadequacy (item 3 on the list of research needs in Section 2.6). The literature review of industrial ecology approaches to UM in Section 2.3 and the critical appraisal of the method in Section 7.3 have identified data limitations as one of the main drawbacks of many UM approaches limiting the implications and contributions of the studies, including the work on the OSNEA method. Therefore, a collective effort from researchers, practitioners and policymakers is required to translate research into action because cities and countries need to be more proficient at collecting the data regarding the system metabolism at all stages of resource use, and making the data available for research analysis and planning purposes.

As advocacy for mainstreaming urban metabolism data, the author calls for initiatives from all urban stakeholders and data organisations, such as the European Commission (EC), the Organisation for Economic Co-operation and Development (OECD), the World Bank and C40, to lead the transformation to collect high-quality urban data and support the incentives to:

- measure urban material stocks and estimate the amount of material that is currently in-use in the built environment
- geo-tag urban components for describing the spatial characteristics of the system
- track and record the movements and pathways of commodity flows across spatial levels from the origins to the end-users in order to analyse the interdependencies within the supply chains of the resource network
- formulate city-level physical input-output tables to acquire the actual amount of resource supply and use in cities
- collect waste data to compute the exergy wasted through emissions from cities including solid wastes, air pollutants and greenhouse gases.
- standardise the timescales and methods used in collecting routine data to ensure a consistent comparison across the wider interconnected systems of cities

8.1.2. Concluding remarks

OSNEA is a novel approach to redefine sustainability in terms of resource utilisation, and intended to enlighten researchers and policymakers in realising the ambition of fully circular cities to shape a better future through sustainable consumption and production. OSNEA is unique not only because it presents a combination of thermodynamics and ecological approaches to study open economies, but also because the effectiveness analysis includes an investigation of the dynamics of internal linkages between individual components of the network. The importance of this work is to highlight the implications of how cities are internally organised as open systems when more and more resources are being imported into the system and to encourage effective operations to maximise the use of limited resources available.

From a broader perspective, strategies to reduce the demands and consumption through better use of the existing resources available are the keys to sustainable development on a planet with finite carrying capacity. As cities are the main drivers of over-consumption and carbon emissions, a systemic change of the resource use behaviours in cities is crucial to end the excessive consumption patterns beyond the planetary limits and minimise the risks of adverse environmental impacts causing biodiversity loss and climate change which affect the whole population worldwide. Characterising the ecological behaviours and the roles of economic sectors in the urban ecosystems form an understanding of the cities' needs and their abilities to consume effectively for future growth. The OSNEA assessment will inform the policymakers about an often-overlooked criterion of urban sustainability based on the effectiveness performances of the cities to utilise their limited resources available and reduce the needs of extracting new resources as levers for sustainable development. This also adds to current policies and helps to facilitate decentralising of urban resource policy (from national policies) to focus on city-level planning and sector-specific economic strategies based on their unique urban characteristics. These include regulations on how sectors connect with each other and the flow connectivity within a city, and between the cities.

OSNEA enables strategic resource management and transition to a circular economy by retaining and circulating resource flows in loops for as long as possible to achieve maximum energy degradation through cascading processes in urban systems, driving national and urban development towards the Sustainable Development Goals (United Nations, 2015a). This also aligns with the UK Industrial Strategy for Clean Growth Grand Challenge (Department for Business Energy and Industrial Strategy, 2017) to reduce consumption and emission while delivering improved industrial productivity and closing the development gap between the sectors and regions. This promotes sustainable urban development to support the objective of delivering economic impact and social prosperity for a productive and resilient nation possessing the ability to develop new processes and technologies. In brief, this helps to accelerate the shift to a circular economy for provision of sustainably managed resources and effective use of existing resources to achieve the targets of net-zero carbon cities in the long-term development agenda.

8.2. Recommendations for further work

This section outlines the research recommendations for further work in this area. These suggestions fall into two categories based on the requirements of data availability, whether (1) the required data are currently available to conduct further research work, or (2) on the basis of the required data become available for further work in the future.

8.2.1. Further work based on the current data available

From the datasets acquired throughout this study, recommendations for further development are as listed in the following:

1. Formulation of analytical proof to identify the theoretical frontier of effectiveness analysis due to the thermodynamic limit, as shown in Figure 4.4, for blueprinting the areas for potential improvements and to facilitate resource utilisation within the cities while maintaining high processing efficiencies and output conversion rate to sustain economic growth within the capacity of the system.
2. Investigation of the cross-sector relationships and interdependencies between the cities and the key channels of resource intake into the system and the external risks the system is exposed to such as climate change and sea level rise. For instance, identifying the possible hazards causing disruptions to resource connections of the urban network can suggest suitable precautionary actions to secure the resource linkages in the supply chains and sustain proper functions of the urban system.
3. Understanding policy adaptation strategies based on the producer or consumer behaviours observed and the impacts on the system to enhance resource management in urban environments for optimised performance.

8.2.2. Further work should the data become available in the future

In addition to the suggestions above, provided the data required are available, the following outlines the potential areas for further research work:

1. A spatially extended OSNEA model to account for resource trade flows across various scales (including flows at intra-city, inter-city, regional, national and global levels) to assess the resource use performances of the industrial clusters and their interactions in order to characterise the geographical specialisation and distribution of economic activities across the interconnected networks of the wider urban systems.
2. Comprehensive applications of OSNEA to different cities or countries worldwide to study the resource interdependencies within the flow networks, and at the global scale to allow comparisons between different systems, including a system of the Earth limited by the planetary biocapacity and finite supplies of natural resources from the environment.
3. Dynamical system modelling to study the temporal changes of the system performances and behaviours rather than a static snapshot to allow forecasting of future scenarios as the city (or the country) develops.

4. Thermodynamic conversion of exergy values based on the actual reference conditions to compute the equivalent exergetic contents of the resources as well as the exergy accounting of waste emissions to include all types of waste exiting the system.
5. Inclusion of energy harvested from renewable sources for accounting the total resource intakes by the system to give credits to the processes that utilise eco-friendly resources, which is a more effective and sustainable operation than utilisation of carbon-intensive fossil fuels.

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Appendix 1: Breakdown of industry mix by GVA share

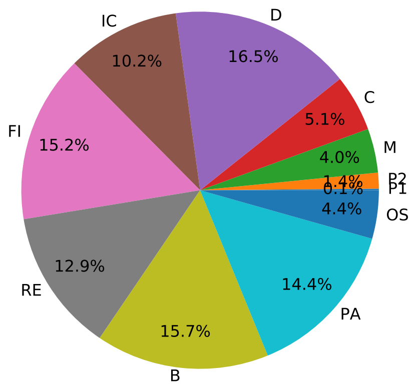

Figure A1.1: London's industry breakdown by GVA, total GVA = £ 413,048 millons (2011).

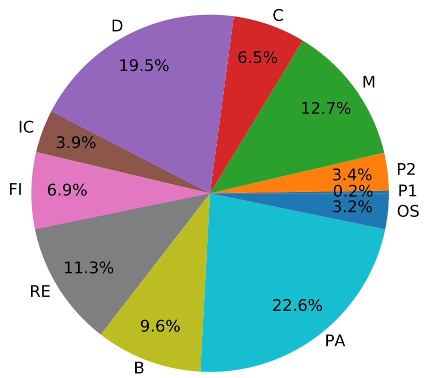

Figure A1.2: West Midlands's industry breakdown by GVA, total GVA = £ 52,211 millons (2011).

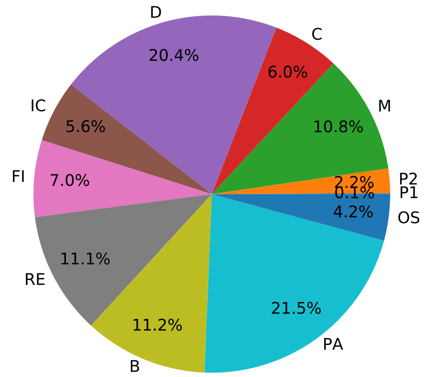

Figure A1.3: Greater Manchester's industry breakdown by GVA, total GVA = £ 52,800 millons (2011).

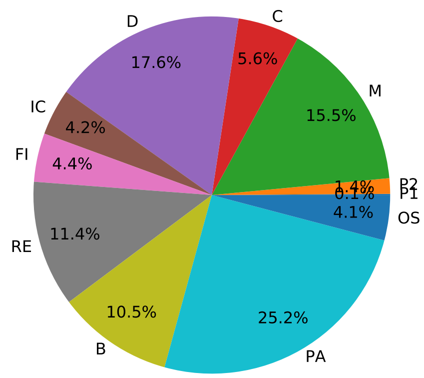

Figure A1.4: Liverpool's industry breakdown by GVA, total GVA = £ 26,784 millons (2011).

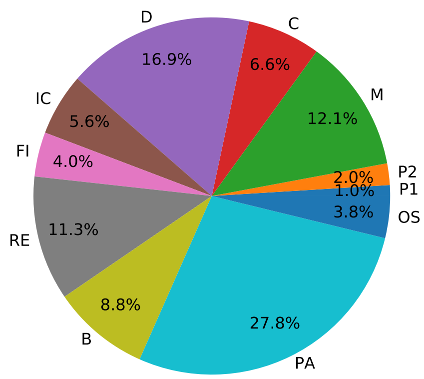

Figure A1.0: Tyneside Conurbation's industry breakdown by GVA, total GVA = £ 25,672 millons (2011).

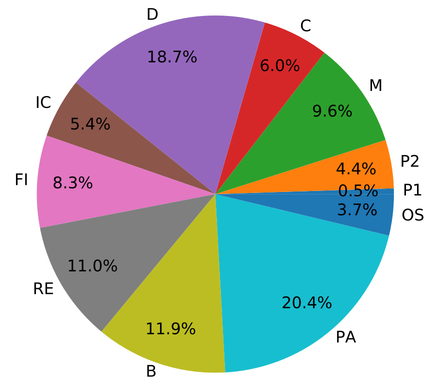

Figure A1.6: Leeds's industry breakdown by GVA, total GVA = £ 26,575 millons (2011).

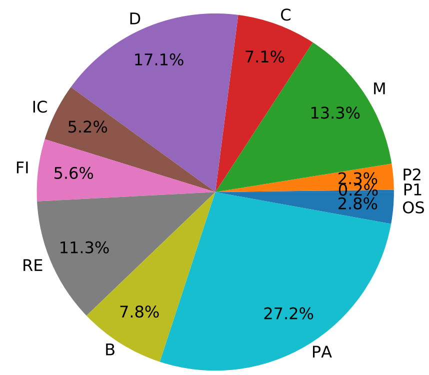

Figure A1.7: Sheffield's industry breakdown by GVA, total GVA = £ 15,597 millons (2011).

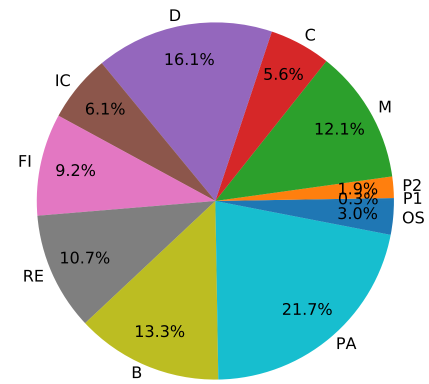

Figure A1.8: Bristol's industry breakdown by GVA, total GVA = £ 23,235 millons (2011).

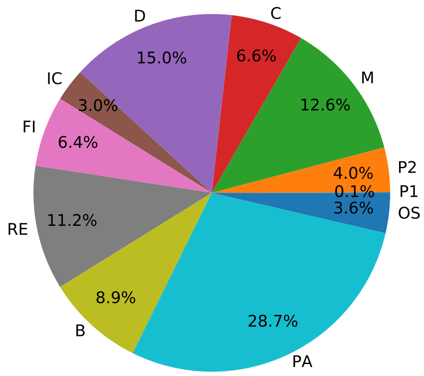

Figure A1.9: Cardiff's industry breakdown by GVA, total GVA = £ 15,418 millons (2011).

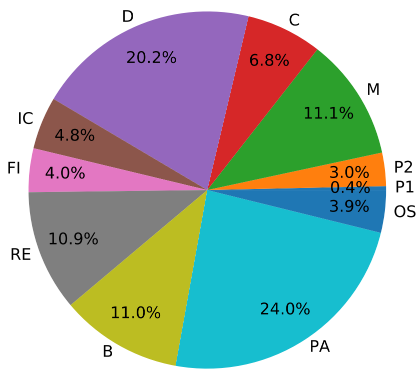

Figure A1.10: Greater Nottingham's industry breakdown by GVA, total GVA = £ 16,528 millons (2011).

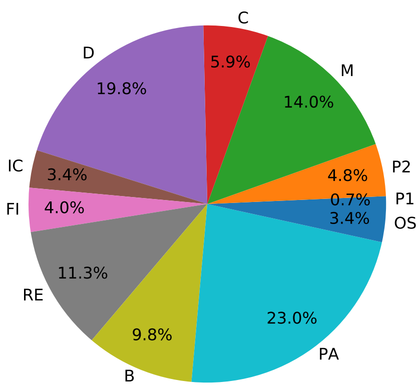

Figure A1.11: Leicester's industry breakdown by GVA, total GVA = £ 15,845 millons (2011).

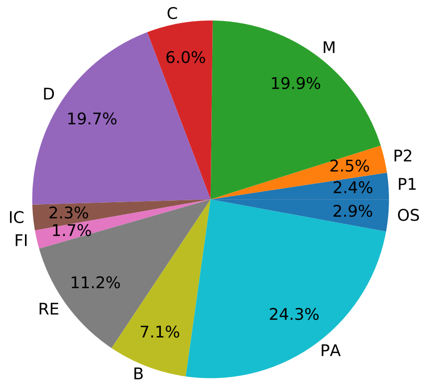

Figure A1.12: Kingston upon Hull's industry breakdown by GVA, total GVA = £ 10,151 millons (2011).

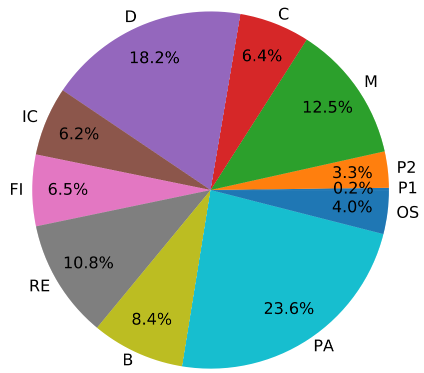

Figure A1.13: Coventry's industry breakdown by GVA, total GVA = £ 10,004 millons (2011).

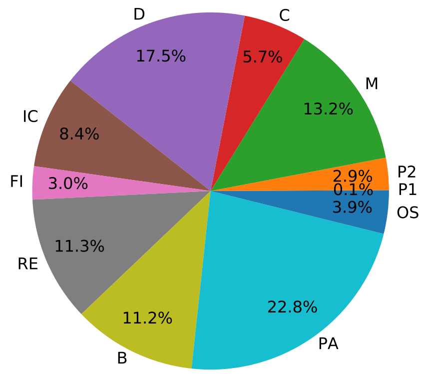

Figure A1.14: Portsmouth's industry breakdown by GVA, total GVA = £ 10,905 millons (2011).

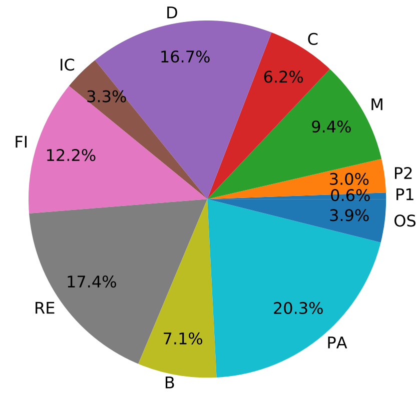

Figure A1.15: Bournemouth's industry breakdown by GVA, total GVA = £ 10,399 millons (2011).

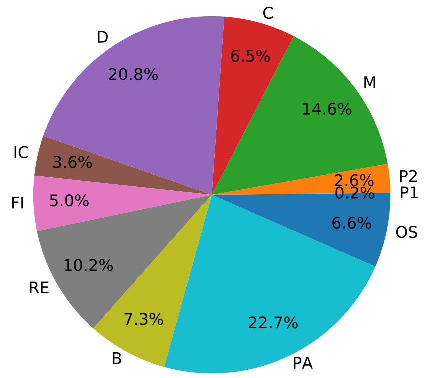

Figure A1.16: Stoke-on-Trent's industry breakdown by GVA, total GVA = £ 7,579 millons (2011).

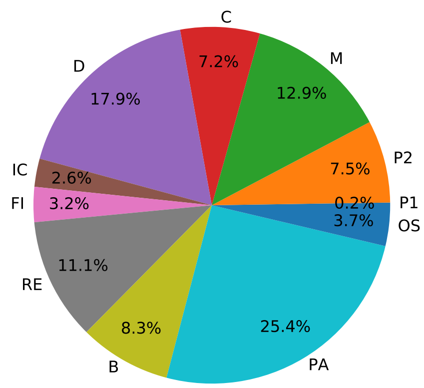

Figure A1.17: Middlesbrough's industry breakdown by GVA, total GVA = £ 7,906 millons (2011).

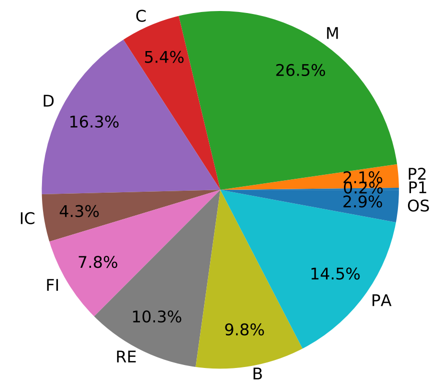

Figure A1.18: Cheshire West and Chester's industry breakdown by GVA, total GVA = £ 8,751 millons (2011).

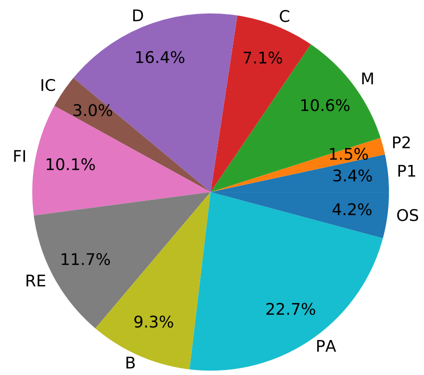

Figure A1.19: Norwich's industry breakdown by GVA, total GVA = £ 8,024 millons (2011).

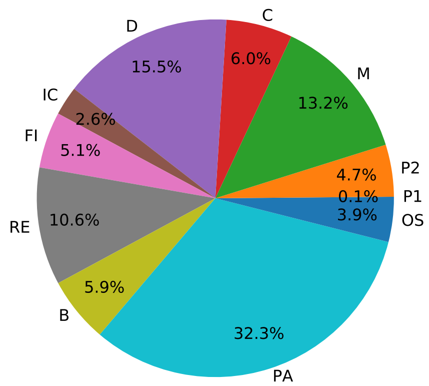

Figure A1.20: Swansea's industry breakdown by GVA, total GVA = £ 5,971 millons (2011).

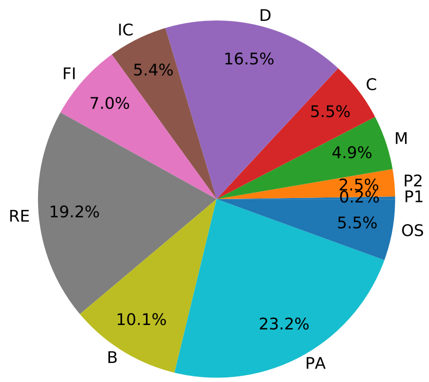

Figure A1.21: Brighton and Hove's industry breakdown by GVA, total GVA = £ 7,287 millons (2011).

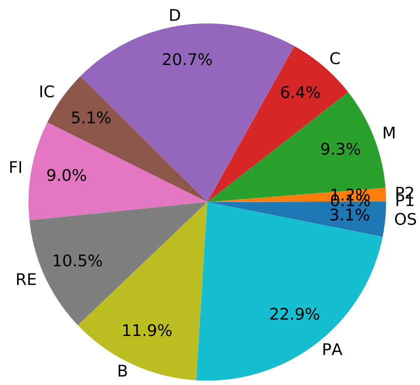

Figure A1.22: Southampton's industry breakdown by GVA, total GVA = £ 8,248 millons (2011).

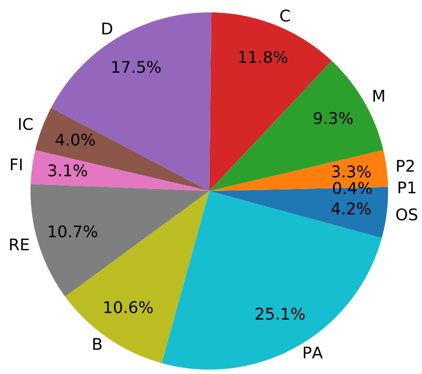

Figure A1.23: Preston's industry breakdown by GVA, total GVA = £ 7,137 millons (2011).

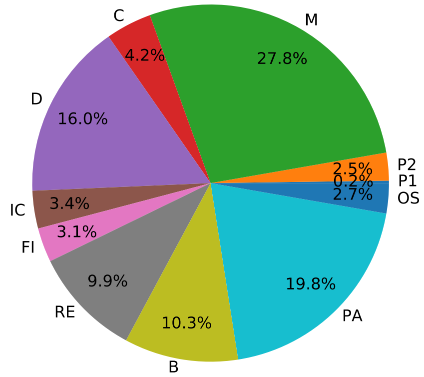

Figure A1.24: Derby's industry breakdown by GVA, total GVA = £ 7,405 millons (2011).

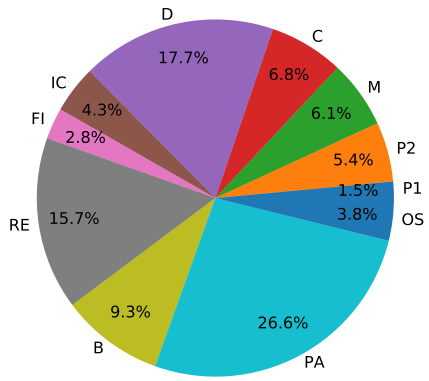

Figure A1.25: Exeter's industry breakdown by GVA, total GVA = £ 6,664 millons (2011).

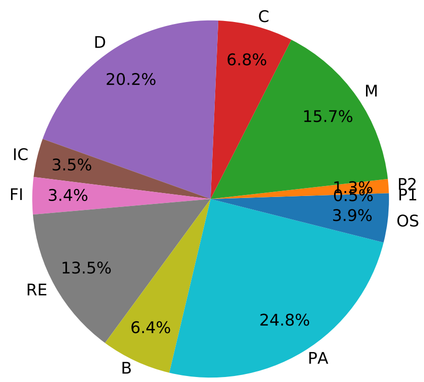

Figure A1.26: Blackpool's industry breakdown by GVA, total GVA = £ 5,359 millons (2011).

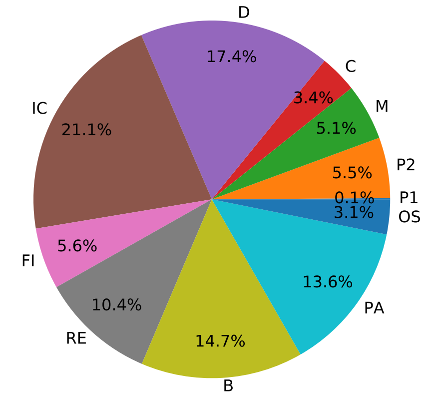

Figure A1.27: Reading's industry breakdown by GVA, total GVA = £ 10,773 millons (2011).

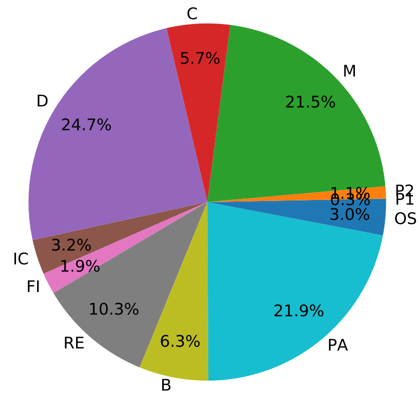

Figure A1.28: Blackburn with Darwen's industry breakdown by GVA, total GVA = £ 4,944 millons (2011).

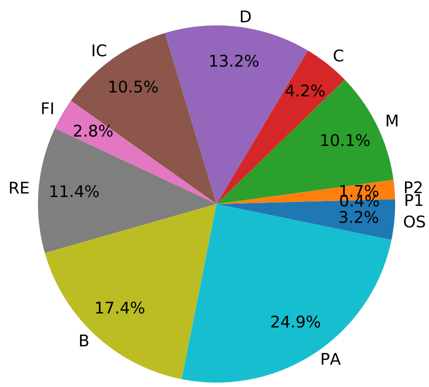

Figure A1.29: Cambridge's industry breakdown by GVA, total GVA = £ 8,321 millons (2011).

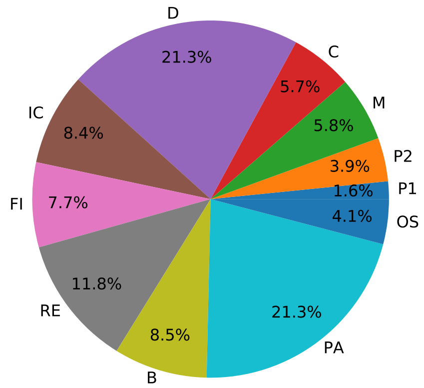

Figure A1.30: Ipswich's industry breakdown by GVA, total GVA = £ 5,630 millons (2011).

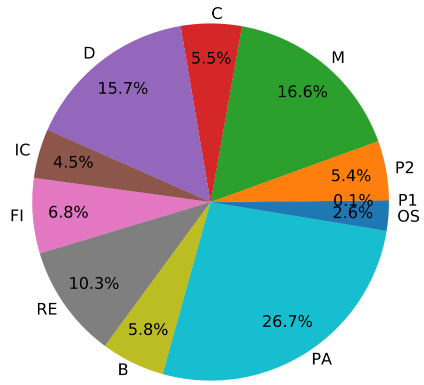

Figure A1.31: Newport's industry breakdown by GVA, total GVA = £ 4,331 millons (2011).

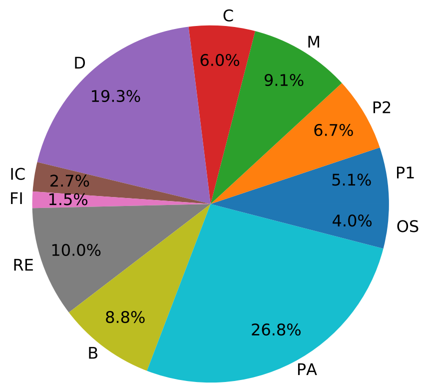

Figure A1.32: Lincoln's industry breakdown by GVA, total GVA = £ 3,883 millons (2011).

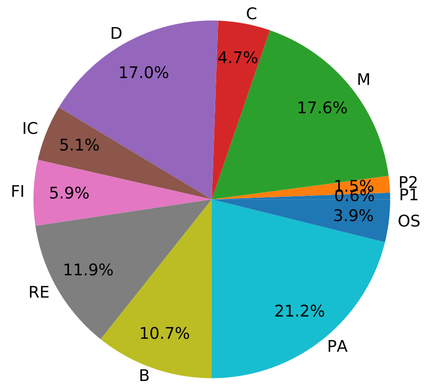

Figure A1.33: Cheltenham's industry breakdown by GVA, total GVA = £ 5,006 millons (2011).

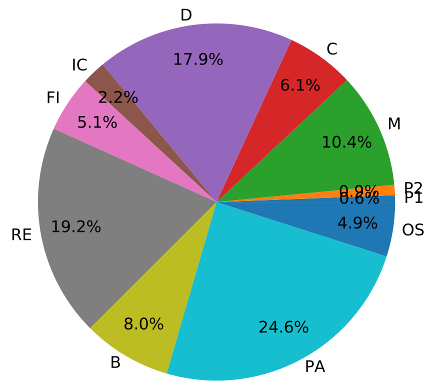

Figure A1.34: Hastings's industry breakdown by GVA, total GVA = £ 2,786 millons (2011).

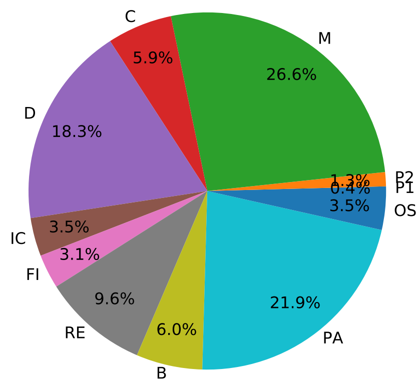

Figure A1.35: Burnley's industry breakdown by GVA, total GVA = £ 2,651 millons (2011).

Appendix 2: Relationship matrices from local intra-city utility analysis

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	1	2	1	2	3	2	1	1
P2	2	1	2	2	2	2	2	2	2	2	2
M	2	2	1	2	2	2	1	1	3	2	2
C	1	2	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	1	2	2	3	2	1	2	1	2	2	3
FI	2	2	1	3	2	2	1	2	2	3	2
RE	3	2	1	2	2	1	2	1	1	3	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	3	3	2	1	2
OS	1	2	2	2	3	3	2	2	2	2	1

Mutualism (1)	27
Exploitation (2)	78
Competition (3)	16

Figure A2.1: London's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	1
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	76
Competition (3)	22

Figure A1.2: West Midlands's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	1
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	76
Competition (3)	22

Figure A1.3: Greater Manchester's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	3	3	3	1	1
P2	3	1	2	2	2	3	2	2	3	2	2
M	2	2	1	2	2	3	2	3	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	1	2	2	2	3
IC	2	3	3	3	2	1	2	1	3	2	2
FI	3	2	2	3	1	2	1	2	2	2	3
RE	3	2	3	2	2	1	2	1	1	2	2
B	3	3	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	68
Competition (3)	30

Figure A1.4: Liverpool's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	2
P2	3	1	2	1	2	3	2	2	2	2	2
M	2	2	1	2	2	2	2	3	3	2	2
C	1	1	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	2	3	2	1	2	1	2	2	3
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	2	3	2	2	1	2	1	1	2	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	2	2	2	3	3	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	80
Competition (3)	20

Figure A1.5: Tyneside Conurbation's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	1	2
P2	2	1	2	2	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	1	3	2	2
C	2	2	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	2	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	1	2	2	1	2	1	1	2	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	2	2	2	3	2	3	2	2	2	1

Mutualism (1)	19
Exploitation (2)	86
Competition (3)	16

Figure A1.6: Leeds's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	2
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	2	2	3
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	2	2	3	3	3	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	78
Competition (3)	22

Figure A1.7: Sheffield's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	1
P2	3	1	2	1	2	2	2	2	2	2	2
M	2	2	1	2	2	2	2	1	3	2	2
C	1	1	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	2	3	2	1	2	1	2	2	3
FI	2	2	2	3	2	2	1	2	2	3	2
RE	3	2	1	2	2	1	2	1	1	2	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	3	2	2	1	2
OS	1	2	2	2	3	3	2	2	2	2	1

Mutualism (1)	25
Exploitation (2)	80
Competition (3)	16

Figure A1.8: Bristol's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	3	3	3	1	1
P2	3	1	2	2	2	2	2	3	2	2	3
M	2	2	1	2	2	3	2	2	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	3	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	3	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	3	2	3	3	2	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	72
Competition (3)	28

Figure A1.9: Cardiff's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	2
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	78
Competition (3)	22

Figure A1.10: Greater Nottingham's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	1	2
P2	2	1	2	2	3	2	2	3	2	2	3
M	2	2	1	2	2	3	2	3	3	2	2
C	2	2	2	1	2	3	3	2	2	2	3
D	2	3	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	1	2	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	3	2	3	3	2	3	2	2	2	1

Mutualism (1)	17
Exploitation (2)	78
Competition (3)	26

Figure A1.11: Leicester's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	3	2
P2	2	1	2	1	2	2	2	3	2	2	3
M	2	2	1	2	2	3	2	3	2	2	3
C	2	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	2	3	2	2
FI	2	2	2	3	2	2	1	2	3	2	2
RE	3	3	3	2	2	2	2	1	2	3	3
B	2	2	2	2	2	3	3	2	1	2	2
PA	3	2	2	2	2	2	2	3	2	1	2
OS	2	3	3	3	3	2	2	3	2	2	1

Mutualism (1)	13
Exploitation (2)	78
Competition (3)	30

Figure A1.12: Kingston upon Hull's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	1
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	2	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	2	3	2	1	2	1	2	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	2	2	2	1	2	1	1	2	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	80
Competition (3)	18

Figure A1.13: Coventry's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	1	3	3	3	1	1
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	3	3	2	2
C	1	1	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	1	2	2	2	3
IC	1	2	2	3	2	1	2	1	2	2	3
FI	3	2	2	3	1	2	1	2	2	2	2
RE	3	3	3	2	2	1	2	1	2	3	2
B	3	2	3	2	2	2	2	2	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	1	2	2	2	3	3	2	2	2	2	1

Mutualism (1)	25
Exploitation (2)	72
Competition (3)	24

Figure A1.14: Portsmouth's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	1	2
P2	2	1	2	1	2	2	2	2	2	2	2
M	2	2	1	2	2	3	2	1	3	2	2
C	2	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	3	3
RE	3	2	1	2	2	1	2	1	1	3	2
B	2	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	3	3	2	1	2
OS	2	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	78
Competition (3)	22

Figure A1.15: Bournemouth's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	3	1	1
P2	3	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	3	3	2	2
C	1	1	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	1	2	2
B	3	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	72
Competition (3)	26

Figure A1.16: Stoke-on-Trent's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	2
P2	3	1	2	2	2	2	2	3	2	2	3
M	2	2	1	2	2	3	2	3	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	2	2	2
B	2	2	3	2	2	3	2	2	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	3	2	3	3	2	3	2	2	2	1

Mutualism (1)	17
Exploitation (2)	78
Competition (3)	26

Figure A1.17: Middlesbrough's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	3	2
P2	2	1	2	1	3	2	2	3	2	2	2
M	2	2	1	2	2	3	2	3	2	2	2
C	2	1	2	1	2	3	3	2	2	2	3
D	2	3	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	2	2	2	2
FI	2	2	2	3	2	2	1	2	3	2	2
RE	3	3	3	2	2	2	2	1	2	3	3
B	2	2	2	2	2	2	3	2	1	2	2
PA	3	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	3	3	2	2	3	2	2	1

Mutualism (1)	13
Exploitation (2)	82
Competition (3)	26

Figure A1.18: Cheshire West and Chester's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	1	3	3
P2	2	1	2	2	2	3	3	2	2	2	2
M	2	2	1	2	2	3	2	1	3	2	2
C	2	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	3	3	2	1	2	1	3	2	2
FI	2	3	2	3	2	2	1	2	2	3	3
RE	3	2	1	2	2	1	2	1	1	2	2
B	1	2	3	2	2	3	2	1	1	2	2
PA	3	2	2	2	2	2	3	2	2	1	2
OS	3	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	19
Exploitation (2)	74
Competition (3)	28

Figure A1.19: Norwich's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	3	1	1
P2	3	1	2	2	2	2	2	3	2	2	3
M	2	2	1	2	2	3	2	3	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	1	2	2
B	3	2	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	1	3	2	3	3	2	3	2	2	2	1

Mutualism (1)	21
Exploitation (2)	72
Competition (3)	28

Figure A1.20: Swansea's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	1	2	2	2	3	2	1	1
P2	2	1	2	3	2	2	2	2	2	2	2
M	2	2	1	2	2	2	2	1	3	2	2
C	1	3	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	2	3	2	1	2	1	2	2	2
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	2	1	2	2	1	2	1	1	3	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	1	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	23
Exploitation (2)	80
Competition (3)	18

Figure A1.21: Brighton and Hove's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	1
P2	3	1	2	2	2	3	3	2	3	2	2
M	2	2	1	2	2	2	2	2	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	2	3	2	1	2	1	3	2	3
FI	2	3	2	3	2	2	1	2	2	3	2
RE	3	2	2	2	2	1	2	1	1	2	2
B	2	3	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	3	2	2	1	2
OS	1	2	2	3	3	3	2	2	2	2	1

Mutualism (1)	21
Exploitation (2)	74
Competition (3)	26

Figure A1.22: Southampton's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	1	2	2	2	3	2	1	2
P2	2	1	2	2	2	2	2	3	2	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	1	2	2	1	2	2	3	2	2	3	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	2	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	2
RE	3	3	2	2	2	1	2	1	2	2	2
B	2	2	3	2	2	3	2	2	1	2	2
PA	1	2	2	3	2	2	2	2	2	1	2
OS	2	2	2	3	3	2	2	2	2	2	1

Mutualism (1)	17
Exploitation (2)	86
Competition (3)	18

Figure A1.23: Preston's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	3	3	3	3	1	2
P2	3	1	2	2	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	3	2	2	2
C	1	2	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	3	2	2	3	2	1	2	1	3	2	2
FI	3	2	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	2	3	2
B	3	2	2	2	2	3	2	2	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	2	3	2	3	2	2	2	1

Mutualism (1)	17
Exploitation (2)	78
Competition (3)	26

Figure A1.24: Derby's **industry breakdown by GVA, total GVA = £7,405 millons (2011)**

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	3	3	2	2	3	1	3	3
P2	2	1	2	2	3	2	2	3	2	2	3
M	2	2	1	2	2	3	2	1	3	2	2
C	3	2	2	1	2	3	3	2	2	3	3
D	3	3	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	3	2	2
FI	2	2	2	3	2	2	1	2	2	2	2
RE	3	3	1	2	2	1	2	1	2	3	2
B	1	2	3	2	2	3	2	2	1	2	2
PA	3	2	2	3	2	2	2	3	2	1	2
OS	3	3	2	3	3	2	2	2	2	2	1

Mutualism (1)	17
Exploitation (2)	70
Competition (3)	34

Figure A1.25: Exeter's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	2	1	2
P2	3	1	2	2	2	3	3	2	3	2	2
M	2	2	1	2	2	3	2	3	3	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	3	3	2	1	2	1	3	2	2
FI	2	3	2	3	2	2	1	2	2	2	3
RE	3	2	3	2	2	1	2	1	1	3	2
B	2	3	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	19
Exploitation (2)	72
Competition (3)	30

Figure A1.26: Blackpool's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	1	2	1	2	3	2	1	1
P2	2	1	2	2	3	3	2	3	2	2	3
M	2	2	1	2	2	2	2	1	3	2	2
C	1	2	2	1	2	2	3	2	2	2	2
D	2	3	2	2	1	3	2	2	2	2	3
IC	1	3	2	2	3	1	2	2	2	3	2
FI	2	2	2	3	2	2	1	2	2	2	2
RE	3	3	1	2	2	2	2	1	1	3	2
B	2	2	3	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	3	2	3	2	1	2
OS	1	3	2	2	3	2	2	2	2	2	1

Mutualism (1)	23
Exploitation (2)	76
Competition (3)	22

Figure A1.27: Reading's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	3	1	2
P2	3	1	2	2	2	3	3	3	3	2	2
M	2	2	1	2	2	3	2	3	2	2	3
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	3	3
IC	2	3	3	3	2	1	2	2	3	2	2
FI	2	3	2	3	2	2	1	2	2	2	2
RE	3	3	3	2	2	2	2	1	2	3	3
B	3	3	2	2	2	3	2	2	1	2	2
PA	1	2	2	2	3	2	2	3	2	1	2
OS	2	2	3	3	3	2	2	3	2	2	1

Mutualism (1)	15
Exploitation (2)	70
Competition (3)	36

Figure A1.28: Blackburn with Darwen's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	1	2
P2	2	1	2	1	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	2	3	2	2
C	2	1	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	1	2	2	2	3
IC	2	2	2	3	2	1	2	3	2	2	2
FI	2	2	2	3	1	2	1	2	3	2	2
RE	3	3	2	2	2	3	2	1	2	3	2
B	2	2	3	2	2	2	3	2	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	2	3	2	2	2	2	2	1

Mutualism (1)	17
Exploitation (2)	76
Competition (3)	18

Figure A1.29: Cambridge's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	3	2	2	3	1	3	3
P2	2	1	2	2	2	2	2	3	2	2	2
M	2	2	1	2	2	2	2	1	3	2	2
C	2	2	2	1	2	3	3	2	2	2	3
D	3	2	2	2	1	2	2	2	2	3	3
IC	2	2	2	3	2	1	2	1	2	2	3
FI	2	2	2	3	2	2	1	2	2	2	3
RE	3	3	1	2	2	1	2	1	1	2	2
B	1	2	3	2	2	2	2	1	1	2	2
PA	3	2	2	2	3	2	2	2	2	1	2
OS	3	2	2	3	3	3	3	2	2	2	1

Mutualism (1)	19
Exploitation (2)	76
Competition (3)	26

Figure A1.30: Ipswich's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	3	3	3	1	2
P2	3	1	2	2	2	2	2	3	2	2	3
M	2	2	1	2	2	3	2	2	2	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	1	2	2	3
FI	3	2	2	3	2	2	1	2	2	2	2
RE	3	3	2	2	2	1	2	1	1	2	2
B	3	2	2	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	3	2	3	3	3	2	2	2	2	1

Mutualism (1)	19
Exploitation (2)	78
Competition (3)	24

Figure A1.31: Newport's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	1	3	3
P2	2	1	2	2	3	2	2	3	2	2	3
M	2	2	1	2	2	3	2	2	3	2	2
C	2	2	2	1	2	3	3	2	2	2	3
D	2	3	2	2	1	2	2	2	2	2	3
IC	2	2	3	3	2	1	2	2	3	2	2
FI	2	2	2	3	2	2	1	2	3	2	2
RE	3	3	2	2	2	2	2	1	2	2	3
B	1	2	3	2	2	3	3	2	1	2	2
PA	3	2	2	2	2	2	2	2	2	1	2
OS	3	3	2	3	3	2	2	3	2	2	1

Mutualism (1)	13
Exploitation (2)	78
Competition (3)	30

Figure A1.32: Lincoln's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	2	2	2	2	3	2	1	2
P2	3	1	2	1	2	3	3	2	3	2	2
M	2	2	1	2	2	3	2	2	2	2	2
C	2	1	2	1	2	3	3	2	2	2	2
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	3	3	2	1	2	1	2	2	2
FI	2	3	2	3	2	2	1	2	2	2	3
RE	3	2	2	2	2	1	2	1	1	3	2
B	2	3	2	2	2	2	2	1	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	2	3	2	3	2	2	2	1

Mutualism (1)	19
Exploitation (2)	80
Competition (3)	22

Figure A1.33: Cheltenham's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	2	2	2	2	2	2	3	2	1	2
P2	2	1	2	2	2	3	3	2	3	2	2
M	2	2	1	2	2	3	2	2	3	2	2
C	2	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	3	3	2	1	2	1	3	2	2
FI	2	3	2	3	2	2	1	2	2	2	3
RE	3	2	2	2	2	1	2	1	1	3	2
B	2	3	3	2	2	3	2	1	1	2	2
PA	1	2	2	2	2	2	2	3	2	1	2
OS	2	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	27
Exploitation (2)	78
Competition (3)	16

Figure A1.34: Hastings's relationship matrix of 11 sectors for 2011.

	P1	P2	M	C	D	IC	FI	RE	B	PA	OS
P1	1	3	2	1	2	2	2	3	3	1	2
P2	3	1	2	2	2	3	3	3	3	2	2
M	2	2	1	2	2	2	2	3	2	2	2
C	1	2	2	1	2	3	3	2	2	2	3
D	2	2	2	2	1	2	2	2	2	2	3
IC	2	3	2	3	2	1	2	1	3	2	2
FI	2	3	2	3	2	2	1	2	2	2	3
RE	3	3	3	2	2	1	2	1	2	2	2
B	3	3	2	2	2	3	2	2	1	2	2
PA	1	2	2	2	2	2	2	2	2	1	2
OS	2	2	2	3	3	2	3	2	2	2	1

Mutualism (1)	17
Exploitation (2)	76
Competition (3)	28

Figure A1.35: Burnley's relationship matrix of 11 sectors for 2011.

Appendix 3: Commodity description and specific exergy values

The specific exergy values were mainly taken from the previous works on chemical exergies in elements [1] and other chemical compound [2, 3], including the metal industries [4]. Exergy accounting of various types of material such as fossil fuels [5], plastics [6], building materials [7], household appliances [8], biomass [9, 10], fertilizer and pesticides [11], food commodities [12] and municipal solid waste [13, 14] were also considered in here. The reference conditions of surrounding temperature and pressure were assumed to be at 25°*C* and 1 *atm.* for all flows. The commodities codes and description in Table A3.1 below are obtained from the Comtrade database [19].

This table is available for download at:
https://drive.google.com/drive/folders/1yFlmzYG_oTIA3bfILPsdRyYmQIMO3w94?usp=sharing

Table A3.1: Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
101	Horses, asses, mules and hinnies; live	0.00	-
104	Sheep and goats; live	7.70	Refers to 204
105	Poultry; live, fowls of the species Gallus domesticus, ducks, geese, turkeys and guinea fowls	7.64	Refers to 207
106	Animals; live, n.e.c. in chapter 01	7.67	Mean value of group 1--
201	Meat of bovine animals; fresh or chilled	6.06	[12]
202	Meat of bovine animals; frozen	6.06	[12]
203	Meat of swine; fresh, chilled or frozen	8.95	[12]
204	Meat of sheep or goats; fresh, chilled or frozen	7.70	[12]
206	Edible offal of bovine animals, swine, sheep, goats, horses, asses, mules or hinnies; fresh, chilled or frozen	11.14	Mean value of group 2--
207	Meat and edible offal of poultry; of the poultry of heading no. 0105, (i.e. fowls of the species Gallus domesticus), fresh, chilled or frozen	7.64	[12]
208	Meat and edible meat offal, n.e.c. in chapter 2; fresh, chilled or frozen	11.14	Mean value of group 2--
209	Pig fat, free of lean meat, and poultry fat, not rendered or otherwise extracted, fresh, chilled, frozen, salted, in brine, dried or smoked	30.42	[12]
210	Meat and edible meat offal; salted, in brine, dried or smoked; edible flours and meals of meat or meat offal	11.14	Mean value of group 2--
301	Fish; live	4.71	[12]
302	Fish; fresh or chilled, excluding fish fillets and other fish meat of heading 0304	4.71	[12]
303	Fish; frozen, excluding fish fillets and other fish meat of heading 0304	4.71	[12]
304	Fish fillets and other fish meat (whether or not minced); fresh, chilled or frozen	4.71	[12]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
305	Fish, dried, salted or in brine; smoked fish, whether or not cooked before or during the smoking process; flours, meals and pellets of fish, fit for human consumption	8.50	[12]
306	Crustaceans; in shell or not, live, fresh, chilled, frozen, dried, salted or in brine; smoked, cooked or not before or during smoking; in shell, steamed or boiled, whether or not chilled, frozen, dried, salted or in brine; edible flours, meals, pellets	5.76	[12]
307	Molluscs; whether in shell or not, live, fresh, chilled, frozen, dried, salted or in brine; smoked molluscs, whether in shell or not, cooked or not before or during the smoking process; flours, meals and pellets of molluscs, fit for human consumption	5.76	[12]
308	Aquatic invertebrates, other than crustaceans and molluscs; live, fresh, chilled, frozen, dried, salted or in brine, smoked, whether or not cooked before or during the smoking process; flours, meals, and pellets, fit for human consumption	5.55	Mean value of group 3--
401	Milk and cream; not concentrated, not containing added sugar or other sweetening matter	7.74	[12]
402	Milk and cream; concentrated or containing added sugar or other sweetening matter	11.08	[12]
403	Buttermilk, curdled milk and cream, yoghurt, kephir, fermented or acidified milk or cream, whether or not concentrated, containing added sugar, sweetening matter, flavoured or added fruit or cocoa	3.36	[12]
404	Whey and products consisting of natural milk constituents; whether or not containing added sugar or other sweetening matter, not elsewhere specified or included	11.61	Mean value of group 4--
405	Butter and other fats and oils derived from milk; dairy spreads	30.59	[12]
406	Cheese and curd	13.32	[12]
407	Birds' eggs, in shell; fresh, preserved or cooked	6.79	[12]
408	Birds' eggs, not in shell; egg yolks, fresh, dried, cooked by steaming or boiling in water, moulded, frozen or otherwise preserved, whether or not containing added sugar or other sweetening matter	6.79	[12]
409	Honey; natural	13.19	[12]
410	Edible products of animal origin; not elsewhere specified or included	11.61	Mean value of group 4--
501	Human hair; unworked, whether or not washed or scoured; waste of human hair	0.00	-
502	Pigs', hogs' or boars' bristles and hair; and waste thereof	0.00	-
504	Guts, bladders and stomachs of animals (other than fish); whole and pieces thereof, fresh, chilled, frozen, salted, in brine, dried or smoked	0.00	-
505	Skins and other parts of birds with feathers, down; feathers, down and parts thereof; not further worked than cleaned, disinfected, treated for preservation; powder, waste and parts of feathers	0.00	-
507	Ivory, tortoise-shell, whalebone and whalebone hair, horns, antlers, hooves, nails, claws and beaks unworked or simply prepared, not cut to shape; waste and powder of these products	0.00	-
508	Coral and similar materials, unworked or simply prepared, shells of molluscs, crustaceans or echinoderms and cuttle-bone, not cut to shape powder and waste thereof	0.00	-
511	Animal products not elsewhere specified or included; dead animals of chapter 1 or 3, unfit for human consumption	0.00	-
601	Bulbs, tubers, tuberous roots, corms, crowns and rhizomes; dormant, in growth or in flower; chicory plants and roots other than roots of heading no. 1212	17.30	[15]
602	Plants, live; n.e.c. in heading no. 0601, (including their roots) cuttings and slips; mushroom spawn	0.00	-
603	Flowers; cut flowers and flower buds of a kind suitable for bouquets or for ornamental purposes, fresh, dried, dyed, bleached, impregnated or otherwise prepared	17.30	[16]
604	Foliage, branches and other parts of plants, without flowers or flower buds, and grasses, mosses and lichens; suitable for bouquets or for ornamental purposes, fresh, dried, dyed, bleached, impregnated etc.	17.30	[16]
701	Potatoes; fresh or chilled	3.05	[12]
702	Tomatoes; fresh or chilled	0.92	[12]
703	Onions, shallots, garlic, leeks and other alliaceous vegetables; fresh or chilled	2.70	[12]
704	Cabbages, cauliflowers, kohlrabi, kale and similar edible brassicas; fresh or chilled	1.04	[12]
705	Lettuce (lactuca sativa) and chicory (cichorium spp.) fresh or chilled	0.56	[12]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
706	Carrots, turnips, salad beetroot, salsify, celeriac, radishes and similar edible roots; fresh or chilled	1.17	[12]
707	Cucumbers and gherkins; fresh or chilled	0.67	[12]
708	Leguminous vegetables; shelled or unshelled, fresh or chilled	2.64	[12]
709	Vegetables; n.e.c. in chapter 07, fresh or chilled	2.72	Mean value of group 7--
710	Vegetables (uncooked or cooked by steaming or boiling in water); frozen	1.56	[12]
711	Vegetables provisionally preserved; (e.g. by sulphur dioxide gas, in brine, in sulphur water or in other preservative solutions), but unsuitable in that state for immediate consumption	2.56	[12]
712	Vegetables, dried; whole, cut, sliced, broken or in powder, but not further prepared	11.69	[12]
713	Vegetables, leguminous; shelled, whether or not skinned or split, dried	3.07	[12]
714	Manioc, arrowroot, salep, Jerusalem artichokes, sweet potatoes and similar roots and tubers with high starch or inulin content; fresh, chilled, frozen or dried, whether or not sliced or in the form of pellets; sago pith	3.70	[12]
801	Nuts, edible; coconuts, Brazil nuts and cashew nuts, fresh or dried, whether or not shelled or peeled	23.78	[12]
802	Nuts (excluding coconuts, Brazils and cashew nuts); fresh or dried, whether or not shelled or peeled	21.13	[12]
803	Bananas, including plantains; fresh or dried	4.22	[12]
804	Dates, figs, pineapples, avocados, guavas, mangoes and mangosteens; fresh or dried	4.98	[12]
805	Citrus fruit; fresh or dried	1.65	[12]
806	Grapes; fresh or dried	2.94	[12]
807	Melons (including watermelons) and papaws (papayas); fresh	1.42	[12]
808	Apples, pears and quinces; fresh	1.99	[12]
809	Apricots, cherries, peaches (including nectarines), plums and sloes, fresh	1.75	[12]
810	Fruit, fresh; n.e.c. in chapter 08	6.86	Mean value of group 8--
811	Fruit and nuts; uncooked or cooked by steaming or boiling in water, frozen, whether or not containing added sugar or other sweetening matter	3.90	[12]
812	Fruit and nuts provisionally preserved; e.g. by sulphur dioxide gas, brine, in sulphur water or in other preservative solutions, but unsuitable in that state for immediate consumption	3.90	[12]
813	Fruit, dried, other than that of heading no. 0801 to 0806; mixtures of nuts or dried fruits of this chapter	10.68	[12]
814	Peel of citrus fruit or melons (including watermelons); fresh, frozen dried or provisionally preserved in brine, in sulphur water or in other preservative solutions	6.86	Mean value of group 8--
901	Coffee, whether or not roasted or decaffeinated; husks and skins; coffee substitutes containing coffee in any proportion	14.27	[12]
902	Tea	13.18	[12]
903	Mate	13.18	[12]
904	Pepper of the genus piper; dried or crushed or ground fruits of the genus capsicum or of the genus pimenta	12.51	[12]
905	Vanilla	12.05	[12]
906	Cinnamon and cinnamon-tree flowers	11.89	[12]
907	Cloves (whole fruit, cloves and stems)	12.97	[12]
908	Nutmeg, mace and cardamoms	19.05	[12]
909	Seeds of anise, badian, fennel, coriander, cumin, caraway or juniper	12.76	[12]
910	Ginger, saffron, tumeric (curcuma), thyme, bay leaves, curry and other spices	9.11	[12]
1001	Wheat and meslin	12.71	[12]
1002	Rye	13.22	[12]
1003	Barley	14.56	[12]
1004	Oats	15.41	[12]
1005	Maize (corn)	14.02	[12]
1006	Rice	14.79	[12]
1007	Grain sorghum	14.24	Mean value of group 10--
1008	Buckwheat, millet and canary seeds; other cereals	14.98	[12]
1101	Wheat or meslin flour	14.69	[12]
1102	Cereal flours; other than of wheat or meslin	14.75	[12]
1103	Cereal groats; meal and pellets	13.70	[12]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
1104	Cereal grains otherwise worked (e.g. hulled, rolled, flaked, pearled, sliced or kibbled) except rice of heading no. 1006; germ of cereals whole, rolled, flaked or ground	14.70	[12]
1105	Flour, meal, powder, flakes, granules and pellets of potatoes	14.94	[12]
1106	Flour, meal and powder; of the dried leguminous vegetables of heading no. 0713, of sago or of roots or tubers of heading no. 0714 or of the products of chapter 8	14.74	[12]
1107	Malt; whether or not roasted	16.74	[12]
1108	Starches; inulin	15.50	[12]
1109	Wheat gluten; whether or not dried	5.86	[12]
1201	Soya beans, whether or not broken	16.32	[12]
1202	Ground-nuts; not roasted or otherwise cooked, whether or not shelled or broken	24.31	[12]
1204	Oil seeds; linseed, whether or not broken	22.34	[12]
1206	Sunflower seeds; whether or not broken	23.97	[12]
1207	Oil seeds and oleaginous fruits, n.e.c. in chapter 12; whether or not broken	19.44	[12]
1208	Flours and meals of oil seeds or oleaginous fruits; other than those of mustard	19.44	[12]
1209	Seeds, fruit and spores; of a kind used for sowing	0.96	[12]
1210	Hop cones, fresh or dried, whether or not ground, powdered or in the form of pellets; lupulin	14.43	Mean value of group 12--
1211	Plants and parts of plants (including seeds and fruits), used primarily in perfumery, pharmacy; for insecticidal, fungicidal or similar purposes, fresh or dried, whether or not crushed or powdered	3.35	[12]
1212	Locust beans, seaweeds and other algae, sugar beet, sugar cane, fresh, chilled, frozen or dried, whether or not ground; fruit stones, kernels and other vegetable products (including unroasted chicory roots) used primarily for human consumption, n.e.c.	8.66	[12]
1213	Cereal straw and husks, unprepared; whether or not chopped, ground, pressed or in the form of pellets	18.98	[12]
1214	Swedes, mangolds, fodder roots, hay, lucerne (alfalfa), clover, sainfoin, forage kale, lupines, vetches and similar forage products, whether or not in the form of pellets	0.96	[12]
1301	Lac; natural gums, resins, gum-resins and oleoresins (for example, balsams)	19.91	[9]
1302	Vegetable saps and extracts; pectic substances, pectinates and pectates; agar-agar and other mucilages and thickeners, whether or not modified, derived from vegetable products	19.91	[9]
1401	Vegetable materials of a kind used primarily for plaiting; (e.g. bamboos, rattans, reeds, rushes, osier, raffia, cleaned, bleached or dyed cereal straw and lime bark)	19.91	[9]
1404	Vegetable products not elsewhere specified or included	19.91	[9]
1501	Pig fat (including lard) and poultry fat, other than that of heading 0209 or 1503	30.42	[12]
1502	Fats of bovine animals, sheep or goats, other than those of heading 1503	1.27	[12]
1504	Fats and oils and their fractions of fish or marine mammals; whether or not refined, but not chemically modified	37.74	[12]
1505	Wool grease and fatty substances derived therefrom (including lanolin)	32.71	Mean value of group 15--
1507	Soya-bean oil and its fractions; whether or not refined, but not chemically modified	37.04	[12]
1508	Ground nut oil and its fractions; whether or not refined, but not chemically modified	37.04	[12]
1509	Olive oil and its fractions; whether or not refined, but not chemically modified	37.66	[12]
1510	Oils and their fractions n.e.c. in chapter 15, obtained solely from olives, whether or not refined, but not chemically modified, including blends of these oils or fractions with oils or fractions of heading no. 1509	32.71	Mean value of group 15--
1511	Palm oil and its fractions; whether or not refined, but not chemically modified	37.66	[12]
1512	Sun-flower seed, safflower or cotton-seed oil and their fractions; whether or not refined, but not chemically modified	37.04	[12]
1513	Coconut (copra), palm kernel or babassu oil and their fractions; whether or not refined but not chemically modified	36.99	[12]
1514	Rape, colza or mustard oil and their fractions; whether or not refined, but not chemically modified	37.66	[12]
1515	Fixed vegetable fats and oils (including jojoba oil) and their fractions, whether or not refined; but not chemically modified	37.66	[12]
1516	Animal or vegetable fats and oils and their fractions; partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised, whether or not refined, but not further prepared	32.71	Mean value of group 15--

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
1517	Margarine; edible mixtures or preparations of animal or vegetable fats or oils or of fractions of different fats or oils of this chapter, other than edible fats or oils of heading no. 1516	25.94	[12]
1518	Animal or vegetable fats, oils, fractions, modified in any way, excluding heading no. 1516; inedible versions of animal or vegetable fats, oils or fractions of this chapter, n.e.c. or included	32.71	Mean value of group 15--
1520	Glycerol, crude; glycerol waters and glycerol lyes	17.96	[2]
1521	Vegetable waxes (other than triglycerides), beeswax, other insect waxes and spermaceti; whether or not refined or coloured	39.31	[10]
1522	Degras; residues resulting from the treatment of fatty substances or animal or vegetable waxes	39.31	[10]
1601	Sausages and similar products of meat, meat offal or blood; food preparations based on these products	10.91	[12]
1602	Prepared or preserved meat, meat offal or blood	12.52	[12]
1603	Extracts and juices of meat, fish or crustaceans, molluscs or other aquatic invertebrates	0.00	-
1604	Prepared or preserved fish; caviar and caviar substitutes prepared from fish eggs	7.91	[12]
1605	Crustaceans, molluscs and other aquatic invertebrates, prepared or preserved	8.32	[12]
1701	Cane or beet sugar and chemically pure sucrose, in solid form	16.02	[2]
1702	Sugars, including lactose, maltose, glucose or fructose in solid form; sugar syrups without added flavouring or colouring matter; artificial honey, whether or not mixed with natural honey; caramel	16.02	[2]
1703	Molasses; resulting from the extraction or refining of sugar	12.13	[12]
1704	Sugar confectionery (including white chocolate), not containing cocoa	14.72	Mean value of group 17--
1801	Cocoa beans; whole or broken, raw or roasted	16.65	[12]
1802	Cocoa; shells, husks, skins and other cocoa waste	16.65	[12]
1803	Cocoa; paste; whether or not defatted	16.65	[12]
1804	Cocoa; butter, fat and oil	16.65	[12]
1805	Cocoa; powder, not containing added sugar or other sweetening matter	16.65	[12]
1806	Chocolate and other food preparations containing cocoa	16.65	[12]
1901	Malt extract; flour/groats/meal/starch/malt extract products, no cocoa (or less than 40% by weight) and food preparations of goods of headings 04.01 to 04.04, no cocoa (or less than 5% by weight), weights calculated on a totally defatted basis, n.e.c.	16.74	[12]
1902	Pasta; whether or not cooked or stuffed with meat or other substance, or otherwise prepared, egg spaghetti, macaroni, noodles, lasagne, gnocchi, ravioli, cannelloni; couscous, whether or not prepared	14.80	[12]
1903	Tapioca and substitutes therefor prepared from starch; in the form of flakes, grains, pearls, siftings or similar forms	10.31	[12]
1904	Prepared foods obtained by swelling or roasting cereals or cereal products (e.g. corn flakes); cereals (other than maize (corn)) in grain form or in the form of flakes or other worked grains (not flour and meal), pre-cooked or otherwise prepared, n.e.c.	15.19	Mean value of group 19--
1905	Bread, pastry, cakes, biscuits, other bakers' wares, whether or not containing cocoa; communion wafers, empty cachets suitable for pharmaceutical use, sealing wafers, rice paper and similar products	18.92	[12]
2001	Vegetables, fruit, nuts and other edible parts of plants; prepared or preserved by vinegar or acetic acid	0.54	[12]
2002	Tomatoes; prepared or preserved otherwise than by vinegar or acetic acid	0.54	[12]
2003	Mushrooms and truffles, prepared or preserved other than by vinegar or acetic acid	0.00	-
2004	Vegetables preparations n.e.c.; prepared or preserved otherwise than by vinegar or acetic acid, frozen, other than products of heading no. 2006	2.11	[12]
2005	Vegetables preparations n.e.c.; prepared or preserved otherwise than by vinegar or acetic acid, not frozen, other than products of heading no. 2006	2.11	[12]
2006	Vegetables, fruit, nuts, fruit-peel and other parts of plants, preserved by sugar (drained, glace or crystallised)	3.00	Mean value of group 20--
2007	Jams, fruit jellies, marmalades, fruit or nut puree and fruit or nut pastes, being cooked preparations; whether or not containing added sugar or other sweetening matter	10.79	[12]
2008	Fruit, nuts and other edible parts of plants; prepared or preserved in ways n.e.c., whether or not containing added sugar or other sweetening matter or spirit, not elsewhere specified or included	3.00	Mean value of group 20--

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
2009	Fruit juices (including grape must) and vegetable juices, unfermented, not containing added spirit; whether or not containing added sugar or other sweetening matter	1.89	[12]
2101	Extracts, essences, concentrates of coffee, tea or mate; preparations with a basis of these products or with a basis of coffee, tea or mate; roasted chicory and other roasted coffee substitutes and extracts, essences and concentrates thereof	12.30	[12]
2102	Yeasts (active or inactive); other single-cell micro-organisms, dead (but not including vaccines of heading no. 3002); prepared baking powders	10.79	[12]
2103	Sauces and preparations therefor; mixed condiments and mixed seasonings, mustard flour and meal and prepared mustard	6.30	[12]
2104	Soups and broths and preparations therefor; homogenised composite food preparations	1.88	[12]
2105	Ice cream and other edible ice; whether or not containing cocoa	9.46	[12]
2106	Food preparations not elsewhere specified or included	8.15	Mean value of group 21--
2201	Waters, including natural or artificial mineral waters and aerated waters, not containing added sugar or other sweetening matter nor flavoured; ice and snow	0.00	-
2202	Waters, including mineral and aerated waters, containing added sugar or sweetening matter, flavoured; other non-alcoholic beverages, not including fruit or vegetable juices of heading no. 2009	1.21	[12]
2203	Beer made from malt	1.64	[12]
2204	Wine of fresh grapes, including fortified wines; grape must other than that of heading no. 2009	3.31	[12]
2205	Vermouth and other wine of fresh grapes, flavoured with plants or aromatic substances	4.57	[12]
2206	Fermented beverages, n.e.c. in chapter 22; (e.g. cider, perry, mead)	3.64	[12]
2207	Ethyl alcohol, undenatured; of an alcoholic strength by volume of 80% vol. or higher; ethyl alcohol and other spirits, denatured, of any strength	10.00	[2]
2208	Ethyl alcohol, undenatured; of an alcoholic strength by volume of less than 80% volume; spirits, liqueurs and other spirituous beverages	10.00	[2]
2209	Vinegar and substitutes for vinegar obtained from acetic acid	1.44	[12]
2301	Flours, meal and pellets, of meat or meat offal, of fish or of crustaceans, molluscs or other aquatic invertebrates, unfit for human consumption; greaves	20.09	[9]
2302	Bran, sharps and other residues; whether or not in the form of pellets derived from the sifting, milling or other working of cereals or of leguminous plants	20.09	[9]
2303	Residues of starch manufacture, similar residues; beet-pulp, bagasse and other waste of sugar manufacture, brewing or distilling dregs and waste, whether or not in the form of pellets	20.09	[9]
2304	Oil-cake and other solid residues; whether or not ground or in the form of pellets, resulting from the extraction of soya-bean oil	20.09	[9]
2306	Oil-cake and other solid residues; whether or not ground or in the form of pellets, resulting from the extraction of vegetable fats or oils other than those of heading no. 2304 or 2305	20.09	[9]
2307	Wine lees; argol	20.09	[9]
2308	Vegetable materials and vegetable waste, vegetable residues and bi-products; whether or not in the form of pellets, of a kind used in animal feeding, not elsewhere specified or included	20.09	[9]
2309	Preparations of a kind used in animal feeding	20.09	[9]
2401	Tobacco, unmanufactured; tobacco refuse	0.00	-
2402	Cigars, cheroots, cigarillos and cigarettes; of tobacco or of tobacco substitutes	0.00	-
2403	Manufactured tobacco and manufactured tobacco substitutes n.e.c; homogenised or reconstituted tobacco; tobacco extracts and essences	0.00	-
2501	Salt (including table salt and denatured salt); pure sodium chloride whether or not in aqueous solution; sea water	0.24	[2]
2502	Iron pyrites; unroasted	11.91	[2]
2503	Sulphur of all kinds; other than sublimed, precipitated and colloidal sulphur	2.38	[1]
2504	Graphite; natural	34.16	[1]
2505	Sands of all kinds; natural, whether or not coloured, other than metal-bearing sands of chapter 26	0.03	[2]
2506	Quartz; (other than natural sands), quartzite, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape	0.03	[2]
2507	Kaolin and other kaolinic clays; whether or not calcined	0.77	[2]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
2508	Clays; (not including expanded clays of heading no. 6806), andalusite kyanite and sillimanite, whether or not calcined; mullite; chamotte or dinas earth	0.77	[2]
2509	Chalk	0.01	[2]
2510	Natural calcium phosphates; natural aluminium calcium phosphates and phosphatic chalk	0.06	[2]
2511	Natural barium sulphate (barytes); natural barium carbonate, (witherite) whether or not calcined, other than barium oxide of heading no. 2816	0.01	[2]
2512	Siliceous fossil meals (e.g. kieselguhr, tripolite and diatomite) and similar siliceous earths; whether or not calcined, of an apparent specific gravity of 1 or less	0.03	[2]
2513	Pumice stone; emery; natural corundum, natural garnet and other natural abrasives, whether or not heat treated	0.03	[2]
2514	Slate, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape	0.03	[2]
2515	Marble, travertine, ecaussine and other calcareous stone; of an apparent specific gravity of less than 2.5, alabaster, whether cut by sawing etc, into blocks, slabs of a rectangular (square) shape	0.03	[2]
2516	Granite, porphyry, basalt, sandstone, other monumental and building stone, whether or not roughly trimmed, cut, by sawing etc, into blocks or slabs of a rectangular (including square) shape	0.03	[2]
2517	Pebbles, gravel, crushed stone for concrete aggregates for road or railway ballast, shingle or flint; macadam of slag, dross etc tarred granules, chippings, powder of stones of heading no. 2515 and 2516	0.03	[2]
2518	Dolomite, whether or not calcined or sintered; including dolomite roughly trimmed, or merely cut by sawing or otherwise into blocks or slabs of rectangular (including square) shape; dolomite ramming mix	0.01	[2]
2519	Natural magnesium carbonate (magnesite); fused magnesia; dead-burned (sintered) magnesia, whether or not containing small quantities of other oxides added before sintering; magnesium oxide, pure or not	0.01	[2]
2520	Gypsum; anhydrite; plasters (consisting of calcined gypsum or calcium sulphate), coloured or not, with or without small quantities of accelerators or retarders	0.05	[2]
2521	Limestone flux; limestone and other calcareous stone, of a kind used for the manufacture of lime or cement	0.05	[2]
2522	Quicklime, slaked lime and hydraulic lime; other than calcium oxide and hydroxide of heading no. 2825	1.97	[2]
2523	Portland cement, aluminous cement (ciment fondu), slag cement, supersulphate cement and similar hydraulic cements, whether or not coloured or in the form of clinkers	1.97	[2]
2525	Mica, including splittings; mica waste	0.03	[2]
2526	Natural steatite; whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a rectangular (including square) shape; talc	0.10	[2]
2528	Natural borates and concentrates thereof (whether or not calcined), but not including borates separated from natural brine; natural boric acid containing not more than 85 % of H3BO3 calculated on the dry weight	1.00	[2]
2529	Feldspar; leucite; nepheline and nepheline syenite; fluorspar	0.35	[2]
2530	Mineral substances not elsewhere specified or included	2.08	Mean value of group 25--
2601	Iron ores and concentrates; including roasted iron pyrites	0.42	[2]
2603	Copper ores and concentrates	0.43	[2]
2604	Nickel ores and concentrates	0.39	[2]
2606	Aluminium ores and concentrates	1.05	[2]
2607	Lead ores and concentrates	0.23	[2]
2608	Zinc ores and concentrates	0.90	[2]
2609	Tin ores and concentrates	0.19	[2]
2610	Chromium ores and concentrates	0.58	[2]
2611	Tungsten ores and concentrates	0.20	[2]
2612	Uranium or thorium ores and concentrates	0.60	[2]
2613	Molybdenum ores and concentrates	0.22	[2]
2614	Titanium ores and concentrates	0.57	[2]
2615	Niobium, tantalum, vanadium or zirconium ores and concentrates	0.66	Mean value of group 25--
2616	Precious metal ores and concentrates	0.29	[2]
2617	Ores and concentrates; n.e.c. in heading no. 2601	0.66	Mean value of group 25--

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
2618	Granulated slag (slag sand) from the manufacture of iron or steel	1.38	[4]
2619	Slag, dross; (other than granulated slag), scalings and other waste from the manufacture of iron or steel	1.38	[4]
2620	Slag, ash and residues; (not from the manufacture of iron or steel) containing metals, arsenic or their compounds	1.80	[4]
2621	Slag and ash n.e.c. in chapter 26; including seaweed ash (kelp) and ash and residues from the incineration of municipal waste	0.66	[4]
2701	Coal; briquettes, ovoids and similar solid fuels manufactured from coal	29.89	[5]
2703	Peat; (including peat litter), whether or not agglomerated	17.85	[5]
2704	Coke and semi-coke; of coal, lignite or peat, whether or not agglomerated; retort carbon	28.90	[5]
2705	Coal gas, water gas, producer gas and similar gases, other than petroleum gases and other gaseous hydrocarbons	23.04	[5]
2706	Tar distilled from coal, from lignite, peat and other mineral tars, whether or not dehydrated or partially distilled; including reconstituted tars	29.40	[5]
2707	Oils and other products of the distillation of high temperature coal tar; similar products in which the weight of the aromatic constituents exceeds that of the non-aromatic constituents	41.81	[5]
2708	Pitch and pitch coke; obtained from coal tar or from other mineral tars	27.09	[5]
2709	Petroleum oils and oils obtained from bituminous minerals; crude	45.84	[5]
2710	Petroleum oils and oils from bituminous minerals, not crude; preparations n.e.c, containing by weight 70% or more of petroleum oils or oils from bituminous minerals; these being the basic constituents of the preparations; waste oils	47.49	[5]
2711	Petroleum gases and other gaseous hydrocarbons	48.09	[5]
2712	Petroleum jelly; paraffin wax, micro-crystalline petroleum wax, slack wax, ozokerite, lignite wax, peat wax, other mineral waxes, similar products obtained by synthesis, other processes; coloured or not	45.50	[5]
2713	Petroleum coke, petroleum bitumen; other residues of petroleum oils or oils obtained from bituminous minerals	34.48	[5]
2714	Bitumen and asphalt, natural; bituminous or oil shale and tar sands; asphaltites and asphaltic rocks	25.53	[5]
2715	Bituminous mixtures based on natural asphalt; on natural bitumen, on petroleum bitumen, on mineral tar or on mineral tar pitch (e.g. bituminous mastics, cut-backs)	25.53	[5]
2716	Electrical energy	3600.00	converted from KWh
2801	Fluorine, chlorine, bromine and iodine	3.83	[2]
2802	Sulphur; sublimed or precipitated, colloidal sulphur	2.38	[2]
2803	Carbon; carbon blacks and other forms of carbon n.e.c.	34.16	[2]
2804	Hydrogen, rare gases and other non-metals	116.88	[1]
2805	Alkali or alkaline-earth metals; rare-earth metals, scandium and yttrium, whether or not intermixed or interalloyed; mercury	0.58	[2]
2806	Hydrogen chloride (hydrochloric acid); chlorosulphuric acid	1.33	[2]
2807	Sulphuric acid; oleum	1.11	[2]
2808	Nitric acid; sulphonitric acids	0.21	[2]
2809	Diphosphorus pentoxide; phosphoric acid and polyphosphoric acids	2.09	[2]
2810	Oxides of boron; boric acids	1.00	[2]
2811	Inorganic acids and other inorganic oxygen compounds of non-metals; n.e.c. in heading no. 2806 to 2810	7.97	Mean value of group 18--
2812	Halides and halide oxides of non-metals	7.97	Mean value of group 18--
2813	Sulphides of non-metals; commercial phosphorus trisulphide	7.97	Mean value of group 18--
2814	Ammonia, anhydrous or in aqueous solution.	19.84	[2]
2815	Sodium hydroxide (caustic soda); potassium hydroxide (caustic potash) peroxides of sodium or potassium	2.74	[2]
2816	Hydroxide and peroxide of magnesium; oxides, hydroxides and peroxides of strontium or barium	2.26	[2]
2817	Zinc; oxide and peroxide	0.61	[2]
2818	Aluminium oxide (including artificial corundum); aluminium hydroxide	1.97	[2]
2819	Chromium oxides and hydroxides	0.24	[2]
2820	Manganese oxides	0.52	[2]
2821	Iron oxides and hydroxides; earth colours containing 70% or more by weight of combined iron evaluated as Fe2o3	0.75	[2]
2822	Cobalt oxides and hydroxides; commercial cobalt oxides	0.63	[2]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
2823	Titanium oxides	0.27	[2]
2824	Lead oxides; red lead and orange lead	0.21	[2]
2825	Hydrazine and hydroxylamine and their inorganic salts; other inorganic bases; other metal oxides, hydroxides and peroxides	19.41	[2]
2826	Fluorides; fluorosilicates, fluoroaluminates and other complex fluorine salts	12.27	[2]
2827	Chlorides; chloride oxides and chloride hydroxides; bromides and bromide oxides; iodides and iodide oxides	1.38	[2]
2828	Hypochlorites; commercial calcium hypochlorite; chlorites; hypobromites	1.38	[2]
2829	Chlorates and perchlorates; bromates and perbromates; iodates and periodates	1.38	[2]
2830	Sulphides; polysulphides whether or not chemically defined	2.38	[2]
2831	Dithionites and sulphoxylates	4.89	[2]
2832	Sulphites; thiosulphates	3.11	[2]
2833	Sulphates; alums; peroxosulphates (persulphates)	6.35	[2]
2834	Nitrites; nitrates	2.09	[2]
2835	Phosphinates (hypophosphites), phosphonates (phosphites), and phosphates; and polyphosphates, whether or not chemically defined	0.06	[2]
2836	Carbonates; peroxocarbonates (percarbonates); commercial ammonium carbonate containing ammonium carbamate	0.41	[2]
2837	Cyanides, cyanide oxides and complex cyanides	32.48	[2]
2839	Silicates; commercial alkali metal silicates	0.54	[2]
2840	Borates; peroxoborates (perborates)	7.97	[2]
2841	Salts of oxometallic or peroxometallic acids	7.97	[2]
2842	Salts of inorganic acids or peroxoacids, n.e.c. including aluminosilicates whether or not chemically defined, but excluding azides	7.97	Mean value of group 18--
2843	Colloidal precious metals; inorganic or organic compounds of precious metals, whether or not chemically defined; amalgams of precious metals	0.25	Mean value of group 18--
2844	Radioactive chemical elements and radioactive isotopes (including the fissile or fertile chemical elements and isotopes); and their compounds; mixtures and residues containing these products	5.00	Mean value of group 18--
2845	Isotopes other than those of heading no. 2844; compounds, inorganic or organic, of such isotopes, whether or not chemically defined	1.11	Mean value of group 18--
2846	Compounds, inorganic or organic, of rare-earth metals; of yttrium or of scandium or of mixtures of these metals	7.97	[2]
2847	Hydrogen peroxide; whether or not solidified with urea	7.97	[2]
2848	Phosphides; whether or not chemically defined, excluding ferrophosphorus	7.97	[2]
2849	Carbides, whether or not chemically defined	22.91	[2]
2850	Hydrides, nitrides, azides, silicides and borides, whether or not chemically defined, other than compounds which are also carbides of heading no. 2849	7.97	[2]
2852	Inorganic or organic compounds of mercury, excluding amalgams, whether or not chemically defined	7.97	Mean value of group 18--
2853	Inorganic compounds n.e.c. (including distilled or conductivity water and water of similar purity); liquid air (rare gases removed or not); compressed air; amalgams, other than precious metal amalgams	7.97	Mean value of group 18--
2901	Acyclic hydrocarbons	47.72	[3]
2902	Cyclic hydrocarbons	41.86	[3]
2903	Halogenated derivatives of hydrocarbons	12.87	[3]
2904	Sulphonated, nitrated or nitrosated derivatives of hydrocarbons; whether or not halogenated	26.42	[3]
2905	Acyclic alcohols and their halogenated, sulphonated, nitrated or nitrosated derivatives	29.14	[3]
2906	Alcohols; cyclic, and their halogenated, sulphonated, nitrated or nitrosated derivatives	36.17	[3]
2907	Phenols; monophenols, polyphenols, and phenol-alcohols	31.47	[3]
2908	Phenols or phenol-alcohols; halogenated, sulphonated, nitrated or nitrosated derivatives	8.75	[3]
2909	Ethers, ether-alcohols, ether-phenols, ether-alcohol-phenols, alcohol peroxides, ether peroxides, ketone peroxides (chemically defined or not); halogenated, sulphonated, nitrated, nitrosated derivative	25.46	[3]
2910	Epoxides, epoxyalcohols, epoxyphenols and epoxyethers; with a three-membered ring and their halogenated, sulphonated, nitrated or nitrosated derivatives	26.36	[3]
2911	Acetals and hemiacetals; whether or not with other oxygen function, and their halogenated, sulphonated, nitrated or nitrostated derivatives	26.42	[3]
2912	Aldehydes, whether or not with other oxygen function; cyclic polymers of aldehydes; paraformaldehyde	28.26	[3]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
2913	Aldehydes; halogenated, sulphonated, nitrated or nitrosated derivatives of products of heading no. 2912	26.42	[3]
2914	Ketones and quinones; whether or not with other oxygen function, and their halogenated, sulphonated, nitrated or nitrostated derivatives	35.04	[3]
2915	Acids; saturated acyclic monocarboxylic acids and their anhydrides, halides, peroxides and peroxyacids; their halogenated, sulphonated, nitrated or nitrosated derivatives	25.33	[3]
2916	Acids; unsaturated acyclic monocarboxylic, cyclic monocarboxylic, their anhydrides, halides, peroxides and peroxyacids; their halogenated, sulphonated, nitrated or nitrosated derivatives	26.97	[3]
2917	Acids; polycarboxylic acids, their anhydrides, halides, peroxides and peroxy-acids; their halogenated, sulphonated, nitrated or nitrosated derivatives	17.50	[3]
2918	Acids; carboxylic acid with additional oxygen function and their anhydrides, halides, peroxides, peroxyacids; their halogenated, sulphonated, nitrated or nitrosated derivatives	13.71	[3]
2919	Esters; phosphoric, and their salts, including lactophosphates, their halogenated, sulphonated, nitrated or nitrosated derivatives	26.42	[3]
2920	Esters of other inorganic acids of non-metals (other than of hydrogen halides) and their salts, their halogenated, sulphonated, nitrated or nitrosated derivatives	26.42	[3]
2921	Amine-function compounds	37.08	[3]
2922	Oxygen-function amino-compounds	25.52	[3]
2923	Quaternary ammonium salts and hydroxides; lecithins and other phosphoaminolipids, whether or not chemically defined	26.42	[3]
2924	Carboxyamide-function compounds; amide-function compounds of carbonic acid	19.03	[3]
2925	Carboxyimide-function compounds (including saccharin and its salts) and imine-function compounds	26.42	[3]
2926	Nitrile-function compounds	24.74	[3]
2927	Diazo-, azo- or azoxy-compounds	26.42	[3]
2928	Organic derivatives of hydrazine or of hydroxylamine	26.42	[3]
2929	Nitrogen-function compounds, n.e.c. in chapter 29	26.42	[3]
2930	Organo-sulphur compounds	26.17	[3]
2931	Other organo-inorganic compounds	16.81	[3]
2932	Heterocyclic compounds with oxygen hetero-atom(s) only	27.69	[3]
2933	Heterocyclic compounds with nitrogen hetero-atom(s) only	24.22	[3]
2934	Nucleic acids and their salts, whether or not chemically defined; other heterocyclic compounds	26.42	[3]
2935	Sulphonamides	26.42	[3]
2936	Provitamins, vitamins; natural or reproduced by synthesis (including natural concentrates) derivatives thereof used as vitamins, and intermixtures of the fore-going, whether or not in any solvent	21.30	[3]
2937	Hormones, prostaglandins, thromboxanes and leukotrienes, natural or reproduced by synthesis; derivatives and structural analogues thereof, including chain modified polypeptides, used primarily as hormones.	31.37	[3]
2938	Glycosides, natural or reproduced by synthesis, and their salts, ethers, esters and other derivatives	26.42	[3]
2939	Alkaloids, vegetable; natural or reproduced by synthesis, and their salts, ethers, esters and other derivatives	26.42	[3]
2940	Sugars, chemically pure, other than sucrose, lactose, maltose, glucose and fructose; sugar ethers, sugar acetals and sugar esters, and their salts, other than the products of heading 29.37, 29.38, or 29.39	26.42	[3]
2941	Antibiotics	26.42	[3]
2942	Organic compounds; n.e.c. in chapter 29	26.42	[3]
3001	Glands and other organs (extracts, secretions thereof) for organo-therapeutic uses, dried, powdered or not; heparin and its salts; other human or animal substances for therapeutic or prophylactic uses n.e.c.	0.00	-
3002	Human blood; animal blood for therapeutic, prophylactic or diagnostic uses; antisera, other blood fractions, immunological products, modified or obtained by biotechnological processes; vaccines, toxins, cultures of micro-organisms (excluding yeasts) etc	0.00	-
3003	Medicaments; (not goods of heading no. 3002, 3005 or 3006) of two or more constituents mixed together for therapeutic or prophylactic use not in measured doses or in forms or packings for retail sale	0.00	-

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
3004	Medicaments; (not goods of heading no. 3002, 3005 or 3006) consisting of mixed or unmixed products for therapeutic or prophylactic use, put up in measured doses (incl. those in the form of transdermal admin. systems) or packed for retail sale	0.00	-
3005	Wadding, gauze, bandages (dressings, adhesive plasters, poultices), impregnated or coated with pharmaceutical substances or in forms or packings for retail sale, for medical, surgical or veterinary use	20.38	[13]
3006	Pharmaceutical goods	0.00	-
3101	Fertilizers; animal or vegetable, whether or not mixed together or chemically treated; fertilizers produced by the mixing or chemical treatment of animal or vegetable products	3.44	Mean value of group 31--
3102	Fertilizers; mineral or chemical, nitrogenous	3.68	[11]
3103	Fertilizers; mineral or chemical, phosphatic	2.25	[11]
3104	Fertilizers; mineral or chemical, potassic	4.39	[11]
3105	Fertilizers; mineral or chemical, containing 2 or 3 of the elements nitrogen, phosphorus, potassium; other fertilisers; goods of chapter 31 in tablets or packages of gross weight not exceeding 10kg	3.44	Mean value of group 31--
3201	Tanning extracts of vegetable origin; tannins and their salts, ethers, esters and other derivatives	31.16	[10]
3202	Tanning substances; synthetic organic or inorganic tanning substances; tanning preparations, whether or not containing natural tanning substances, enzymatic preparations for pre-tanning	31.16	[10]
3203	Colouring matter of vegetable or animal origin (including dyeing extracts, not animal black); whether or not chemically defined; preparations based on colouring matter of vegetable or animal origin	31.16	[10]
3204	Synthetic organic colouring matter and preparations based thereon; synthetic organic products used as fluorescent brightening agents or as luminophores; whether or not chemically defined	31.16	[10]
3205	Colour lakes; preparations based on colour lakes as specified in note 3 to this chapter	31.16	[10]
3206	Colouring matter and preparations thereof n.e.c. in heading no. 3203, 3204, 3205; inorganic products, kind used as luminophores whether or not chemically defined	31.16	[10]
3207	Pigments, prepared; opacifiers, colours, vitrifiable enamels, glazes, engobes (slips), liquid lustres etc as used in the ceramic enamelling or glass industry; glass frit and powder, granules or flakes	31.16	[10]
3208	Paints, varnishes; (enamels and lacquers) based on synthetic polymers or chemically modified natural polymers, dispersed or dissolved in a non-aqueous medium	31.16	[10]
3209	Paints and varnishes (including enamels and lacquers) based on synthetic or chemically modified natural polymers, dispersed or dissolved in an aqueous medium	31.16	[10]
3210	Paints and varnishes (including enamels, lacquers and distempers), excluding those of heading no. 3209, prepared water pigments of a kind used for finishing leather	31.16	[10]
3211	Driers; prepared	31.16	[10]
3212	Pigments (metallic powders and flakes) dispersed in non-aqueous media in liquid or paste form, as used in manufacture of paints (including enamels); stamping foils, dyes etc in forms, packing for retail sale	31.16	[10]
3213	Colours; artists, students, or signboard painters, modifying tints, amusement colours and the like; in tablets, tubes, jars, bottles, pan or in similar forms or packings	31.16	[10]
3214	Glaziers' putty, grafting putty, resin cements, caulking compounds and other mastics; painters' fillings; non-refractory surfacing preparations for facades, indoor walls, floors, ceilings or the like	31.16	[10]
3215	Ink; printing, writing or drawing ink and other inks; whether or not concentrated or solid	31.16	[10]
3301	Oils; essential (concretes, absolutes); concentrates thereof in fats, fixed oils, waxes or the like (obtained by enfleurage or maceration); aqueous distillates, solutions and terpenic by-products thereof; resinoids; extracted oleoresins	29.69	[2]
3302	Odoriferous substances and mixtures (including alcoholic solutions) with a basis of one or more of these substances, of a kind used as raw materials in industry; other preparations based on odoriferous substances, of a kind used for beverage manufacture	0.00	-
3303	Perfumes and toilet waters	29.69	[2]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
3304	Cosmetic and toilet preparations; beauty, make-up and skin care preparations (excluding medicaments, including sunscreen or sun tan preparations), manicure or pedicure preparations	0.00	-
3305	Hair preparations; for use on the hair	0.00	-
3306	Oral or dental hygiene preparations; including fixative pastes and powders; yarn used to clean between the teeth (dental floss), in individual retail packages	0.00	-
3307	Perfumery, cosmetic or toilet preparations; pre-shave, shaving, after-shave, bath preparations; personal deodorants and depilatories; room deodorisers, perfumed or not with disinfectant properties or not	29.69	[2]
3401	Soap; organic surface-active preparations used as soap, skin washing, in bars, cakes, moulded pieces, shapes, liquid or cream, containing soap or not; for retail, paper, wadding, felt and nonwovens, impregnated, coated or covered with soap or detergent	44.27	Mean value of group 34--
3402	Organic surface-active agents (not soap); surface-active, washing (including auxiliary washing) and cleaning preparations, containing soap or not, excluding those of heading no. 3401	44.27	Mean value of group 34--
3403	Lubricating preparations and those used in oil or grease treatment of textile and similar materials; excluding preparations containing 70% or more (by weight) of petroleum or bituminous mineral oils	41.81	[5]
3404	Waxes; artificial, prepared	45.50	[5]
3405	Polishes, creams, scouring pastes, powders and similar; in any form, (including articles impregnated, coated or covered with such), for furniture, footwear, floors, coachwork, glass or metal	44.27	Mean value of group 34--
3406	Candles, tapers and the like	45.50	[5]
3407	Modelling pastes, including those for children; dental wax, impression compounds, in sets or packings for retail sale or in plates and similar forms; dentistry preparations with plaster base	0.00	-
3501	Casein, caseinates and other casein derivatives; casein glues	15.24	[2]
3502	Albumins (including concentrates of two or more whey proteins, containing by weight more than 80% whey proteins, calculated on the dry matter), albuminates and other albumin derivatives	3.76	[2]
3503	Gelatin (including gelatin in rectangular sheets, whether or not surface-worked or coloured) and gelatin derivatives; isinglass; other glues of animal origin, excluding casein glues of heading no. 3501	14.50	[2]
3504	Peptones and their derivatives; other protein substances and their derivatives n.e.c. or included; hide powder, whether or not chromed	13.99	Mean value of group 35--
3505	Dextrins and other modified starches (e.g. pregelatinised or esterified starches); glues based on starches or on dextrins or other modified starches	16.82	[2]
3506	Prepared glues and other prepared adhesives, n.e.c. or included; products suitable for use as glues or adhesives, put up for retail sale as glues or adhesives, not exceeding 1kg net weight	0.00	-
3507	Enzymes; prepared enzymes not elsewhere specified or included	13.99	Mean value of group 35--
3601	Explosives; propellent powders	0.00	-
3602	Prepared explosives, other than propellent powders	0.00	-
3603	Safety fuses; detonating fuses; percussion or detonating caps; igniters; electric detonators	0.00	-
3604	Fireworks, signalling flares, rain rockets, fog signals and other pyrotechnic articles	0.00	-
3605	Matches; other than pyrotechnic articles of heading no. 3604	19.61	[13]
3606	Ferro-cerium and other pyrophoric alloys in all forms; articles of combustible materials n.e.c. in chapter 36	13.99	Mean value of group 36--
3701	Photographic plates and film in the flat, sensitised, unexposed, of any material other than paper, paperboard or textiles; instant print film in the flat, sensitised, unexposed, whether or not in packs	34.52	[6]
3702	Photographic film in rolls, sensitised, unexposed, of any material other than paper, paperboard or textiles; instant print film in rolls, sensitised, unexposed	34.52	[6]
3703	Photographic paper, paperboard and textiles; sensitised, unexposed	15.06	[13]
3704	Photographic plates, film, paper, paperboard and textiles, exposed but not developed	15.06	[13]
3705	Photographic plates and film; exposed and developed, other than cinematographic film	34.52	[6]
3706	Cinematographic film; exposed and developed, whether or not incorporating sound track or consisting only of sound track	34.52	[6]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
3707	Chemical preparations for photographic uses (other than varnishes, glues, adhesives and similar preparations); unmixed products for photographic uses, put up in measured portions or for retail sale	0.00	-
3801	Artificial graphite; colloidal or semi-colloidal graphite; preparations based on graphite or other carbon in the form of pastes, blocks, plates or other semi-manufactures	34.46	[13]
3802	Activated carbon; activated natural mineral products; animal black, including spent animal black	34.46	[13]
3803	Tall oil, whether or not refined	39.60	[13]
3804	Residual lyes from the manufacture of wood pulp, whether or not concentrated, desugared or chemically treated, including lignin sulphonates, but excluding tall oil of heading no. 3803	20.15	[9]
3805	Gum, wood or sulphate turpentine, other terpenic oils; crude dipentene; sulphite turpentine, other crude para-cymene; pine oil containing alpha-terpineol as the main constituent	20.15	[9]
3806	Rosin and resin acids and derivatives thereof; rosin spirit and rosin oils; run gums	20.15	[9]
3807	Wood tar; wood tar oils; wood creosote; wood naphtha; vegetable pitch; brewers' pitch and similar preparations based on rosin, resin acids or on vegetable pitch	20.15	[9]
3808	Insecticides, rodenticides, fungicides, herbicides, anti-sprouting products, plant growth regulators, disinfectants and the like, put up in forms or packings for retail sale or as preparations or articles	23.33	[11]
3809	Finishing agents, dye carriers to accelerate the dyeing, fixing of dyestuffs, other products and preparations, of a kind used in the textile, paper, leather or like industries, n.e.c. or included	0.00	-
3810	Metal-pickling preparations; fluxes etc for soldering, brazing; welding powders, pastes of metal and other materials; preparations used as cores or coatings for welding electrodes or rods	0.00	-
3811	Anti-knock preparations, oxidation and gum inhibitors, viscosity improvers, anti-corrosive preparations and the like, for mineral oils (including gasoline) or other liquids used for the same purposes	0.00	-
3812	Prepared rubber accelerators; compound plasticisers for rubber or plastics, n.e.c. or included; anti-oxidising preparations and other compound stabilisers for rubber or plastics	0.00	-
3813	Preparations and charges for fire extinguishers; charged fire-extinguishing grenades	0.00	-
3814	Organic composite solvents and thinners, not elsewhere specified or included; prepared paint or varnish removers	0.00	-
3815	Reaction initiators, reaction accelerators and catalytic preparations n.e.c. or included	0.00	-
3816	Refractory cements, mortars, concretes and similar compositions; other than products of heading no. 3801	0.00	-
3817	Mixed alkylbenzenes and mixed alkylnaphthalenes, other than those of heading no. 2707 or 2902	44.08	[13]
3818	Chemical elements doped for use in electronics, in the form of discs, wafers or similar forms; chemical compounds doped for use in electronics	0.00	-
3819	Hydraulic brake fluids and other prepared liquids for hydraulic transmission, not containing or containing less than 70% by weight of petroleum oils or oils obtained from bituminous minerals	0.00	-
3820	Anti-freezing preparations and prepared de-icing fluids	23.96	[13]
3821	Prepared culture media for the development or maintenance of micro-organisms (including viruses and the like) or of plant, human or animal cells	0.00	-
3822	Reagents; diagnostic or laboratory reagents on a backing and prepared diagnostic or laboratory reagents whether or not on a backing, other than those of heading no. 3002 or 3006; certified reference material	0.00	-
3823	Industrial monocarboxylic fatty acids; acid oils from refining; industrial fatty alcohols	39.60	[13]
3824	Prepared binders for foundry moulds or cores; chemical products and preparations of the chemical or allied industries (including those consisting of mixtures of natural products), not elsewhere specified or included	28.92	Mean value of group 38--
3825	Residual products of the chemical or allied industries, not elsewhere specified or included; municipal waste; sewage sludge; other residual products.	28.92	Mean value of group 38--
3826	Biodiesel and mixtures thereof; not containing or containing less than 70% by weight of petroleum oils or oils obtained from bituminous minerals	27.00	[10]
3901	Polymers of ethylene, in primary forms	42.85	[6]
3902	Polymers of propylene or of other olefins, in primary forms	46.00	[6]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
3903	Polymers of styrene, in primary forms	39.52	[6]
3904	Polymers of vinyl chloride or of other halogenated olefins, in primary forms	20.85	[6]
3905	Polymers of vinyl acetate or of other vinyl esters, in primary forms; other vinyl polymers in primary forms	34.46	[13]
3906	Acrylic polymers in primary forms	34.46	Mean value of group 39--
3907	Polyacetals, other polyethers and epoxide resins, in primary forms; polycarbonates, alkyd resins, polyallyl esters and other polyesters, in primary forms	34.46	Mean value of group 39--
3908	Polyamides in primary forms	34.46	Mean value of group 39--
3909	Amino-resins, phenolic resins and polyurethanes, in primary forms	34.46	Mean value of group 39--
3910	Silicones in primary forms	34.46	[13]
3911	Petroleum resins, coumarone-indene resins, polyterpenes, polysulphides, polysulphones and similar products of chemical synthesis n.e.c. in chapter 39, in primary forms	34.46	Mean value of group 39--
3912	Cellulose and its chemical derivatives, n.e.c. or included, in primary forms	34.46	Mean value of group 39--
3913	Natural polymers (e.g. alginic acid) and modified natural polymers (e.g. hardened proteins, chemical derivatives of natural rubber), n.e.c. or included, in primary forms	34.46	[13]
3914	Ion-exchangers; based on polymers of heading no. 3901 to 3913, in primary forms	34.46	Mean value of group 39--
3915	Waste, parings and scrap, of plastics	34.46	[6]
3916	Monofilament of which any cross-sectional dimension exceeds 1mm, rods, sticks and profile shapes, whether or not surface-worked but not otherwise worked, of plastics	34.46	[6]
3917	Tubes, pipes and hoses and fittings thereof (for example, joints, elbows, flanges), of plastics	20.85	[6]
3918	Floor coverings of plastics, self-adhesive or not, in rolls or tiles; wall or ceiling coverings of plastics, in rolls of a width not less than 45cm	20.85	[6]
3919	Self-adhesive plates, sheets, film, foil, tape, strip and other flat shapes, of plastics, whether or not in rolls	34.46	[6]
3920	Plastics; plates, sheets, film, foil and strip (not self-adhesive); non-cellular and not reinforced, laminated, supported or similarly combined with other materials, n.e.c. in chapter 39	34.46	[6]
3921	Plastic plates, sheets, film, foil and strip n.e.c. in chapter 39	34.46	[6]
3922	Sanitary ware; baths, shower-baths, sinks, wash-basins, bidets, lavatory pans, seats and covers, flushing cisterns and sanitary ware, of plastics	20.85	[6]
3923	Plastic articles for the conveyance or packing of goods; stoppers, lids, caps and other closures of plastics	34.46	[6]
3924	Tableware, kitchenware, other household articles and hygienic or toilet articles, of plastics	23.09	[6]
3925	Plastics; builders' wares n.e.c. or included	34.46	[6]
3926	Articles of plastics and articles of other materials of heading no. 3901 to 3914, n.e.c. in chapter 39	34.46	[6]
4001	Natural rubber, balata, gutta-percha, guayule, chicle and similar gums; in primary forms or in plates, sheets or strip	31.99	[13]
4002	Synthetic rubber and factice derived from oils, in primary forms or in plates, sheets or strip; mixtures of heading no. 4001 and 4002, in primary forms or in plates, sheets or strip	31.99	[13]
4003	Reclaimed rubber in primary forms or in plates, sheets or strip	31.99	[13]
4005	Compounded rubber, unvulcanised, in primary forms or in plates, sheets or strip	31.99	[13]
4006	Unvulcanised rubber in other forms (e.g. rods, tubes and profile shapes) and articles (e.g. discs and rings)	31.99	[13]
4007	Vulcanised rubber thread and cord	31.99	[13]
4008	Plates, sheets, strip, rods and profile shapes, of vulcanised rubber other than hard rubber	31.99	[13]
4009	Tubes, pipes and hoses, of vulcanised rubber (other than hard rubber), with or without their fittings (e.g. joints, elbows, flanges)	31.99	[13]
4010	Conveyor or transmission belts or belting, of vulcanised rubber	31.99	[13]
4011	New pneumatic tyres, of rubber	31.99	[13]
4012	Retreaded or used pneumatic tyres of rubber; solid or cushion tyres, tyre treads and tyre flaps, of rubber	31.99	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
4013	Inner tubes, of rubber	31.99	[13]
4014	Hygienic or pharmaceutical articles (including teats), of vulcanised rubber other than hard rubber, with or without fittings of hard rubber	31.99	[13]
4015	Articles of apparel and clothing accessories (including gloves, mittens and mitts), for all purposes, of vulcanised rubber other than hard rubber	31.99	[13]
4016	Articles of vulcanised rubber other than hard rubber, n.e.c. in chapter 40	31.99	[13]
4017	Hard rubber (e.g. ebonite) in all forms, including waste and scrap; articles of hard rubber	31.99	[13]
4101	Raw hides and skins of bovine (including buffalo) or equine animals (fresh, salted, dried, limed, pickled, otherwise preserved but not tanned, parchment dressed or further prepared), whether or not dehaired or split	0.00	-
4102	Raw skins of sheep or lambs (fresh, salted, dried, limed, pickled or otherwise preserved, but not further prepared), whether or not with wool on or split	0.00	-
4103	Raw hides and skins n.e.c in headings no. 4101, 4102; fresh, salted, dried, pickled or otherwise preserved, not further prepared, whether or not dehaired or split	0.00	-
4104	Tanned or crust hides and skins of bovine (including buffalo) or equine animals, without hair on, whether or not split, but not further prepared	0.00	-
4105	Tanned or crust skins of sheep and lambs, without wool on, whether or not split, but not further prepared	0.00	-
4106	Tanned or crust hides and skins of other animals, without wool or hair on, whether or not split, but not further prepared	0.00	[13]
4107	Leather further prepared after tanning or crusting, including parchment-dressed leather, of bovine (including buffalo) or equine animals, without hair on, whether or not split, other than leather of heading 41.14	22.89	[13]
4112	Leather further prepared after tanning or crusting, including parchment dressed leather, of sheep or lamb, without wool on, whether or not split, other than leather of heading 41.14	22.89	[13]
4113	Leather further prepared after tanning or crusting, including parchment-dressed leather, of animals (other than ovine), without wool or hair on, whether or not split, other than leather of heading 41.14	22.89	[13]
4114	Chamois (including combination chamois) leather; patent leather and patent laminated leather; metallised leather	22.89	[13]
4115	Composition leather with a basis of leather or leather fibre, in slabs, sheets or strip, in rolls or not; parings and other waste of leather or of composition leather, not suitable for the manufacture of leather articles; leather dust, powder and flour	22.89	[13]
4201	Saddlery and harness for any animal (including traces, leads, knee pads, muzzles, saddle cloths, saddle bags, dog coats and the like) of any material	22.89	[13]
4202	Trunks; suit, camera, jewellery, cutlery cases; travel, tool, similar bags; wholly or mainly covered by leather, composition leather, plastic sheeting, textile materials, vulcanised fibre, paperboard	22.89	[13]
4203	Articles of apparel and clothing accessories, of leather or of composition leather	22.89	[13]
4205	Leather or composition leather articles n.e.c. in chapter 42	22.89	Mean value of group 42--
4206	Articles of gut (other than silk-worm gut), of goldbeater's skin, of bladders or of tendons	0.00	-
4301	Raw furskins (including heads, tails, paws, other pieces or cuttings, suitable for furriers' use), excluding raw hides and skins of heading no. 4101, 4102 or 4103	0.00	-
4302	Tanned or dressed furskins (including heads, tails, paws, other pieces, cuttings), unassembled, or assembled (without addition of other materials), excluding those of heading no. 4303	22.89	[13]
4303	Articles of apparel, clothing accessories and other articles of furskin	22.89	[13]
4304	Artificial fur and articles thereof	22.89	[13]
4401	Fuel wood, in logs, billets, twigs, faggots or similar forms; wood in chip or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms	19.61	[13]
4402	Wood charcoal (including shell or nut charcoal), whether or not agglomerated	19.61	[13]
4403	Wood in the rough, whether or not stripped of bark or sapwood, or roughly squared	19.61	[13]
4404	Hoopwood; split poles; piles, pickets, stakes of wood, pointed, not sawn lengthwise; wooden sticks, roughly trimmed, not turned, bent, etc., suitable for walking sticks, umbrellas, tool handles, etc.	19.61	[13]
4405	Wood wool; wood flour	19.61	[13]
4407	Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness exceeding 6mm	19.61	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
4408	Sheets for veneering (including those obtained by slicing laminated wood), for plywood or for similar laminated wood and other wood, sawn lengthwise, sliced or peeled, planed or not, sanded, spliced or end-jointed, of a thickness not exceeding 6 mm	19.61	[13]
4409	Wood (including strips, friezes for parquet flooring, not assembled), continuously shaped (tongued, grooved, v-jointed, beaded or the like) along any edges, ends or faces, whether or not planed, sanded or end-jointed	19.61	[13]
4410	Particle board, oriented strand board (OSB) and similar board (e.g. waferboard) of wood or other ligneous materials, whether or not agglomerated with resins or other organic binding substances	19.61	[13]
4411	Fibreboard of wood or other ligneous materials, whether or not bonded with resins or other organic substances	19.61	[13]
4412	Plywood, veneered panels and similar laminated wood	19.61	[13]
4413	Densified wood, in blocks, plates, strips or profile shapes	19.61	[13]
4414	Wooden frames; for paintings, photographs, mirrors or similar objects	19.61	[13]
4415	Packing cases, boxes, crates, drums and similar packings, of wood; cable-drums of wood; pallets, box pallets and other load boards, of wood; pallet collars of wood	19.61	[13]
4416	Casks, barrels, vats, tubs and other coopers' products and parts thereof, of wood, including staves	19.61	[13]
4417	Tools, tool bodies, tool handles, broom or brush bodies and handles, of wood; boot or shoe lasts and trees, of wood	19.61	[13]
4418	Builders' joinery and carpentry of wood, including cellular wood panels, assembled flooring panels, shingles and shakes	19.61	[13]
4419	Tableware and kitchenware, of wood	19.61	[13]
4420	Wood marquetry and inlaid wood; caskets and cases for jewellery or cutlery, and similar articles of wood; statuettes and other ornaments of wood; wooden articles of furniture not falling in chapter 94	19.61	[13]
4421	Wooden articles n.e.c. in heading no. 4414 to 4420	19.61	[13]
4501	Natural cork, raw or simply prepared; waste cork; crushed, granulated or ground cork	17.30	[17]
4502	Natural cork, debacked or roughly squared, or in rectangular (including square) blocks, plates, sheets or strip, (including sharp-edged blanks for corks or stoppers)	17.30	[17]
4503	Cork; articles of natural cork	17.30	[17]
4504	Agglomerated cork (with or without a binding substance) and articles of agglomerated cork	17.30	[17]
4601	Plaits and similar products of plaiting materials, assembled into strips or not; plaiting materials, plaits and the like bound together in parallel strands or woven in sheet form, finished articles or not	17.30	[17]
4602	Basketwork, wickerwork and other articles, made directly to shape from plaiting materials or made up from goods of heading no. 4601; articles of loofah	17.30	[17]
4701	Wood pulp, mechanical wood pulp	19.61	[13]
4702	Chemical wood pulp, dissolving grades	19.61	[13]
4703	Chemical wood pulp, soda or sulphate, other than dissolving grades	19.61	[13]
4704	Chemical wood pulp, sulphite, other than dissolving grades	19.61	[13]
4705	Wood pulp obtained by a combination of mechanical and chemical pulping processes	19.61	[13]
4706	Pulps of fibres derived from recovered (waste and scrap) paper or paperboard or of other fibrous cellulosic material	19.61	[13]
4707	Waste and scrap of paper and paperboard	15.06	[13]
4801	Newsprint, in rolls or sheets	15.06	[13]
4802	Uncoated paper and paperboard, used for writing, printing or other graphics, non perforated punch-cards and punch tape paper, in rolls or rectangular sheets, of any size, other than paper of heading 4801 or 4803; hand-made paper and paperboard	15.06	[13]
4803	Tissue, towel, napkin stock or similar; for household or sanitary uses, cellulose wadding, webs of cellulose fibres, in rolls over 36cm in width or rectangular sheets with one side exceeding 36cm when unfolded	15.06	[13]
4804	Uncoated kraft paper and paperboard, in rolls or sheets, other than that of heading no. 4802 or 4803	15.06	[13]
4805	Uncoated paper and paperboard n.e.c., in rolls or sheets	15.06	[13]
4806	Vegetable parchment, greaseproof papers, tracing papers, glassine and other glazed transparent or translucent papers, in rolls or sheets	15.06	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
4807	Composite paper and paperboard, (made by sticking layers together with an adhesive), not surface-coated or impregnated, whether or not internally reinforced, in rolls or sheets	15.06	[13]
4808	Paper and paperboard, corrugated (with or without glued flat surface sheets), creped, crinkled, embossed or perforated, in rolls or sheets other than paper of the kind described in heading 4803	15.06	[13]
4809	Carbon paper, self copy paper, and other copying or transfer papers (including coated or impregnated paper for duplicator stencils or offset plates), whether or not printed, in rolls or sheets	15.06	[13]
4810	Paper and paperboard, coated one or both sides with kaolin (china clay) or inorganic substances, with binder or not, no other coating, surface coloured or not, surface decorated or printed, in rolls or rectangular (including square) sheets, of any size	15.06	[13]
4811	Paper, paperboard, cellulose wadding and webs of cellulose fibres, coated, impregnated, covered, surface-coloured, decorated or printed, rolls or sheets, other than goods of heading no. 4803, 4809, or 4810	15.06	[13]
4812	Filter blocks, slabs and plates of paper pulp	15.06	[13]
4813	Cigarette paper, whether or not cut to size or in the form of booklets or tubes	15.06	[13]
4814	Wallpaper and similar wall coverings; window transparencies of paper	15.06	[13]
4816	Carbon paper, self-copy paper and other copying or transfer papers, (other than those of heading no. 4809), duplicator stencils and offset plates, of paper whether or not put up in boxes	15.06	[13]
4817	Envelopes, letter cards, plain postcards and correspondence cards, of paper, paperboard; boxes, pouches, wallets and writing compendiums, of paper or paperboard containing assortment of paper stationery	15.06	[13]
4818	Toilet paper, width 36cm or less or cut to size/shape; handkerchiefs, tissues, towels, serviettes, bed sheets and similar household or hospital articles, apparel and clothing accessories of paper pulp, paper, cellulose wadding or webs of cellulose fibres	15.06	[13]
4819	Cartons, boxes, cases, bags and the like, of paper, paperboard, cellulose wadding or fibres; box files, letter trays and the like, of paper or paperboard, of a kind used in offices, shops or the like	15.06	[13]
4820	Registers, account books, diaries and similar; albums for samples or collections, of paper or paperboard	15.06	[13]
4821	Paper or paperboard labels of all kinds, whether or not printed	15.06	[13]
4822	Bobbins, spools, cops and similar supports of paper pulp, paper or paperboard (whether or not perforated or hardened)	15.06	[13]
4823	Paper, paperboard, cellulose wadding and webs of cellulose fibres; cut to size or shape, articles of paper pulp, paper and paper-board, cellulose wadding or webs of cellulose fibres, n.e.c. in chapter 48	15.06	[13]
4901	Printed books, brochures, leaflets and similar printed matter, whether or not in single sheets	15.06	[13]
4902	Newspapers, journals and periodicals, whether or not illustrated or containing advertising material	15.06	[13]
4903	Children's picture, drawing or colouring books	15.06	[13]
4904	Music, printed or in manuscript, whether or not bound or illustrated	15.06	[13]
4905	Maps and hydrographic or similar charts of all kinds, including atlases, wall maps, topographical plans and globes, printed	15.06	[13]
4906	Plans and drawings; for architectural, engineering, industrial, commercial, topographical or similar, being originals drawn by hand; hand-written texts; photo- graphic reproductions; their carbon copies	15.06	[13]
4907	Unused postage, revenue or similar stamps of current or new issue in the country in which they have, or will have, a recognised face value; stamp-impressed paper; cheque forms; banknotes, stock, share or bond certificates and the like of similar title	15.06	[13]
4908	Transfers (decalcomanias)	15.06	[13]
4909	Printed or illustrated postcards; printed cards bearing personal greetings, messages or announcements, whether or not illustrated, with or without envelopes or trimmings	15.06	[13]
4910	Calendars of any kind, printed, including calendar blocks	15.06	[13]
4911	Printed matter, n.e.c., including printed pictures and photographs	15.06	[13]
5001	Silk-worm cocoons suitable for reeling	0.00	-
5002	Raw silk (not thrown)	21.02	[18]
5003	Silk waste (including cocoons unsuitable for reeling, yarn waste and garnetted stock)	21.02	[18]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
5004	Silk; yarn (other than yarn spun from silk waste), not put up for retail sale	21.02	[18]
5006	Silk yarn and yarn spun from silk waste, put up for retail sale; silk-worm gut	21.02	[18]
5007	Woven fabrics of silk or of silk waste	21.02	[18]
5101	Wool, not carded or combed	22.28	[13]
5102	Fine or coarse animal hair, not carded or combed	22.28	[13]
5105	Wool and fine or coarse animal hair; carded or combed (including combed wool in fragments)	22.28	[13]
5106	Yarn of carded wool, not put up for retail sale	22.28	[13]
5107	Yarn of combed wool, not put up for retail sale	22.28	[13]
5109	Yarn of wool or of fine animal hair, put up for retail sale	22.28	[13]
5111	Woven fabrics of carded wool or of carded fine animal hair	22.28	[13]
5112	Woven fabrics of combed wool or of combed fine animal hair	22.28	[13]
5113	Woven fabrics of coarse animal hair or of horsehair	22.28	[13]
5201	Cotton; not carded or combed	17.08	[13]
5202	Cotton waste (including yarn waste and garnetted stock)	17.08	[13]
5203	Cotton, carded or combed	17.08	[13]
5204	Cotton sewing thread, whether or not put up for retail sale	17.08	[13]
5205	Cotton yarn (other than sewing thread), containing 85% or more by weight of cotton, not put up for retail sale	17.08	[13]
5206	Cotton yarn (other than sewing thread), containing less than 85% by weight of cotton, not put up for retail sale	17.08	[13]
5207	Cotton yarn (other than sewing thread), put up for retail sale	17.08	[13]
5208	Woven fabrics of cotton, containing 85% or more by weight of cotton, weighing not more than 200 g/m2	17.08	[13]
5209	Woven fabrics of cotton, containing 85% or more by weight of cotton, weighing more than 200g/m2	17.08	[13]
5210	Woven fabrics of cotton, containing less than 85% by weight of cotton, mixed mainly or solely with man-made fibres, weighing not more than 200 g/m2	17.08	[13]
5211	Woven fabrics of cotton, containing less than 85% by weight of cotton, mixed mainly or solely with man-made fibres, weighing more than 200g/m2	17.08	[13]
5212	Other woven fabrics of cotton, n.e.c. in chapter 52	17.08	[13]
5301	Flax, raw or processed but not spun; flax tow and waste (including yarn waste and garnetted stock)	17.30	[13]
5303	Jute and other textile bast fibres (not flax, true hemp and ramie), raw or processed but not spun; tow and waste of these fibres, including yarn waste and garnetted stock	17.30	[13]
5305	Coconut, abaca (Manila hemp or Musa textilis Nee), ramie and other vegetable textile fibres n.e.c., raw or processed but not spun; tow, noils and waste of these fibres (including yarn waste and garnetted stock)	17.30	[13]
5306	Flax yarn	17.30	[13]
5307	Yarn of jute or of other textile bast fibres of heading no. 5305	17.30	[13]
5308	Yarn of other vegetable textile fibres; paper yarn	17.30	[13]
5309	Woven fabrics of flax	17.30	[13]
5310	Woven fabrics of jute, other textile bast fibres of heading no. 5303	17.30	[13]
5311	Woven fabrics of other vegetable textile fibres; woven fabrics of paper yarn	17.30	[13]
5401	Sewing thread of man-made filaments, whether or not put up for retail sale	23.67	[17]
5402	Synthetic filament yarn (other than sewing thread), not put up for retail sale, including synthetic monofilament of less than 67 decitex	23.67	[17]
5403	Artificial filament yarn (other than sewing thread), not put up for retail sale, including artificial monofilament of less than 67 decitex	23.67	[17]
5404	Synthetic monofilament of 67 decitex or more, of which no cross-sectional dimension exceeds 1mm; strip and the like (e.g. artificial straw) of synthetic textile materials of an apparent width not exceeding 5mm	23.67	[17]
5405	Artificial monofilament of 67 decitex or more, no cross-sectional dimension exceeds 1mm; strip and the like (e.g. artificial straw), of artificial textile materials of a width not exceeding 5mm	23.67	[17]
5406	Man-made filament yarn (other than sewing thread), put up for retail sale	23.67	[17]
5407	Woven fabrics of synthetic filament yarn, including woven fabrics obtained from materials of heading no. 5404	23.67	[17]
5408	Woven fabrics of artificial filament yarn including woven fabrics obtained from materials of heading no. 5404	23.67	[17]
5501	Synthetic filament tow	23.67	[13]
5502	Artificial filament tow	23.67	[13]
5503	Synthetic staple fibres, not carded, combed or otherwise processed for spinning	23.67	[13]
5504	Artificial staple fibres, not carded, combed or otherwise processed for spinning	23.67	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
5506	Synthetic staple fibres, carded, combed or otherwise processed for spinning	23.67	[13]
5507	Artificial staple fibres, carded, combed or otherwise processed for spinning	23.67	[13]
5508	Sewing thread of man-made staple fibres, whether or not put up for retail sale	23.67	[13]
5509	Yarn (other than sewing thread) of synthetic staple fibres, not put up for retail sale	23.67	Mean value of group 55--
5510	Yarn (other than sewing thread) of artificial staple fibres, not put up for retail sale	23.67	Mean value of group 55--
5511	Yarn (not sewing thread), of man-made staple fibres, put up for retail sale	23.67	[13]
5512	Woven fabrics of synthetic staple fibres, containing 85% or more by weight of synthetic staple fibres	23.67	[13]
5513	Woven fabrics of synthetic staple fibres, containing less than 85% by weight of such fibres, mixed mainly or solely with cotton, of a weight not exceeding 170g/m2	23.67	[13]
5514	Woven fabrics of synthetic staple fibres, containing less than 85% by weight of such fibres, mixed mainly or solely with cotton, of a weight exceeding 170g/m2	23.67	[13]
5515	Woven fabrics of synthetic staple fibres, n.e.c. in chapter 55	23.67	[13]
5516	Woven fabrics of artificial staple fibres	23.67	Mean value of group 55--
5601	Wadding of textile materials and articles thereof; textile fibres, not exceeding 5 mm in length (flock), textile dust and mill neps	17.08	[13]
5602	Felt; whether or not impregnated, coated, covered or laminated	22.28	[13]
5603	Nonwovens; whether or not impregnated, coated, covered or laminated	23.67	[13]
5604	Rubber thread and cord, textile covered; textile yarn and strip and the like of heading no. 5404, 5405; impregnated, coated, covered or sheathed with rubber or plastics	31.99	[13]
5605	Yarn; metallised, whether or not gimped, of textile yarn, or strip or the like of heading no. 5404 or 5405, combined with metal in the form of thread, strip or powder or covered with metal	25.57	Mean value of group 56--
5606	Yarn and strip and the like of heading no. 5404 or 5405, gimped (other than those of heading no. 5606 and gimped horsehair yarn); chenille yarn (including flock chenille yarn); loop wale-yarn	25.57	Mean value of group 56--
5607	Twine, cordage, ropes and cables, whether or not plaited or braided; whether or not impregnated, coated, covered or sheathed with rubber or plastics	34.73	[13]
5608	Twine, cordage or rope; knotted netting, made up fishing nets and other made up nets, of textile materials	23.67	[13]
5609	Articles of yarn, strip or the like of heading no. 5404 or 5405; twine, cordage, rope or cables n.e.c. or included	25.57	Mean value of group 56--
5701	Carpets and other textile floor coverings; knotted, whether or not made up	22.28	[13]
5702	Carpets and other textile floor coverings; woven, (not tufted or flocked), whether or not made up, including kelem, schumacks, karamanie and similar hand-woven rugs	22.28	[13]
5703	Carpets and other textile floor coverings; tufted, whether or not made up	22.97	[13]
5704	Carpets and other textile floor coverings; of felt, (not tufted or flocked), whether or not made up	22.51	Mean value of group 57--
5705	Carpets and other textile floor coverings; n.e.c. in chapter 57, whether or not made up	22.51	Mean value of group 57--
5801	Fabrics; woven pile and chenille fabrics, other than fabrics of heading no. 5802 or 5806	19.72	Mean value of group 58--
5802	Fabrics; terry towelling and similar woven terry fabrics other than narrow fabrics of heading no. 5806; tufted textile fabrics, excluding products of heading no. 5703	17.08	[13]
5803	Gauze; other than narrow fabrics of heading no. 5806	17.08	[13]
5804	Tulles and other net fabrics; not including woven, knitted or crocheted fabrics; lace in the piece, in strips or in motifs, (other than fabrics of headings 60.02 to 60.06)	23.67	[13]
5805	Tapestries; hand-woven, (Gobelins, Flanders, Aubusson, Beauvais and the like) and needle-worked tapestries (e.g. petit point, cross-stitch) whether or not made up	19.72	Mean value of group 58--
5806	Fabrics; narrow woven, other than goods of heading no. 5807; narrow fabrics consisting of warp without weft assembled by means of an adhesive (bolducs)	20.38	[13]
5807	Labels, badges and similar articles; of textile materials, in the piece, in strips or cut to shape or size, not embroidered	19.72	Mean value of group 58--
5808	Braids in the piece; ornamental trimmings in the piece, without embroidery, other than knitted or crocheted; tassels, pompons and similar articles	19.72	Mean value of group 58--
5809	Fabrics, woven; of metal thread and metallised yarn of heading no. 5605, of a kind used in apparel, as furnishing fabrics or similar purposes; n.e.c. or included	19.72	Mean value of group 58--

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
5810	Embroidery; in the piece, in strips or in motifs	20.38	[13]
5811	Quilted textile products; in the piece, composed of one or more layers of textile materials assembled with padding by stitching or otherwise (excluding embroidery of heading no. 5810)	19.72	Mean value of group 58--
5901	Textile fabrics, gum or amylaceous substance coated, used for outer book covers and like; tracing cloth, prepared painting canvas; buckram and similar stiffened textile fabrics used for hat foundation	23.67	[13]
5902	Textile fabrics; tyrecord of high tenacity yarn of nylon or other polyamides polyesters or viscose rayon	23.67	[13]
5903	Textile fabrics impregnated, coated, covered or laminated with plastics, other than those of heading no. 5902	20.85	[13]
5904	Linoleum, whether or not cut to shape; floor coverings consisting of a coating or covering applied on a textile backing, whether or not cut to shape	19.33	[14]
5905	Textile wall coverings	23.67	[13]
5906	Textile fabrics, rubberised; other than those of heading no. 5902	27.83	[13]
5907	Textile fabrics; otherwise impregnated, coated or covered; painted canvas being theatrical scenery, studio back-cloths or the like	23.17	Mean value of group 59--
5908	Textile wicks, woven, plaited or knitted; for lamps, stoves, lighters, candles or the like; incandescent gas mantles and tubular knitted gas mantle fabric therefor, whether or not impregnated	23.17	Mean value of group 59--
5909	Textile hose piping and similar textile tubing; with or without lining, armour or accessories of other materials	23.17	Mean value of group 59--
5910	Textiles; transmission or conveyor belts or belting, of textile material, whether or not impregnated, coated, covered or laminated with plastics, or reinforced with metal or other material	23.17	Mean value of group 59--
5911	Textile products and articles for technical uses; specified in note 7 to this chapter	23.17	Mean value of group 59--
6001	Fabrics; pile fabrics, including long pile fabrics and terry fabrics, knitted or crocheted	19.68	[13]
6002	Fabrics; knitted or crocheted, other than those of heading 60.01, of a width not exceeding 30cm, containing by weight 5% or more of elastomeric yarn or rubber thread	20.52	Mean value of group 59--
6003	Fabrics; knitted or crocheted fabrics, other than those of heading 60.01 and 60.02, of a width not exceeding 30 cm,	21.01	[13]
6004	Fabrics; knitted or crocheted fabrics of a width exceeding 30 cm, other than those of heading 60.01, containing by weight 5% or more of elastomeric yarn or rubber thread	20.52	Mean value of group 59--
6005	Fabrics; warp knit (including those made on galloon knitting machines), other than those of headings 60.01 to 60.04	20.38	[13]
6006	Fabrics; knitted or crocheted fabrics, other than those of headings 60.01 to 60.04	21.01	[13]
6101	Coats; men's or boys' overcoats, car-coats, capes, cloaks, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles; knitted or crocheted, other than those of heading no. 6103	20.38	[13]
6102	Coats; women's or girls' overcoats, car-coats, capes, cloaks, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles, knitted or crocheted, other than those of heading no. 6104	21.01	[13]
6103	Suits, ensembles, jackets, blazers, trousers, bib and brace overalls, breeches, shorts (not swimwear); men's or boys', knitted or crocheted	21.01	[13]
6104	Suits, ensembles, jackets, dresses, skirts, divided skirts, trousers, bib and brace overalls, breeches and shorts (not swimwear), women's or girls', knitted or crocheted	21.01	[13]
6105	Shirts; men's or boys', knitted or crocheted	20.38	[13]
6106	Blouses, shirts and shirt-blouses; women's or girls', knitted or crocheted	20.38	[13]
6107	Underpants, briefs, nightshirts, pyjamas, bathrobes, dressing gowns and similar articles; men's or boys', knitted or crocheted	20.38	[13]
6108	Slips, petticoats, briefs, panties, nightdresses, pyjamas, negligees, bathrobes, dressing gowns and similar articles; women's or girls', knitted or crocheted	20.38	[13]
6109	T-shirts, singlets and other vests; knitted or crocheted	20.38	[13]
6110	Jerseys, pullovers, cardigans, waistcoats and similar articles; knitted or crocheted	21.01	[13]
6111	Garments and clothing accessories, babies'; knitted or crocheted	20.38	[13]
6112	Track suits, ski suits and swimwear; knitted or crocheted	20.38	[13]
6113	Garments made up of knitted or crocheted fabrics of heading no. 5903, 5906 and 5907	20.63	Mean value of group 61--
6114	Garments; knitted or crocheted, n.e.c. in chapter 61	20.38	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
6115	Hosiery; panty hose, tights, stockings, socks and other hosiery, including graduated compression hosiery (for example, stockings for varicose veins) and footwear without applied soles, knitted or crocheted	21.01	[13]
6116	Gloves, mittens and mitts; knitted or crocheted	21.01	[13]
6117	Clothing accessories; made up, knitted or crocheted, knitted or crocheted parts of garments or of clothing accessories	20.63	Mean value of group 61--
6201	Overcoats, car-coats, capes, cloaks, anoraks (including ski-jackets), wind-cheaters, wind-jackets and similar articles, men's or boys', other than those of heading no. 6203 (not knitted or crocheted)	20.38	[13]
6202	Coats; women's or girls' overcoats, carcoats, capes, cloaks, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles, other than those of heading no. 6204 (not knitted or crocheted)	20.38	[13]
6203	Suits, ensembles, jackets, blazers, trousers, bib and brace overalls, breeches and shorts (other than swimwear); men's or boys' (not knitted or crocheted)	20.38	[13]
6204	Suits, ensembles, jackets, dresses, skirts, divided skirts, trousers, bib and brace overalls, breeches and shorts (other than swimwear); women's or girls' (not knitted or crocheted)	20.38	[13]
6205	Shirts; men's or boys' (not knitted or crocheted)	20.38	[13]
6206	Blouses, shirts and shirt-blouses; women's or girls' (not knitted or crocheted)	20.38	[13]
6207	Singlets and other vests, underpants, briefs, night-shirts, pyjamas, bathrobes, dressing gowns and similar articles; men's or boys' (not knitted or crocheted)	20.38	[13]
6208	Singlets and other vests, slips, petticoats, briefs, panties, nightdresses, pyjamas, negligees, bathrobes, dressing gowns and similar articles; women's or girls' (not knitted or crocheted)	20.38	[13]
6209	Garments and clothing accessories; babies' (not knitted or crocheted)	20.38	[13]
6210	Garments made up of fabrics of heading no. 5602, 5603, 5903, 5906 or 5907 (not knitted or crocheted)	20.38	[13]
6211	Track suits, swimwear and other garments (not knitted or crocheted)	20.38	[13]
6212	Brassieres, girdles, corsets, braces, suspenders, garters and similar articles and parts thereof; whether or not knitted or crocheted	20.38	[13]
6213	Handkerchiefs (not knitted or crocheted)	20.38	[13]
6214	Shawls, scarves, mufflers, mantillas, veils and the like (not knitted or crocheted)	21.01	[13]
6215	Ties, bow ties and cravats (not knitted or crocheted)	20.43	[13]
6216	Gloves, mittens and mitts (not knitted or crocheted)	20.43	Mean value of group 62--
6217	Clothing accessories n.e.c.; parts of garments or accessories other than those of heading no. 6212 (not knitted or crocheted)	20.43	Mean value of group 62--
6301	Blankets and travelling rugs	21.01	[13]
6302	Bed linen, table linen, toilet linen and kitchen linen	20.38	[13]
6303	Curtains (including drapes) and interior blinds; curtain or bed valances	20.38	[13]
6304	Furnishing articles; excluding those of heading no. 9404	20.38	[13]
6305	Sacks and bags, of a kind used for the packing of goods	21.16	Mean value of group 63--
6306	Tarpaulins, awnings and sunblinds; tents; sails for boats, sailboards or landcraft; camping goods	23.67	[13]
6307	Textiles; made up articles n.e.c. in chapter 63, including dress patterns	21.16	Mean value of group 63--
6308	Textiles; sets of woven fabric and yarn, with or without accessories, for making into rugs, tapestries, embroidered tablecloths, serviettes and similar textile articles, in packings for retail sale	21.16	Mean value of group 63--
6309	Textiles; worn clothing and other worn articles	21.16	Mean value of group 63--
6310	Rags; used or new, scrap twine, cordage, rope and cables and worn out articles of twine, cordage, rope or cables, of textile materials	21.16	Mean value of group 63--
6401	Footwear; waterproof, with outer soles and uppers of rubber or plastics, (uppers not fixed to the sole nor assembled by stitch, rivet, nail, screw, plug or similar)	33.23	[13]
6402	Footwear; with outer soles and uppers of rubber or plastics (excluding waterproof footwear)	33.23	[13]
6403	Footwear; with outer soles of rubber, plastics, leather or composition leather and uppers of leather	33.23	[13]
6404	Footwear; with outer soles of rubber, plastics, leather or composition leather and uppers of textile materials	33.23	[13]
6405	Footwear; other footwear n.e.c. in chapter 64	33.23	[13]
6406	Footwear; parts of footwear; removable in-soles, heel cushions and similar articles; gaiters, le.g.ings and similar articles, and parts thereof	33.23	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
5810	Embroidery; in the piece, in strips or in motifs	20.38	[13]
5811	Quilted textile products; in the piece, composed of one or more layers of textile materials assembled with padding by stitching or otherwise (excluding embroidery of heading no. 5810)	19.72	Mean value of group 58--
5901	Textile fabrics, gum or amylaceous substance coated, used for outer book covers and like; tracing cloth, prepared painting canvas; buckram and similar stiffened textile fabrics used for hat foundation	23.67	[13]
5902	Textile fabrics; tyrecord of high tenacity yarn of nylon or other polyamides polyesters or viscose rayon	23.67	[13]
5903	Textile fabrics impregnated, coated, covered or laminated with plastics, other than those of heading no. 5902	20.85	[13]
5904	Linoleum, whether or not cut to shape; floor coverings consisting of a coating or covering applied on a textile backing, whether or not cut to shape	19.33	[14]
5905	Textile wall coverings	23.67	[13]
5906	Textile fabrics, rubberised; other than those of heading no. 5902	27.83	[13]
5907	Textile fabrics; otherwise impregnated, coated or covered; painted canvas being theatrical scenery, studio back-cloths or the like	23.17	Mean value of group 59--
5908	Textile wicks, woven, plaited or knitted; for lamps, stoves, lighters, candles or the like; incandescent gas mantles and tubular knitted gas mantle fabric therefor, whether or not impregnated	23.17	Mean value of group 59--
5909	Textile hose piping and similar textile tubing; with or without lining, armour or accessories of other materials	23.17	Mean value of group 59--
5910	Textiles; transmission or conveyor belts or belting, of textile material, whether or not impregnated, coated, covered or laminated with plastics, or reinforced with metal or other material	23.17	Mean value of group 59--
5911	Textile products and articles for technical uses; specified in note 7 to this chapter	23.17	Mean value of group 59--
6001	Fabrics; pile fabrics, including long pile fabrics and terry fabrics, knitted or crocheted	19.68	[13]
6002	Fabrics; knitted or crocheted, other than those of heading 60.01, of a width not exceeding 30cm, containing by weight 5% or more of elastomeric yarn or rubber thread	20.52	Mean value of group 59--
6003	Fabrics; knitted or crocheted fabrics, other than those of heading 60.01 and 60.02, of a width not exceeding 30 cm,	21.01	[13]
6004	Fabrics; knitted or crocheted fabrics of a width exceeding 30 cm, other than those of heading 60.01, containing by weight 5% or more of elastomeric yarn or rubber thread	20.52	Mean value of group 59--
6005	Fabrics; warp knit (including those made on galloon knitting machines), other than those of headings 60.01 to 60.04	20.38	[13]
6006	Fabrics; knitted or crocheted fabrics, other than those of headings 60.01 to 60.04	21.01	[13]
6101	Coats; men's or boys' overcoats, car-coats, capes, cloaks, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles; knitted or crocheted, other than those of heading no. 6103	20.38	[13]
6102	Coats; women's or girls' overcoats, car-coats, capes, cloaks, anoraks, ski-jackets, wind-cheaters, wind-jackets and similar articles, knitted or crocheted, other than those of heading no. 6104	21.01	[13]
6103	Suits, ensembles, jackets, blazers, trousers, bib and brace overalls, breeches, shorts (not swimwear); men's or boys', knitted or crocheted	21.01	[13]
6104	Suits, ensembles, jackets, dresses, skirts, divided skirts, trousers, bib and brace overalls, breeches and shorts (not swimwear), women's or girls', knitted or crocheted	21.01	[13]
6105	Shirts; men's or boys', knitted or crocheted	20.38	[13]
6106	Blouses, shirts and shirt-blouses; women's or girls', knitted or crocheted	20.38	[13]
6107	Underpants, briefs, nightshirts, pyjamas, bathrobes, dressing gowns and similar articles; men's or boys', knitted or crocheted	20.38	[13]
6108	Slips, petticoats, briefs, panties, nightdresses, pyjamas, negligees, bathrobes, dressing gowns and similar articles; women's or girls', knitted or crocheted	20.38	[13]
6109	T-shirts, singlets and other vests; knitted or crocheted	20.38	[13]
6110	Jerseys, pullovers, cardigans, waistcoats and similar articles; knitted or crocheted	21.01	[13]
6111	Garments and clothing accessories, babies'; knitted or crocheted	20.38	[13]
6112	Track suits, ski suits and swimwear; knitted or crocheted	20.38	[13]
6113	Garments made up of knitted or crocheted fabrics of heading no. 5903, 5906 and 5907	20.63	Mean value of group 61--
6114	Garments; knitted or crocheted, n.e.c. in chapter 61	20.38	[13]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
6904	Ceramic building bricks, floor blocks, support or filler tiles and the like	0.14	[2]
6905	Roofing tiles, chimney-pots, cowls, chimney liners, architectural ornaments and other ceramic constructional goods	0.14	[2]
6906	Ceramic pipes, conduits, guttering and pipe fittings	0.14	[2]
6907	Ceramic flags and paving, hearth or wall tiles, unglazed; unglazed ceramic mosaic cubes and the like, whether or not on a backing	0.14	[2]
6908	Ceramic flags and paving, hearth or wall tiles, glazed; glazed ceramic mosaic cubes and the like, whether or not on a backing	0.14	[2]
6909	Ceramic ware for laboratory, chemical, other technical uses; ceramic troughs, tubs, similar receptacles used in agriculture; ceramic pots, jars and similar used in the conveyance or packing of goods	0.14	[2]
6910	Ceramic sinks, wash basins, wash basin pedestals, baths, bidets, water closet pans, flushing cisterns, urinals and similar sanitary fixtures	0.14	[2]
6911	Tableware, kitchenware, other household articles and toilet articles; of porcelain or china	0.14	[2]
6912	Ceramic tableware, kitchenware, other household articles and toilet articles; other than of porcelain or china	0.14	[2]
6913	Statuettes and other ornamental ceramic articles	0.14	[2]
6914	Ceramic articles; n.e.c. in chapter 69	0.14	[2]
7001	Glass; cullet and other waste and scrap of glass, glass in the mass	0.14	[2]
7002	Glass in balls (other than microspheres of heading no. 7018), rods or tubes, unworked	0.14	[2]
7003	Glass; cast glass and rolled glass in sheets or profiles, whether or not having an absorbent, reflecting or non-reflecting layer, but not otherwise worked	0.14	[2]
7004	Glass; drawn glass and blown glass, in sheets, whether or not having an absorbent, reflecting or non-reflecting layer, but not otherwise worked	0.14	[2]
7005	Glass; float glass and surface ground or polished glass, in sheets, whether or not having an absorbent, reflecting or non-reflecting layer, but not otherwise worked	0.14	[2]
7006	Glass of heading no. 7003, 7004 or 7005, bent, edge-worked, engraved, drilled, enamelled or otherwise worked, not framed or fitted with other materials	0.14	[2]
7007	Safety glass, consisting of toughened (tempered) or laminated glass	0.14	[2]
7008	Glass; multiple-walled insulating units of glass	0.14	[2]
7009	Glass mirrors; whether or not framed, including rear-view mirrors	0.14	[2]
7010	Carboys, bottles, flasks, jars, pots, phials, ampoules, containers of glass of a kind used for the conveyance or packing of goods; preserving jars of glass; stoppers, lids and other closures of glass	0.14	[2]
7011	Glass envelopes (including bulbs and tubes), open and glass parts thereof, without fittings, for electric lamps, cathode-ray tubes or the like	0.14	[2]
7013	Glassware of a kind used for table, kitchen, toilet, office, indoor decoration or similar purposes (other than of heading no. 7010 or 7018)	0.14	[2]
7014	Signalling glassware and optical elements of glass (other than those of heading no. 7015), not optically worked	0.14	[2]
7015	Clock, watch and similar glasses, glasses for non-corrective or corrective spectacles, curved, bent, hallowed etc, not optically worked; hollow glass spheres and their segments for manufacture	0.14	[2]
7016	Glass; paving blocks, slabs, bricks, tiles etc, of pressed, moulded glass, whether or not wired, glass smallwares for decorative purposes leaded lights and the like; multicellular or foam glass	0.14	[2]
7017	Laboratory, hygienic or pharmaceutical glassware, whether or not graduated or calibrated	0.14	[2]
7018	Glass beads, imitation pearls, precious or semi-precious stones and similar glass smallwares, statuettes and other ornaments of worked glass; glass microspheres not exceeding 1mm in diameter	0.14	[2]
7019	Glass fibres (including glass wool) and articles thereof (e.g. yarn, woven fabrics)	0.14	[2]
7020	Glass; articles n.e.c. in chapter 70	0.14	[2]
7101	Pearls; natural or cultured, whether or not worked or graded but not strung, mounted or set; pearls, natural or cultured, temporarily strung for the convenience of transport	0.00	-
7102	Diamonds, whether or not worked, but not mounted or set	0.00	-
7103	Precious (excluding diamond) and semi-precious stone; worked, graded, not strung, mounted, set; ungraded precious (excluding diamond) and semi-precious stone, temporarily strung for convenience of transport	0.00	-
7104	Synthetic, reconstructed precious, semi-precious stone worked, graded or not, not strung or mounted, set; ungraded synthetic, reconstructed precious, semi-precious stones, temporarily strung for transport	0.00	-

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
7105	Dust and powder of natural or synthetic precious or semi-precious stone	0.00	-
7106	Silver (including silver plated with gold or platinum); unwrought or in semi-manufactured forms, or in powder form	0.00	-
7107	Base metals clad with silver; not further worked than semi-manufactured	0.00	-
7108	Gold (including gold plated with platinum) unwrought or in semi-manufactured forms, or in powder form	0.00	-
7109	Base metals or silver, clad with gold, not further worked than semi-manufactured	0.00	-
7110	Platinum; unwrought or in semi-manufactured forms, or in powder form	0.00	-
7111	Base metals, silver or gold, clad with platinum; not further worked than semi-manufactured	0.00	-
7112	Waste and scrap of precious metal or of metal clad with precious metal; other waste and scrap containing precious metal compounds, of a kind uses principally for the recovery of precious metal	0.00	-
7113	Jewellery articles and parts thereof, of precious metal or of metal clad with precious metal	0.00	-
7114	Articles of goldsmiths' or silversmiths' wares and parts thereof, of precious metal or of metal clad with precious metal	0.00	-
7115	Articles of precious metal or of metal clad with precious metal	0.00	-
7116	Articles of natural or cultured pearls, precious or semi-precious stones (natural, synthetic or reconstructed)	0.00	-
7117	Imitation jewellery	0.00	-
7118	Coin	0.00	-
7201	Pig iron and spiegeleisen in pigs, blocks or other primary forms	8.00	[4]
7202	Ferro-alloys	8.00	[4]
7203	Ferrous products obtained by direct reduction of iron ore and other spongy ferrous products, in lumps, pellets or the like; iron having a minimum purity of 99.94%, in lumps, pellets or similar forms	8.00	[4]
7204	Ferrous waste and scrap; remelting scrap ingots of iron or steel	8.00	[4]
7205	Granules and powders, of pig iron, spiegeleisen, iron or steel	8.00	[4]
7206	Iron and non-alloy steel in ingots or other primary forms (excluding iron of heading no. 7203)	8.00	[4]
7207	Iron or non-alloy steel; semi-finished products thereof	8.00	[4]
7208	Iron or non-alloy steel; flat-rolled products of a width of 600mm or more, hot-rolled, not clad, plated or coated	8.00	[4]
7209	Iron or non-alloy steel; flat-rolled products, width 600mm or more, cold-rolled (cold-reduced), not clad, plated or coated	8.00	[4]
7210	Iron or non-alloy steel; flat-rolled products, width 600mm or more, clad, plated or coated	8.00	[4]
7211	Iron or non-alloy steel; flat-rolled products, width less than 600mm, not clad, plated or coated	8.00	[4]
7212	Iron or non-alloy steel; flat-rolled products, width less than 600mm, clad, plated or coated	8.00	[4]
7213	Iron or non-alloy steel; bars and rods, hot-rolled, in irregularly wound coils	8.00	[4]
7214	Iron or non-alloy steel; bars and rods, not further worked than forged, hot-rolled, hot drawn or hot-extruded, but including those twisted after rolling	8.00	[4]
7215	Iron or non-alloy steel; bars and rods, n.e.c. in chapter 72	8.00	[4]
7216	Iron or non-alloy steel, angles, shapes and sections	8.00	[4]
7217	Wire of iron or non-alloy steel	8.00	[4]
7218	Stainless steel in ingots or other primary forms; semi-finished products of stainless steel	6.75	[4]
7219	Stainless steel; flat-rolled products of width of 600mm or more	6.75	[4]
7220	Stainless steel; flat-rolled products of width less than 600mm	6.75	[4]
7221	Stainless steel bars and rods, hot-rolled, in irregularly wound coils	6.75	[4]
7222	Stainless steel bars and rods, angles, shapes and sections	6.75	[4]
7223	Stainless steel wire	6.75	[4]
7224	Alloy steel in ingots or other primary forms, semi-finished products of other alloy steel	6.75	[4]
7225	Alloy steel flat-rolled products, of a width 600mm or more	6.75	[4]
7226	Alloy steel flat-rolled products, of a width of less than 600mm	6.75	[4]
7227	Steel, alloy; bars and rods, hot-rolled, in irregularly wound coils	6.75	[4]
7228	Alloy steel bars, rods, shapes and sections; hollow drill bars and rods, of alloy or non-alloy steel	6.75	[4]
7229	Wire of other alloy steel	6.75	[4]
7301	Iron or steel sheet piling, whether or not drilled, punched or made from assembled elements; welded angles, shapes and sections, of iron or steel	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
7302	Railway or tramway track constructions of iron or steel; rails, check and track rails, switch blades, crossing frogs, point rods, sleepers, fish-plates, chair wedges, sole plates, bedplates, ties and the like	6.75	[4]
7303	Tubes, pipes and hollow profiles, of cast iron	8.00	[4]
7304	Tubes, pipes and hollow profiles, seamless, of iron (other than cast iron) or steel	8.00	[4]
7305	Iron or steel (excluding cast iron); tubes and pipes (e.g. welded, riveted or similarly closed), having circular cross-sections, external diameter of which exceeds 406.4mm, not seamless	8.00	[4]
7306	Iron or steel (excluding cast iron); tubes, pipes and hollow profiles (not seamless), n.e.c. in chapter 73	8.00	[4]
7307	Tube or pipe fittings (e.g. couplings, elbows, sleeves), of iron or steel	8.00	[4]
7308	Structures of iron or steel and parts thereof; plates, rods, angles, shapes, sections, tubes and the like, prepared for use in structures	8.00	[4]
7309	Reservoirs, tanks, vats and similar containers; for any material (excluding compressed or liquefied gas), of iron or steel, capacity exceeding 300l, whether or not lined or heat insulated	8.00	[4]
7310	Tanks, casks, drums, cans, boxes and similar containers, for any material (excluding compressed or liquefied gas), of iron or steel, capacity not exceeding 300l, whether or not lined or heat-insulated	8.00	[4]
7311	Containers for compressed or liquefied gas, of iron or steel	8.00	[4]
7312	Stranded wire, ropes, cables, plaited bands, slings and the like, of iron or steel, not electrically insulated	8.00	[4]
7313	Barbed wire of iron or steel; twisted hoop or single flat wire, barbed or not and loosely twisted double wire, of a kind used for fencing, of iron or steel	8.00	[4]
7314	Cloth (including endless bands), grill, netting and fencing, of iron or steel wire; expanded metal of iron or steel	8.00	[4]
7315	Chain and parts thereof, of iron or steel	8.00	[4]
7316	Anchors, grapnels and parts thereof, of iron or steel	8.00	[4]
7317	Nails, tacks, drawing pins, corrugated nails, staples (not those of heading no. 8305) and the like, of iron or steel, with heads of other material or not, but excluding articles with heads of copper	8.00	[4]
7318	Screws, bolts, nuts, coach screws, screw hooks, rivets, cotters, cotter-pins, washers (including spring washers) and similar articles, of iron or steel	8.00	[4]
7319	Sewing and knitting needles, bodkins, crochet hooks, embroidery stilettos and similar articles, for use in the hand, of iron or steel; safety pins and other pins of iron or steel, not elsewhere specified or included	8.00	[4]
7320	Springs and leaves for springs, of iron or steel	8.00	[4]
7321	Stoves, ranges, grates, cookers (those with subsidiary boilers for central heating), barbecues, braziers, gas-rings, plate warmers and similar non-electric domestic appliances and parts, of iron or steel	8.00	[4]
7322	Radiators for central heating, not electrically heated and parts thereof, of iron or steel; air heaters, hot air distributors not electrically heated, with motor fan or blower	8.00	[4]
7323	Table, kitchen, other household articles and parts, of iron or steel; iron or steel wool; pot scourers and scouring or polishing pads, gloves and the like, of iron or steel	8.00	[4]
7324	Sanitary ware and parts thereof, of iron or steel	8.00	[4]
7325	Iron or steel; cast articles	8.00	[4]
7326	Iron or steel; articles, n.e.c. in chapter 73	8.00	[4]
7401	Copper mattes; cement copper (precipitated copper)	2.11	[4]
7402	Copper; unrefined, copper anodes for electrolytic refining	2.11	[4]
7403	Copper; refined and copper alloys, unwrought	2.11	[4]
7404	Copper; waste and scrap	2.11	[4]
7405	Copper; master alloys	2.11	[4]
7406	Copper; powders and flakes	2.11	[4]
7407	Copper; bars, rods and profiles	2.11	[4]
7408	Copper wire	2.11	[4]
7409	Copper plates, sheets and strip; of a thickness exceeding 0.15mm	2.11	[4]
7410	Copper foil (whether or not printed or backed with paper, paperboard, plastics or similar backing materials) of a thickness (excluding any backing) not exceeding 0.15mm	2.11	[4]
7411	Copper tubes and pipes	2.11	[4]
7412	Copper; tube or pipe fittings (e.g. couplings, elbows, sleeves)	2.11	[4]
7413	Copper; stranded wire, cables, plaited bands and the like, not electrically insulated	2.11	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
7415	Copper, nails, tacks, drawing pins, staples (not those of heading no. 8305) and the like, of copper or iron or steel with heads of copper; screws bolts, nuts, screws hooks, rivets, cotters, washers	2.11	[4]
7418	Copper; table, kitchen or other household articles and parts thereof; pot scourers, scouring, polishing pads, gloves and the like; sanitary ware and parts thereof	2.11	[4]
7419	Copper; articles thereof n.e.c. in chapter 74	2.11	[4]
7501	Nickel mattes; nickel oxide sinters and other intermediate products of nickel metallurgy	3.96	[4]
7502	Nickel; unwrought	3.96	[4]
7503	Nickel; waste and scrap	3.96	[4]
7504	Nickel; powders and flakes	3.96	[4]
7505	Nickel; bars, rods, profiles and wire	3.96	[4]
7506	Nickel; plates, sheets, strip and foil	3.96	[4]
7507	Nickel; tubes, pipes and tube or pipe fittings (e.g. couplings, elbows, sleeves)	3.96	[4]
7508	Nickel; articles thereof n.e.c. in chapter 75	3.96	[4]
7601	Aluminium; unwrought	32.80	[4]
7602	Aluminium; waste and scrap	32.80	[4]
7603	Aluminium; powders and flakes	32.80	[4]
7604	Aluminium; bars, rods and profiles	32.80	[4]
7605	Aluminium wire	32.80	[4]
7606	Aluminium; plates, sheets and strip, thickness exceeding 0.2mm	32.80	[4]
7607	Aluminium foil (whether or not printed or backed with paper, paperboard, plastics or similar backing materials) of a thickness (excluding any backing) not exceeding 0.2mm	32.80	[4]
7608	Aluminium; tubes and pipes	32.80	[4]
7609	Aluminium; tube or pipe fittings (e.g. couplings, elbows, sleeves)	32.80	[4]
7610	Aluminium; structures (excluding prefabricated buildings of heading no. 9406) and parts (e.g. bridges and sections, towers, lattice masts, etc) plates, rods, profiles and tubes for structures	32.80	[4]
7611	Aluminium; reservoirs, tanks, vats and the like for material (not compressed or liquefied gas) of capacity over 300l, whether or not lined, heat-insulated, not fitted with mechanical, thermal equipment	32.80	[4]
7612	Aluminium casks, drums, cans, boxes etc (including rigid, collapsible tubular containers), for materials other than compressed, liquefied gas, 300l capacity or less, lined, heat-insulated or not	32.80	[4]
7613	Aluminium; containers for compressed or liquefied gas	32.80	[4]
7614	Aluminium; stranded wire, cables, plaited bands and the like, (not electrically insulated)	32.80	[4]
7615	Aluminium; table, kitchen or other household articles and parts thereof, pot scourers and scouring or polishing pads, gloves and the like, sanitary ware and parts thereof	32.80	[4]
7616	Aluminium; articles n.e.c. in chapter 76	32.80	[4]
7801	Lead; unwrought	1.12	[4]
7802	Lead; waste and scrap	1.12	[4]
7804	Lead; plates, sheets, strip and foil, lead powders and flakes	1.12	[4]
7806	Lead; articles n.e.c. in chapter 78	1.12	[4]
7901	Zinc; unwrought	5.18	[4]
7902	Zinc; waste and scrap	5.18	[4]
7903	Zinc; dust, powders and flakes	5.18	[4]
7904	Zinc; bars, rods, profiles and wire	5.18	[4]
7905	Zinc; plates, sheets, strip and foil	5.18	[4]
7907	Zinc; articles n.e.c. in chapter 79	5.18	[4]
8001	Tin; unwrought	4.59	[4]
8002	Tin; waste and scrap	4.59	[4]
8003	Tin; bars, rods, profiles and wire	4.59	[4]
8007	Tin; articles n.e.c. in chapter 80	4.59	[4]
8101	Tungsten (wolfram); articles thereof, including waste and scrap	4.50	[1]
8102	Molybdenum; articles thereof, including waste and scrap	7.61	[1]
8103	Tantalum; articles thereof, including waste and scrap	2.20	[1]
8104	Magnesium; articles thereof, including waste and scrap	26.08	[1]
8105	Cobalt; mattes and other intermediate products of cobalt metallurgy, cobalt and articles thereof, including waste and scrap	4.50	[1]
8106	Bismuth; articles thereof, including waste and scrap	1.31	[1]
8107	Cadmium; articles thereof, including waste and scrap	2.61	[1]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8108	Titanium; articles thereof, including waste and scrap	18.94	[1]
8109	Zirconium; articles thereof, including waste and scrap	8.61	[1]
8110	Antimony; articles thereof, including waste and scrap	3.58	[1]
8111	Manganese; articles thereof, including waste and scrap	8.78	[1]
8112	Beryllium, chromium, germanium, vanadium, gallium, hafnium, indium, niobium (columbium), rhenium and thallium; and articles of these metals, including waste and scrap	5.49	[1]
8113	Cermets; articles thereof, including waste and scrap	7.85	Mean value of group 81--
8201	Tools, hand; spades, shovels, mattocks, picks, hoes, forks, rakes; axes, bill hooks etc; secateurs and pruners of any kind; scythes, sickles, hay knives, hedge shears, timber wedges and other tools used in agriculture, horticulture, forestry	6.75	[4]
8202	Tools, hand; saws and blades for saws of all kinds (including slitting, slotting or toothless blades)	6.75	[4]
8203	Tools, hand; files, rasps, pliers (including cutting pliers), pincers, tweezers, metal cutting shears, pipe cutters, bolt croppers, perforating punches and similar	6.75	[4]
8204	Tools, hand; hand-operated spanners and wrenches (including torque meter wrenches but not including tap wrenches), interchangeable spanner sockets, with or without handles	6.75	[4]
8205	Tools, hand; (including glaziers' diamonds) n.e.c.; blow lamps; vices, clamps etc, other than accessories for and parts of, machine tools; anvils; portable forges; hand or pedal operated grinding wheels with frameworks	6.75	[4]
8206	Tools, hand; two or more of heading no. 8202 to 8205, put up in sets for retail sale	6.75	[4]
8207	Tools, interchangeable; for hand tools, whether or not power-operated, or for machine tools (pressing, stamping, punching, drilling etc), including dies for drawing or extruding metal, and rock drilling or earth boring tools	6.75	[4]
8208	Knives and cutting blades, for machines or for mechanical appliances	6.75	[4]
8209	Tools; plates, sticks, tips and the like for tools, unmounted, of sintered metal carbides or cermets	6.75	[4]
8210	Tools; hand-operated mechanical appliances, weighing 10kg or less, used in the preparation, conditioning or serving of food or drink	6.75	[4]
8211	Knives; with cutting blades, serrated or not (including pruning knives), other than knives of heading no. 8208, and blades therefore	6.75	[4]
8212	Razors and razor blades; (including razor blade blanks in strips)	6.75	[4]
8213	Scissors; tailors' shears and similar shears, and blades therefore	6.75	[4]
8214	Cutlery; other articles, (e.g. hair clippers, butchers' or kitchen cleavers, choppers and mincing knives, paper knives), manicure or pedicure sets and instruments (including nail files)	6.75	[4]
8215	Cutlery; spoons, forks, ladles, skimmers, cake-servers, fish-knives, butter knives, sugar tongs and similar kitchen or tableware	6.75	[4]
8301	Padlocks and locks (key, combination, electrically operated) of base metal; clasps and frames with clasps incorporating locks, of base metal, keys for any or the foregoing articles, of base metal	6.75	[4]
8302	Base metal mountings, fittings and similar articles for furniture, doors, staircases, windows, trunks, chests etc, castors with mountings of base metal, automatic door closers of base metal	6.75	[4]
8303	Safes; armoured or reinforced, strong-boxes, doors and safe deposit lockers for strong-rooms, cash or deed boxes and the like, of base metal	6.75	[4]
8304	Office equipment; filing cabinets, card-index cabinets, paper trays and rests, pen trays, office-stamp stands and the like, of base metal, other than office furniture of heading no. 9403	6.75	[4]
8305	Stationery; fittings for loose-leaf binders or files, letter clips, letter corners, paper clips, indexing tags and the like, staples in strips (for offices, upholstery, packaging), of base metal	6.75	[4]
8306	Bells, gongs and the like; non-electric, statuettes, other ornaments, photograph, picture, similar frames, mirrors, of base metal	6.75	[4]
8307	Tubing; flexible, with or without fittings, of base metal	6.75	[4]
8308	Clasps; frames with clasps, buckles, hooks, eyes, eyelets etc used for clothing, footwear, awnings, handbags, travel goods or other articles, tubular, bifurcated rivets, beads, spangles, of base metal	6.75	[4]
8309	Stoppers, caps, lids (including crown corks, screw caps, pouring stoppers); capsules for bottles, threaded bungs, bung covers, seals and other packaging accessories, of base metal	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8310	Sign plates, name plates, address plates and similar plates, numbers, letters and other symbols, of base metal, excluding those of heading no. 9405	6.75	[4]
8311	Wires, rods, tubes, plates, electrodes of base metal or metal carbides; of a kind used for soldering, brazing, welding; wires and rods for metal spraying	6.75	[4]
8401	Nuclear reactors; fuel elements (cartridges), non-irradiated, for nuclear reactors, machinery and apparatus for isotopic separation	6.75	[4]
8402	Boilers; steam or other vapour generating (other than central heating hot water boilers, capable also of producing low pressure steam), super heated water boilers	6.75	[4]
8403	Central heating boilers; excluding those of heading no. 8402	6.75	[4]
8404	Auxiliary plant for use with boilers of heading no. 8402 or 8403; e.g. economisers, super-heaters, soot removers, gas recoverers), condensers for steam or other vapour power units	6.75	[4]
8405	Generators for producer or water gas with or without their purifiers acetylene gas generators and similar water process gas generators, with or without their purifiers	6.75	[4]
8406	Turbines; steam and other vapour turbines	6.75	[4]
8407	Reciprocating or rotary internal combustion piston engines	6.75	[4]
8408	Compression-ignition internal combustion piston engines (diesel or semi-diesel engines)	6.75	[4]
8409	Parts suitable for use solely or principally with the engines of heading no. 8407 or 8408	6.75	[4]
8410	Turbines; hydraulic water wheels and regulators therefor	7.06	Mean value of group 84--
8411	Turbo-jets, turbo-propellers and other gas turbines	32.80	[4]
8412	Engines and motors; n.e.c. (e.g. reaction engines, hydraulic power engines, pneumatic power engines)	6.75	[4]
8413	Pumps; for liquids, whether or not fitted with measuring device, liquid elevators	6.75	[4]
8414	Air or vacuum pumps, air or other gas compressors and fans; ventilating or recycling hoods incorporating a fan whether or not fitted with filters	6.75	[4]
8415	Air conditioning machines; comprising a motor driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated	6.75	[4]
8416	Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical grates, mechanical ash dischargers and similar appliances	6.75	[4]
8417	Furnaces and ovens; industrial or laboratory, including incinerators, non-electric	6.75	[4]
8418	Refrigerators, freezers and other refrigerating or freezing equipment, electric or other; heat pumps other than air conditioning machines of heading no. 8415	6.75	[4]
8419	Machinery, plant (not domestic), or laboratory equipment; electrically heated or not, (excluding items in 85.14) for the treatment of materials by a process involving change of temperature; including instantaneous or non electric storage water heaters	6.75	[4]
8420	Machines; calendering or other rolling machines, for other than metal or glass and cylinders therefor	6.75	[4]
8421	Centrifuges, including centrifugal dryers; filtering or purifying machinery and apparatus for liquids or gases	6.75	[4]
8422	Dish washing machines; machinery for cleaning, drying, filling, closing, sealing, capsuling or labelling bottles, cans, boxes, bags, etc, machinery for aerating beverages	6.75	[4]
8423	Weighing machines; excluding balances of a sensitivity of 5cg or better, including weight operated counting or checking machines and weights of all kinds	6.75	[4]
8424	Mechanical appliances for projecting, dispersing or spraying liquids or powders; fire extinguishers, spray guns, steam, sand blasting machines	6.75	[4]
8425	Pulley tackle and hoists other than skip hoists; winches and capstans; jacks	6.75	[4]
8426	Derricks, cranes, including cable cranes, mobile lifting frames, straddle carriers and works trucks fitted with a crane	6.75	[4]
8427	Fork-lift and other works trucks; fitted with lifting or handling equipment	6.75	[4]
8428	Lifting, handling, loading or unloading machinery; n.e.c. in heading no. 8425, 8426 or 8427 (e.g. lifts, escalators, conveyors, teleferics)	6.75	[4]
8429	Bulldozers, graders, levellers, scrapers, angledozers, mechanical shovels, excavators, shovel loaders, tamping machines and road rollers, self-propelled	6.75	[4]
8430	Moving, grading, levelling, scraping, excavating, tamping, compacting, extracting or boring machinery, for earth, minerals, or ores; pile drivers and extractors; snow ploughs and snow blowers	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8431	Machinery parts; used solely or principally with the machinery of heading no. 8425 to 8430	6.75	[4]
8432	Agricultural, horticultural or forestry machinery for soil preparation or cultivation; lawn or sports-ground rollers	6.75	[4]
8433	Harvesting and threshing machinery, straw and fodder balers, grass or hay mowers; machines for cleaning, sorting or grading eggs, fruit or other agricultural produce, other than machinery of heading no 8437	6.75	[4]
8434	Milking machines and dairy machinery	6.75	[4]
8435	Presses, crushers and similar machinery; used in the manufacture of wine, cider, fruit juices or similar beverages	6.75	[4]
8436	Agricultural, horticultural, forestry, poultry-keeping, bee-keeping machinery; including germination plant fitted with mechanical or thermal equipment; poultry incubators and brooders	6.75	[4]
8437	Machines for cleaning, sorting, grading seed, grain, dried leguminous vegetables; machinery used in the milling industry for the working of cereals or dried leguminous vegetables, not farm type machinery	6.75	[4]
8438	Machinery n.e.c. in this chapter, for the industrial preparation or manufacture of food or drink; other than machinery for extraction or preparation of animal or fixed vegetable fats or oils	6.75	[4]
8439	Machinery; for making pulp of fibrous cellulosic material, or for making or finishing paper or paperboard	6.75	[4]
8440	Book-binding machinery; including book-sewing machines	6.75	[4]
8441	Machines; for making up paper pulp, paper or paperboard, including cutting machines of all kinds	6.75	[4]
8442	Machinery, apparatus and equipment (excluding machine-tools of heading no. 8456 to 8465) for preparing or making printing components; plates, cylinders and other printing components; lithographic stones prepared for printing purposes	6.75	[4]
8443	Printing machinery; used for printing by means of plates, cylinders and other printing components of heading 84.42; other printers, copying machines and facsimile machines, whether or not combined; parts and accessories thereof	6.75	[4]
8444	Textile machinery; for extruding, drawing, texturing or cutting man-made textile materials	6.75	[4]
8445	Textile machinery; spinning, doubling, twisting machines, textile reeling or winding machines and machines for preparing textile yarns for use on machines of heading no. 8446 and 8447	6.75	[4]
8446	Weaving machines (looms)	6.75	[4]
8447	Knitting machines, stitch-bonding machines and machines for making gimped yarn, tulle, lace, embroidery, trimmings, braid or net and machines for tufting	6.75	[4]
8448	Machinery, auxiliary; for use with machines of heading no. 8444 to 8447 (e.g. dobbies, jacquards, automatic stop motions, shuttle changing mechanisms) parts, accessories for machines of heading no. 8444, 8447	6.75	[4]
8449	Machinery; for manufacture or finishing felt or non-wovens in the piece or in shapes, including machinery for making felt hats, blocks for making hats	6.75	[4]
8450	Household or laundry-type washing machines; including machines which both wash and dry	6.75	[4]
8451	Machinery (not of heading no. 8450) for washing, cleaning, wringing, drying, ironing, pressing, bleaching, dyeing, dressing, finishing, coating or impregnating textile yarn, fabrics or made up articles	6.75	[4]
8452	Sewing machines; other than book-sewing machines of heading no. 8440; furniture, bases and covers specially designed for sewing machines; sewing machine needles	6.75	[4]
8453	Machinery for preparing, tanning or working hides, skins or leather or for making or repairing footwear or other articles of hides, skins or leather, other than sewing machines	6.75	[4]
8454	Converters, ladles, ingot moulds and casting machines; of a kind used metallurgy or in metal foundries	6.75	[4]
8455	Metal-rolling mills and rolls therefor	6.75	[4]
8456	Machine-tools; for working any material by removal of material, by laser or other light or photon beam, ultrasonic, electro-discharge, electro-chemical, electron beam, ionic-beam, or plasma arc processes; water-jet cutting machines	6.75	[4]
8457	Machining centres, unit construction machines (single station) and multi-station transfer machines for working metal	6.75	[4]
8458	Lathes for removing metal	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8459	Machine-tools; (including way-type unit head machines) for drilling, boring, milling, threading or tapping by removing metal, other than lathes of heading no. 8458	6.75	[4]
8460	Machine-tools; for deburring, sharpening, grinding, honing, lapping, polishing or otherwise finishing metal, sintered metal carbides or cermets by means of grinding stones, abrasives or polishing products	6.75	[4]
8461	Machine-tools; for planing, shaping, slotting, broaching, gear cutting and grinding, finishing, sawing, cutting off and other tools working by removing metal, sintered metal carbides or cermets n.e.c.	6.75	[4]
8462	Machine-tools; (including presses) for working metal by forging, hammering or die-stamping, for bending, folding, straightening, flattening, shearing or punching metal	6.75	[4]
8463	Machine-tools; n.e.c. for working metal, sintered metal carbides or cermets without removing material	6.75	[4]
8464	Machine-tools; for working stone, ceramics, concrete, asbestos-cement or like mineral materials or for cold working glass	6.75	[4]
8465	Machine-tools; (including machines for nailing, stapling, glueing or otherwise assembling) for working wood, cork, bone, hard plastics or rubber or similar hard materials	6.75	[4]
8466	Machine-tools; parts and accessories suitable for use solely or principally with the machines of headings 8456 to 8465, and tool holders for any type of tool for working in the hand	6.75	[4]
8467	Tools; for working in the hand, pneumatic, hydraulic or with self-contained electric or non-electric motor	6.75	[4]
8468	Machinery and apparatus for soldering, brazing, welding, whether or not capable of cutting, other than those of heading no. 8515; gas-operated surface tempering machines and appliances	6.75	[4]
8469	Typewriters (other than printers of heading no. 8443) and word-processing machines	6.75	[4]
8470	Calculating machines and pocket-size data recording, reproducing and displaying machines with calculating functions; accounting machines, postage-franking machines, ticket-issuing machines and similar, incorporating a calculating device; cash registers	6.75	[4]
8471	Automatic data processing machines and units thereof, magnetic or optical readers, machines for transcribing data onto data media in coded form and machines for processing such data, not elsewhere specified or included	6.75	[4]
8472	Office machines; not elsewhere classified	6.75	[4]
8473	Machinery; parts and accessories (not covers, carrying cases and the like) suitable for use solely or principally with machines of heading no. 8469 to 8472	6.75	[4]
8474	Machinery for sorting, screening, separating, washing, crushing, grinding, mixing or kneading earth, stone, ores in solid form, shaping, moulding machinery for solid mineral fuels	6.75	[4]
8475	Machines; for assembling electric or electronic lamps, tubes, valves, flashbulbs, in glass envelopes, machines for manufacturing or hot working glass or glassware	6.75	[4]
8476	Automatic goods-vending machines (e.g. postage stamp, cigarette, food or beverage machines), including money-changing machines	6.75	[4]
8477	Machinery; for working rubber or plastics or for the manufacture of products from these materials, n.e.c. in this chapter	6.75	[4]
8478	Machinery; for preparing or making up tobacco, n.e.c. in this chapter	6.75	[4]
8479	Machinery and mechanical appliances; having individual functions, n.e.c. in this chapter	6.75	[4]
8480	Moulding boxes for metal foundry, moulding patterns, moulds for metals (excluding ingot moulds), metal carbides, glass, mineral materials, rubber or plastics	6.75	[4]
8481	Taps, cocks, valves and similar appliances for pipes, boiler shells, tanks, vats or the like, including pressure-reducing valves and thermostatically controlled valves	6.75	[4]
8482	Ball or roller bearings	6.75	[4]
8483	Transmission shafts (including cam and crank) and cranks; bearing housings and plain shaft bearings; gears and gearing; ball or roller screws; gear boxes and other speed changers; flywheels and pulleys; clutches and shaft couplings	6.75	[4]
8484	Gaskets and similar joints of metal sheeting combined with other material or of two or more layers of metal; sets or assortments of gaskets and similar joints, dissimilar in composition, put up in pouches, envelopes or similar packings; mechanical seals	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8486	Machines and apparatus of a kind used solely or principally for the manufacture of semiconductor boules or wafers, semiconductor devices, electronic integrated circuits or flat panel displays; machines and apparatus specified in note 9-C to this Chapter	6.75	[4]
8487	Machinery parts; not containing electrical connectors, insulators, coils, contacts or other electrical features, n.e.c. in this chapter	6.75	[4]
8501	Electric motors and generators (excluding generating sets)	6.75	[4]
8502	Electric generating sets and rotary converters	6.75	[4]
8503	Electric motors and generators; parts suitable for use solely or principally with the machines of heading no. 8501 or 8502	6.75	[4]
8504	Electric transformers, static converters (e.g. rectifiers) and inductors	6.75	[4]
8505	Electro-magnets; permanent magnets, intended permanent magnets; electro-magnetic, permanent magnet chucks, clamps, similar; electromagnetic couplings, clutches, brakes; electro-magnetic lifting heads	8.00	[4]
8506	Cells and batteries; primary	1.08	-
8507	Electric accumulators, including separators therefor; whether or not rectangular (including square)	0.65	-
8508	Vacuum cleaners	6.75	[4]
8509	Electro-mechanical domestic appliances; with self-contained electric motor, other than vacuum cleaners of heading 85.08.	6.75	[4]
8510	Shavers, hair clippers and hair removing appliances, with self-contained electric motor	6.75	[4]
8511	Ignition or starting equipment; used for spark-ignition or compression-ignition internal combustion engines; generators and cut outs used in conjunction with such engines	6.75	[4]
8512	Lighting or visual signalling equipment (excluding articles of heading no. 8539), windscreen wipers, defrosters and demisters; electrical, of a kind used for cycles or motor vehicles	6.75	[4]
8513	Lamps; portable, electric, designed to function by their own source of energy (e.g. dry batteries, accumulators, magnetos), excluding lighting equipment of heading no. 8512	6.75	[4]
8514	Industrial or laboratory electric furnaces and ovens (including those functioning by induction or dielectric loss); other industrial or laboratory equipment for the heat treatment of materials by induction or dielectric loss	0.14	[2]
8515	Electric (electrically heated gas) soldering, brazing, welding machines and apparatus, capable or not of cutting, electric machines and apparatus for hot spraying of metals or sintered carbides	8.00	[4]
8516	Electric water, space, soil heaters; electro-thermic hair-dressing apparatus; hand dryers, irons; electro-thermic appliances for domestic purposes; electro heating resistors, not of heading no. 8545	6.75	[4]
8517	Telephone sets, including telephones for cellular networks or for other wireless networks; other apparatus for the transmission or reception of voice, images or other data (including wired/wireless networks), excluding items of 8443, 8525, 8527, or 8528	6.75	[4]
8518	Microphones and their stands; loudspeakers, mounted or not in their enclosures; headphones and earphones, combined or not with a microphone, and sets of a microphone and one or more loudspeakers; audio frequency and electric sound amplifiers and sets	5.62	Mean value of group 85--
8519	Sound recording or reproducing apparatus	6.75	[4]
8521	Video recording or reproducing apparatus	6.75	[4]
8522	Sound or video recording apparatus; parts and accessories suitable for use solely or principally with the apparatus of heading 8519 or 8521	6.75	[4]
8523	Discs, tapes, solid-state non-volatile storage devices, smart cards and other media for the recording of sound or of other phenomena, whether or not recorded, including matrices and masters for the production of discs, excluding products of Chapter 37	0.13	[4]
8525	Transmission apparatus for radio-broadcasting or television, whether or not incorporating reception apparatus or sound recording or reproducing apparatus; television cameras, digital cameras and video camera recorders	6.75	[4]
8526	Radar apparatus, radio navigational aid apparatus and radio remote control apparatus	6.75	[4]
8527	Reception apparatus for radio-broadcasting, whether or not combined, in the same housing, with sound recording or reproducing apparatus or a clock.	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8528	Monitors and projectors, not incorporating television reception apparatus; reception apparatus for television, whether or not incorporating radio-broadcast receivers or sound or video recording or reproducing apparatus	0.14	[2]
8529	Transmission apparatus; parts suitable for use solely or principally with the apparatus of heading no. 8525 to 8528	6.75	[4]
8530	Signalling, safety or traffic control equipment; for railways, tramways, roads, inland waterways, parking facilities, port installations, airfields, excluding those of heading no. 8608	6.75	[4]
8531	Signalling apparatus; electric sound or visual (e.g. bells, sirens, indicator panels, burglar or fire alarms), excluding those of heading no. 8512 or 8530	6.75	[4]
8532	Electrical capacitors; fixed, variable or adjustable (pre-set)	0.14	[2]
8533	Electrical resistors (including rheostats and potentiometers), excluding heating resistors	5.62	Mean value of group 85--
8534	Circuits; printed	2.11	[4]
8535	Electrical apparatus for switching, protecting electrical circuits, for making connections to or in electrical circuits; for a voltage exceeding 1000 volts	2.11	[4]
8536	Electrical apparatus for switching, protecting electrical circuits, for making connections to or in electrical circuits, for a voltage not exceeding 1000 volts; connectors for optical fibres, optical fibre bundles or cables	2.11	[4]
8537	Boards, panels, consoles, desks, cabinets, bases with apparatus of heading no. 8535, 8536 for electricity control and distribution, (other than switching apparatus of heading no. 8517)	6.75	[4]
8538	pesticices	6.75	[4]
8539	Lamps; electric filament or discharge lamps, including sealed beam lamp units and ultra-violet or infra-red lamps, arc-lamps	0.14	[2]
8540	Thermionic, cold cathode or photo-cathode valves and tubes (e.g. vacuum, vapour, gas filled valves and tubes, mercury arc rectifying valves and tubes, cathode-ray and television camera tubes)	0.14	[2]
8541	Diodes, transistors, similar semiconductor devices; including photovoltaic cells assembled or not in modules, panels, light emitting mounted piezo-electric crystals	0.14	[2]
8542	Electronic integrated circuits	2.11	[4]
8543	Electrical machines and apparatus; having individual functions, not specified or included elsewhere in this chapter	5.62	Mean value of group 85--
8544	Insulated wire, cable and other electric conductors, connector fitted or not; optical fibre cables of individually sheathed fibres, whether or not assembled with electric conductors or fitted with connectors	2.11	[4]
8545	Carbon electrodes, carbon brushes, lamp carbons, battery carbons and other articles of graphite or other carbon; with or without metal, of a kind used for electrical purposes	34.16	[1]
8546	Electrical insulators of any material	17.30	[2]
8547	Insulating fittings; for electrical machines, appliances, equipment, excluding insulators of heading no. 8546, electrical conduit tubing and joints therefore	0.14	[4]
8548	Waste and scrap of primary cells, primary batteries and electric accumulators; spent primary cells, spent primary batteries and spent electric accumulators; electrical parts of machinery or apparatus, n.e.c. or included elsewhere in chapter 85	5.62	Mean value of group 85--
8601	Rail locomotives; powered from an external source of electricity or by electric accumulators	6.75	[4]
8603	Railway or tramway coaches, vans and trucks; self-propelled tenders, other than those of heading no. 8604	6.75	[4]
8604	Railway or tramway maintenance or service vehicles; whether or not self-propelled (e.g. workshops, cranes, ballast tampers, trackliners, testing coaches and track inspection vehicles)	6.75	[4]
8605	Railway or tramway goods vans and wagons, not self-propelled.	6.75	[4]
8606	Railway or tramway coaches; passenger coaches, luggage vans, post office coaches and other special purpose railway or tramway coaches, not self-propelled (excluding those of heading no. 8604)	6.75	[4]
8607	Railway or tramway locomotives or rolling stock; parts thereof	6.75	[4]
8608	Railway or tramway track fixtures and fittings; mechanical (including electro-mechanical) signalling, safety or traffic control equipment for railways, tramways, roads, inland waterways, parking facilities, port installations or airfields; parts thereof	6.75	[4]
8609	Containers; (including containers for transport of fluids) specially designed and equipped for carriage by one or more modes of transport	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
8701	Tractors; (other than tractors of heading no 8709)	6.75	[4]
8702	Vehicles; public transport passenger type	6.75	[4]
8703	Motor cars and other motor vehicles; principally designed for the transport of persons (other than those of heading no. 8702), including station wagons and racing cars	6.75	[4]
8704	Vehicles; for the transport of goods	6.75	[4]
8705	Special purpose motor vehicles; not those for the transport of persons or goods (e.g. breakdown lorries, road sweeper lorries, spraying lorries, mobile workshops, mobile radiological units etc)	6.75	[4]
8706	Chassis; fitted with engines, for the motor vehicles of heading no. 8701 to 8705	6.75	[4]
8707	Bodies; (including cabs) for the motor vehicles of heading no. 8701 to 8705	6.75	[4]
8708	Motor vehicles; parts and accessories, of heading no. 8701 to 8705	6.75	[4]
8709	Works trucks, self-propelled, (not fitted with lifting or handling equipment), for factories, warehouses etc, for short distance transport of goods, tractors used on railway station platforms; parts thereof	6.75	[4]
8711	Motorcycles (including mopeds) and cycles; fitted with an auxiliary motor, with or without side-cars; side-cars	6.75	[4]
8712	Bicycles and other cycles; including delivery tricycles, not motorised	6.75	[4]
8713	Carriages for disabled persons; whether or not motorised or otherwise mechanically propelled	6.75	[4]
8714	Vehicles; parts and accessories of heading no. 8711 to 8713	6.75	[4]
8715	Baby carriages and parts thereof	6.75	[4]
8716	Trailers and semi-trailers; other vehicles, not mechanically propelled; parts thereof	6.75	[4]
8801	Balloons and dirigibles; gliders, hang gliders and other non-powered aircraft.	26.08	[6]
8802	Aircraft n.e.c. in heading no. 8801 (e.g. helicopters, aeroplanes); spacecraft (including satellites) and suborbital and spacecraft launch vehicles	32.80	[4]
8803	Aircraft; parts of heading no. 8801 or 8802	32.80	[4]
8804	Parachutes (including dirigible parachutes and paragliders) and rotochutes; parts thereof and accessories thereto	26.08	[6]
8805	Aircraft launching gear, deck-arrestor or similar gear, ground flying trainers; parts of the foregoing articles	32.80	[4]
8901	Cruise ships, excursion boats, ferry-boats, cargo ships, barges and similar vessels for the transport of persons or goods	32.80	[4]
8903	Yachts and other vessels; for pleasure or sports, rowing boats and canoes	32.80	[4]
8904	Tugs and pusher craft	32.80	[4]
8905	Light-vessels, fire-floats, dredgers, floating cranes, other vessels; the navigability of which is subsidiary to main function; floating docks, floating, submersible drilling, production platforms	32.80	[4]
8906	Vessels; other, including warships and lifeboats, other than rowing boats	32.80	[4]
8907	Boats, floating structures, other (for e.g. rafts, tanks, coffer-dams, landing stages, buoys and beacons)	26.08	[6]
8908	Vessels and other floating structures; for breaking up	32.80	[4]
9001	Optical fibres and optical fibre bundles; optical fibre cables not of heading no. 8544; sheets, plates of polarising material; lenses, prisms, mirrors, of any material; unmounted; not non optical glass	0.14	[2]
9002	Lenses, prisms, mirrors and other optical elements, of any material, mounted, being parts or fittings for instruments or apparatus, other than such elements of glass not optically worked	0.14	[2]
9003	Frames and mountings; for spectacles, goggles or the like, and parts	34.46	[6]
9004	Spectacles, goggles and the like; corrective, protective or other	34.46	[6]
9005	Binoculars, monoculars, other optical telescopes, mountings therefore; other astronomical instruments, mountings therefore, but not including instruments for radio-astronomy	6.75	[4]
9006	Cameras, photographic (excluding cinematographic); photographic flashlight apparatus and flashbulbs other than discharge lamps of heading no. 8539	6.75	[4]
9007	Cinematographic cameras and projectors, whether or not incorporating sound recording or reproducing apparatus	6.75	[4]
9008	Image projectors, other than cinematographic; photographic (other than cinematographic) enlargers and reducers	6.75	[4]
9010	Photographic (including cinematographic) laboratory apparatus and equipment, n.e.c. in chapter 90; negatoscopes; projection screens	6.75	[4]
9011	Microscopes, compound optical; including those for photomicrography, cinephotomicrography or microprojection	6.75	[4]
9012	Microscopes (excluding optical microscopes); diffraction apparatus	6.75	[4]

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
9013	Liquid crystal devices not constituting articles provided for more specifically in other headings; lasers, not laser diodes; other optical appliances and instruments n.e.c. in this chapter	6.75	[4]
9014	Navigational instruments and appliances; direction finding compasses	34.46	[6]
9015	Surveying (including photogrammetrical surveying), hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances, excluding compasses, rangefinders	6.75	[4]
9016	Balances; of a sensitivity of 5cg or better, with or without weights	6.75	[4]
9017	Drawing, marking-out, mathematical calculating instruments (drafting machines, protractors, drawing sets etc); instruments for measuring length (e.g. measuring rods, tapes, micrometers, callipers) n.e.c.	6.75	[4]
9018	Instruments and appliances used in medical, surgical, dental or veterinary sciences, including scintigraphic apparatus, other electro-medical apparatus and sight testing instruments	6.75	[4]
9019	Mechano-therapy, massage appliances; psychological aptitude testing apparatus; ozone, oxygen, aerosol therapy, artificial respiration or other therapeutic respiration apparatus	6.75	[4]
9020	Breathing appliances and gas masks; excluding protective masks having neither mechanical parts nor replaceable filters and excluding apparatus of item no. 9019.20	17.08	[13]
9021	Orthopaedic appliances; including crutches, surgical belts and trusses; splints and other fracture appliances; artificial parts of the body; hearing aids and other which are worn, carried or implanted in the body to compensate for a defect or disability	9.42	Mean value of group 90--
9022	X-ray, alpha, beta, gamma radiation apparatus; x-ray tubes, x-ray generators, high tension generators, control panels and desks, screens, examination or treatment tables, chairs and the like	6.75	[4]
9023	Instruments, apparatus and models, designed for demonstrational purposes (in education or exhibitions), unsuitable for other uses	6.75	[4]
9024	Machines and appliances for testing the hardness, strength, compressibility, elasticity of other mechanical properties of materials (e.g. metals, wood, textiles, paper, plastics)	6.75	[4]
9025	Hydrometers and similar floating instruments, thermometers, pyrometers, barometers, hygrometers and psychrometers, recording or not	6.75	[4]
9026	Instruments, apparatus for measuring or checking the flow, level, pressure of liquids, gases (e.g. flow meters, heat meters etc), not instruments and apparatus of heading no. 9014, 9015, 9028 or 9032	6.75	[4]
9027	Instruments and apparatus; for physical or chemical analysis (e.g. polarimeters, spectrometers), for measuring or checking viscosity, porosity, etc, for measuring quantities of heat, sound or light	6.75	[4]
9028	Gas, liquid or electricity supply or production meters, including calibrating meters therefor	6.75	[4]
9029	Revolution counter, production counters, taximeters, mileometers, pedometers and the like, speed indicators and tachometers, other than those of heading no. 9015, stroboscopes	6.75	[4]
9030	Instruments, apparatus for measuring, checking electrical quantities not meters of heading no. 9028; instruments, apparatus for measuring or detecting alpha, beta, gamma, x-ray, cosmic and other radiations	6.75	[4]
9031	Measuring or checking instruments, appliances and machines, n.e.c. or included in this chapter; profile projectors	6.75	[4]
9032	Regulating or controlling instruments and apparatus; automatic type	6.75	[4]
9033	Machines and appliances, instruments or apparatus of chapter 90; parts and accessories n.e.c. in chapter 90	9.42	Mean value of group 90--
9101	Wrist-watches, pocket-watches, stop-watches and other watches; with case of precious metal or of metal clad with precious metal	0.00	-
9102	Wrist-watches, pocket-watches, stop-watches and other watches, other than those of heading no. 9101	0.00	-
9103	Clocks; with watch movements, excluding clocks of heading no. 9104	0.00	-
9104	Instrument panel clocks and clocks of a similar type for vehicles, aircraft, spacecraft or vessels	0.00	-
9105	Clocks, other, n.e.c.	0.00	-
9106	Time of day recording apparatus and apparatus for measuring, recording or otherwise indicating intervals of time, with clock, watch movement or synchronous motor	0.00	-
9107	Time switches; with clock, watch movement or synchronous motor	0.00	-

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
9108	Watch movements; complete and assembled	0.00	-
9109	Clock movements; complete and assembled	0.00	-
9110	Watch or clock movements, complete, unassembled or partly assembled (movement sets); incomplete watch or clock movements, assembled; rough watch or clock movements	0.00	-
9111	Watch cases and parts thereof	0.00	-
9112	Clock cases and cases of a similar type for other goods of this chapter and parts thereof	0.00	-
9113	Watch straps, watch bands, watch bracelets and parts thereof	0.00	-
9114	Clock or watch parts; n.e.c. in chapter 91	0.00	-
9201	Pianos; including automatic pianos, harpsichords and other keyboard stringed instruments	0.00	-
9202	Musical instruments; string, n.e.c. in heading no. 9201, (e.g. guitars, violins, harps)	0.00	-
9205	Musical instruments; wind (e.g. keyboard pipe organs, accordions, clarinets, trumpets, bagpipes), other than fairground organs and mechanical street organs	0.00	-
9206	Musical instruments; percussion (e.g. drums, xylophones, cymbals, castanets, maracas)	0.00	-
9207	Musical instruments; the sound of which is produced or must be amplified, electrically (e.g. organs, guitars, accordions)	0.00	-
9208	Musical boxes, fairground and mechanical street organs, mechanical singing birds, musical saws and musical instruments n.e.c. in chapter 92; decoy calls of all kinds; whistles; call horns and other mouth-blown sound signalling instruments	0.00	-
9209	Musical instrument parts (for example, mechanisms for musical boxes) and accessories (for example, cards, discs and rolls for mechanical instruments); metronomes, tuning forks and pitch pipes	0.00	-
9303	Firearms; other similar devices (e.g. sporting shotguns and rifles, muzzle-loading firearms, very pistols, devices for firing flares or blank ammunition, captive bolt humane killers, line throwing guns)	0.00	-
9304	Firearms; (e.g. spring, air or gas guns and pistols, truncheons), excluding those of heading no. 9307	0.00	-
9306	Bombs, grenades, torpedoes, mines, missiles and similar munitions of war and parts thereof; cartridges and other ammunition, projectiles and parts thereof, including shot and cartridge wads	0.00	-
9401	Seats (not those of heading no. 9402), whether or not convertible into beds and parts thereof	13.18	[13]
9402	Furniture; medical, surgical, dental or veterinary (e.g. operating tables, hospital beds, dentists' chairs) barbers' chairs; parts	6.75	[4]
9403	Furniture and parts thereof, n.e.c. in chapter 94	13.18	[13]
9404	Mattress supports; articles of bedding (e.g. mattresses, quilts, eiderdowns, cushions pouffes and pillows), fitted with springs or stuffed, whether or not covered	33.23	[13]
9405	Lamps, light fittings; including searchlights, spotlights and parts thereof, n.e.c.; illuminated signs, name-plates and the like, having permanently fixed light source and parts thereof n.e.c. or included	13.18	[13]
9406	Buildings; prefabricated	6.75	[4]
9503	Tricycles, scooters, pedal cars and similar wheeled toys; dolls' carriages; dolls; other toys; reduced-size (scale) models and similar recreational models, working or not; puzzles of all kinds	6.75	[4]
9504	Video game consoles and machines, articles for funfair, table or parlour games, including pintables, billiards, special tables for casino games and automatic bowling alley equipment	20.56	[4]
9505	Festive, carnival or other entertainment articles, including conjuring tricks and novelty jokes	0.00	-
9506	Gymnastics, athletics, other sports (including table tennis) or outdoor games equipment, n.e.c. in this chapter, swimming pools and paddling pools	0.00	-
9507	Fishing rods, fish-hooks and other line fishing tackle; fish landing nets and the like; decoy birds (not those of heading no. 9208 or 9705) and similar hunting or shooting requisites	33.23	[13]
9508	Roundabouts, swings, shooting galleries, other fairground amusements, travelling circuses, travelling menageries and travelling theatres	0.00	-
9601	Ivory, bone, tortoise-shell, horn, antlers, coral, mother-of-pearl and other animal carving material and articles of these materials; worked, (including articles obtained by moulding)	0.00	-

Table A3.1: (Cont'd) Commodity description and specific exergy values.

HS-4	Commodity Description	Specific exergy (kJ/kg)	Source(s)
9602	Vegetable, mineral carving material and articles of these materials, moulded or carved articles of wax, stearin, natural gums, resins or modelling pastes, worked unhardened gelatin (not heading no. 3503)	39.31	[4]
9603	Brooms, brushes (including parts of machines), hand operated floor sweepers, mops and feather dusters; knots and tufts for broom or brush making; paint pads and rollers; squeegees	23.67	[13]
9604	Hand sieves and hand riddles	6.75	[4]
9605	Travel sets; for personal toilet, sewing, shoe or clothes cleaning	0.00	-
9606	Buttons, press-fasteners, snap-fasteners and press-studs, button moulds and other parts of these articles; button blanks	34.46	[6]
9607	Slide fasteners and parts thereof	6.75	[4]
9608	Pens; ball-point, felt tipped, other porous tipped pens; fountain pens, stylograph pens duplicating stylos, propelling or sliding pencils; parts of the foregoing, excluding those of heading no. 9609	34.46	[6]
9609	Pencils (not of heading no. 9608), crayons, pencil leads, pastels, drawing charcoals, writing or drawing chalks and tailors' chalks	34.16	[4]
9610	Slates and boards, with writing or drawing surfaces, whether or not framed	6.75	[2]
9611	Stamps; date, numbering, sealing stamps and the like (including devices for printing or embossing labels), designed for operating by hand; hand operated composing sticks and printing sets	31.99	[13]
9612	Typewriter, similar ribbons, inked, otherwise prepared for giving impressions, whether or not on spools or in cartridges; ink pads, whether or not inked, with or without boxes	25.93	Mean value of group 96--
9613	Cigarette lighters and other lighters, whether or not mechanical or electrical and parts thereof other than flints and wicks	51.49	[5]
9614	Smoking pipes (including pipe bowls) and cigar or cigarette holders, and parts thereof	34.36	[6]
9615	Combs, hair-slides and similar; hairpins, curling pins, curling grips and hair curlers and the like, other than those of heading no. 8516 and parts thereof	34.36	[6]
9616	Scent sprays and similar toilet sprays and mounts and heads therefor; powder-puffs and pads for the application of cosmetics or toilet preparations	25.93	Mean value of group 96--
9617	Vacuum flasks and other vacuum vessels, complete with cases; parts thereof other than glass inners	0.14	[2]
9618	Tailors' dummies and other lay figures; automata and other animated displays used for shop window dressing	33.23	[13]
9619	Sanitary towels (pads) and tampons, napkins and napkin liners for babies and similar articles, of any material	17.08	[13]
9701	Paintings, drawings, pastels, executed entirely by hand; not drawings of heading no. 4906 and not hand-painted, hand-decorated manufactured articles; collages and similar decorative plaques	0.00	-
9702	Engravings, prints and lithographs; original	0.00	-
9703	Sculptures and statuary; original, in any material	0.00	-
9704	Stamps, postage or revenue; stamp-postmarks, first-day covers, postal stationery (stamped paper) and like, used or unused, other than those of heading 4907	0.00	-
9705	Collections and collectors' pieces; of zoological, botanical, mineralogical, anatomical, historical, archaeological, palaeontological, ethnographic or numismatic interest	0.00	-
9706	Antiques; of an age exceeding one hundred years	0.00	-
9999	Commodities not specified according to kind	0.00	-

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Appendix 4: Script for Singapore case study

The script and other supplementary data are available for download at:
https://drive.google.com/drive/folders/1qNjG1xIZBa1JHIvu_zFo_uZ3Csxxvsq1?usp=sharing

```
from openpyxl import Workbook
import xlrd
import numpy as np
import networkx as nx
import matplotlib.pyplot as plt

#Exergy flows from HSCode to IOSec
#Load Workbook and Data sheets

wb = Workbook()
ws = wb.active
book_comdata = xlrd.open_workbook('Flow2013CC3.xlsx')

sheet_exconvdata = book_comdata.sheet_by_name("HS2012ExConv")
ncom_exconvdata = (sheet_exconvdata.nrows)
data_exconv = [[sheet_exconvdata.cell_value(r, c)  for c in range(0, 2)] for r in
    range(1, ncom_exconvdata)]
ExConv = np.asarray(data_exconv)
list_ExConvCom = list(ExConv[:, 0])

#Step6-1: Import Extended Exergy Data

book_EEdata = xlrd.open_workbook('Extended Exergy Data.xlsx')

sheet_Wages = book_EEdata.sheet_by_name("Wages")
nrow_Wages = (sheet_Wages.nrows)
ncol_Wages = (sheet_Wages.ncols)
data_Wages = [[sheet_Wages.cell_value(r, c)  for c in range(1, ncol_Wages)] for r
    in range(1, nrow_Wages)]
data_Wages = np.copy(data_Wages)
data_Wages = np.asarray(data_Wages)

sheet_Hours = book_EEdata.sheet_by_name("Hours")
nrow_Hours = (sheet_Hours.nrows)
ncol_Hours = (sheet_Hours.ncols)
data_Hours = [[sheet_Hours.cell_value(r, c)  for c in range(1, ncol_Hours)] for r
    in range(1, nrow_Hours)]
data_Hours = np.copy(data_Hours)
```

```
data_Hours = np.asarray(data_Hours)

sheet_Employment = book_EEdata.sheet_by_name("Employment")
nrow_Employment = (sheet_Employment.nrows)
ncol_Employment = (sheet_Employment.ncols)
data_Employment = [[sheet_Employment.cell_value(r, c)  for c in range(1,
  ncol_Employment)] for r in range(1, nrow_Employment)]
data_Employment = np.copy(data_Employment)
data_Employment = np.asarray(data_Employment)

sheet_Population = book_EEdata.sheet_by_name("Population")
nrow_Population = (sheet_Population.nrows)
ncol_Population = (sheet_Population.ncols)
data_Population = [[sheet_Population.cell_value(r, c)  for c in range(1,
  ncol_Population)] for r in range(1, nrow_Population)]
data_Population = np.copy(data_Population)
data_Population = np.asarray(data_Population)

sheet_HDI = book_EEdata.sheet_by_name("HDI")
nrow_HDI = (sheet_HDI.nrows)
ncol_HDI = (sheet_HDI.ncols)
data_HDI = [[sheet_HDI.cell_value(r, c)  for c in range(1, ncol_HDI)] for r in
  range(1, nrow_HDI)]
data_HDI = np.copy(data_HDI)
data_HDI = np.asarray(data_HDI)

sheet_Extrt = book_EEdata.sheet_by_name("Local Production")
data_Extrt = [[sheet_Extrt.cell_value(r, c)  for c in range(1, sheet_Extrt.ncols)
  ] for r in range(1, sheet_Extrt.nrows)]
data_Extrt = np.asarray(data_Extrt)

sheet_EF = book_EEdata.sheet_by_name("Emission factor")
nrow_EF = (sheet_EF.nrows)
ncol_EF = (sheet_EF.ncols)
data_EF = [[sheet_EF.cell_value(r, c)  for c in range(1, ncol_EF)] for r in range
  (1, nrow_EF)]
data_EF = np.copy(data_EF)
data_EF = np.asarray(data_EF)

f0 = 0.055
esurv = 365*1e-5 #Survival energy per person per year #TJ
data_f = np.copy(data_HDI)
for i in range (0, len(data_HDI)):
    data_f = data_HDI/f0

#Result1: OSNEA
YEAR = ['YEAR']
INV_GEN = ['INV_GEN']
EXERGY_GEN = ['EXERGY_GEN']
EXERGY_WASTE = ['EXERGY_WASTE']
EXERGY_DES = ['EXERGY_DES']
EXERGY_IN = ['EXERGY_IN']
EXERGY_OUT = ['EXERGY_OUT']
EXERGY_IMCOM = ['EXERGY_IMCOM']
```

```
EXERGY_EXCOM = ['EXERGY_EXCOM']
EXERGY_IM27XX = ['EXERGY_IM27XX']
EXERGY_EX27XX = ['EXERGY_EX27XX']
EFF_UTL = ['EFF_UTL']
EFF_GEN = ['EFF_GEN']
TIF_RATIO = ['TIF_RATIO']
CONNECTANCE = ['CONNECTANCE']
EEL_TOT = ['EEL_TOT']
EEC_TOT = ['EEC_TOT']
EF_GHG = ['EF_GHG']

#Result2: Exergy

#Result3: ENA
ENA_MI_EXT = ['ENA_MI_EXT']
ENA_SI_EXT = ['ENA_SI_EXT']
ENA_RM_EXT = ['ENA_RM_EXT']
ENA_RE_EXT = ['ENA_RE_EXT']
ENA_RC_EXT = ['ENA_RC_EXT']
ENA_MI_IO = ['ENA_MI_IO']
ENA_SI_IO = ['ENA_SI_IO']
ENA_RM_IO = ['ENA_RM_IO']
ENA_RE_IO = ['ENA_RE_IO']
ENA_RC_IO = ['ENA_RC_IO']


YearItems = [2005, 2007, 2010, 2012, 2013, 2014]
EXERGY_IMPORT = np.zeros(((np.size(YearItems)), nrow_Employment+5))
EXERGY_IMPORT[:, 0] = YearItems
EXERGY_EXPORT = np.zeros(((np.size(YearItems)), nrow_Employment+5))
EXERGY_EXPORT[:, 0] = YearItems
EXERGY_EFFICIENCY = np.zeros(((np.size(YearItems)), nrow_Employment+1))
EXERGY_EFFICIENCY[:, 0] = YearItems
EXERGY_DIFF = np.zeros(((np.size(YearItems)), nrow_Employment+1))
EXERGY_DIFF[:, 0] = YearItems
#
for year in YearItems:
    YearRange = np.arange(2005, 2018)

    sheet_tradedata = book_comdata.sheet_by_name('Comtrade%s' %year)
    ncom_tradedata = (sheet_tradedata.nrows)
    data_tradedata = [[sheet_tradedata.cell_value(r, c)  for c in (0, 1, 6)] for
  r in range(1, ncom_tradedata)]
    M_tradedata = np.asarray(data_tradedata)
    M_tradedata = np.ndarray.astype(M_tradedata, float, order = 'K', casting = '
  unsafe', subok = True, copy = True)
    HSCode = M_tradedata[:, 0]
    HSCodelist = np.ndarray.tolist(np.copy(HSCode))

    #Exergy Import/Export in TJ
    Exergy_imCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1))),
  np.zeros((len(HSCode), 1))))
    for i in range(0, len(M_tradedata)):
        for com in list_ExConvCom:
```

```
          if Exergy_imCom[i, 0] == com:
              Exergy_imCom[i, 1] = np.multiply(M_tradedata[i, 1], ExConv[list_ExConvCom.index(com), 1])*1e-6
  Exergy_exCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1))), np.zeros((len(HSCode), 1))))
  for i in range(0, len(M_tradedata)):
      for com in list_ExConvCom:
          if Exergy_exCom[i, 0] == com:
              Exergy_exCom[i, 1] = np.multiply(M_tradedata[i, 2], ExConv[list_ExConvCom.index(com), 1])*1e-6

  Exergy_im = Exergy_imCom[:, 1]
  Exergy_ex = Exergy_exCom[:, 1]

  for y in YearRange:
      if y == year:
          if y < 2010:
              IOHS_version = "RIO2005_HS2007X"
              ############
              IO_r = range(6, 142)
              IO_c = range(3, 139)
              PGCE_c = range(141, 143)
              GFCF_c = 143
              VA_r = 149
              ChangeInv_c = 144
              Abroad_r = 143
              Abroad_c = 145
              ############
              IU_r = range(6, 143)
              IU_c = range(3, 139)
              IUFD_c = range(141, 145)
              IUTTL_c = 146
              ############
              Sec1 = list(range(0, 5))+[21]+list(range(75, 79))
              Sec2 = list(range(5, 21))+list(range(22, 75))
              Sec3 = [79, 80]
              Sec4 = list(range(81, 85))
              Sec5 = list(range(87, 98))
              Sec6 = [85, 86]
              Sec7 = [99, 108, 109, 127]
              Sec8 = list(range(100, 105))
              Sec9 = [98, 105, 106, 107]+list(range(110, 122))+[123]
              Sec10 = [122]+list(range(124, 127))+list(range(128, 135))
              ############
          if 2010 <= y < 2012:
              IOHS_version = "IO2010_HS2007"
              ############
              IO_r = range(10, 137)
              IO_c = range(3, 130)
              PGCE_c = range(132, 134)
              GFCF_c = 134
              VA_r = 144
              ChangeInv_c = 135
              Abroad_r = 138
```

```
                Abroad_c = 136
                ############
                IU_r = range(10, 138)
                IU_c = range(3, 130)
                IUFD_c = range(132, 136)
                IUTTL_c = 137
                ############
                Sec1 = list(range(0, 5))+[20]+list(range(66, 70))
                Sec2 = list(range(5, 20))+list(range(21, 66))
                Sec3 = list(range(70, 73))
                Sec4 = [73, 74]
                Sec5 = list(range(75, 86))
                Sec6 = [86, 87]
                Sec7 = list(range(88, 92))
                Sec8 = list(range(92, 97))
                Sec9 = [97]+list(range(99, 115))
                Sec10 = [98]+list(range(115, 127))
                ############
            if 2012 <= y < 2017:
                IOHS_version = "IO2012_HS2012"
                ############
                IO_r = range(10, 81)
                IO_c = range(3, 74)
                PGCE_c = range(76, 78)
                GFCF_c = 78
                VA_r = 88
                ChangeInv_c = 79
                Abroad_r = 82
                Abroad_c = 80
                ############
                IU_r = range(10, 82)
                IU_c = range(3, 74)
                IUFD_c = range(76, 80)
                IUTTL_c = 81
                ############
                Sec1 = [0, 6]+list(range(28, 32))
                Sec2 = list(range(1, 6))+list(range(7, 28))
                Sec3 = list(range(32, 34))
                Sec4 = list(range(34, 36))
                Sec5 = list(range(36, 41))
                Sec6 = list(range(41, 43))
                Sec7 = list(range(43, 47))
                Sec8 = list(range(47, 51))
                Sec9 = [51]+list(range(53, 65))
                Sec10 = [52]+list(range(65, 71))
                ############

    sheet_IOHS = book_comdata.sheet_by_name(IOHS_version)
    IOHS = [[sheet_IOHS.cell_value(r, c)  for c in range (0, 3)] for r in range
  (1, sheet_IOHS.nrows)]
    M_IOHS = np.copy(IOHS)
    M_IOHS = np.asarray(M_IOHS)

    PRepeat = []
```

```python
    for i in range(0, len(M_IOHS)):
        if M_IOHS[i, 2] == 'P':
            PRepeat.append(M_IOHS[i, 1])
    PUnique = np.unique(PRepeat)
    PCount = np.zeros((len(PUnique), 2))
    PCount[:, 0] = PUnique
    for i in range(0, len(PUnique)):
        nCount = list(PRepeat).count(PUnique[i])
        PCount[i, 1] = nCount

    Exergy_imP = np.copy(Exergy_im)
    HSCodePCount = np.ones((len(HSCode), 1))
    for i in range(0, len(PCount)):
        for j in range (0, len(HSCode)):
            if PCount[i, 0] == HSCode[j]:
                Exergy_imP[j] = Exergy_im[j]/PCount[i, 1]
                HSCodePCount[j] = PCount[i, 1]
                HSCodePCount[(len(HSCode)-1)] = 0 #HSCode 9999

    Exergy_exP = np.copy(Exergy_ex)
    HSCodePCount = np.ones((len(HSCode), 1))
    for i in range(0, len(PCount)):
        for j in range (0, len(HSCode)):
            if PCount[i, 0] == HSCode[j]:
                Exergy_exP[j] = Exergy_ex[j]/PCount[i, 1]
                HSCodePCount[j] = PCount[i, 1]
                HSCodePCount[(len(HSCode)-1)] = 0 #HSCode 9999

    COM27XX = []
    for i in range(0, len(M_tradedata)):
        if int(str(M_tradedata[i, 0])[:2]) == 27:
            COM27XX.append(i)

    IOSec = np.unique(M_IOHS[:, 0])
    IOSeclist = np.ndarray.tolist(np.copy(IOSec))
    HSCodetoIOSecID = {x:[] for x in range (0, len(IOSec))}
    for i in range(0, len(IOSec)):
        for j in range (0, len(M_IOHS)):
            if IOSec[i] == M_IOHS[j, 0]:
                  HSCodetoIOSecID[i].append(M_IOHS[j, 1])

    HSCodetoIOSec = HSCodetoIOSecID.copy()
    for x in IOSeclist:
        for y in HSCodetoIOSec.keys():
            if IOSeclist.index(x) == y:
                HSCodetoIOSec[x] = HSCodetoIOSec.pop(y)

    Exergy_im_IOSec = np.zeros(((len(IOSec), 1)), float)
    Exergy_ex_IOSec = np.zeros(((len(IOSec), 1)), float)
    HSCodelist = sorted(HSCode.tolist())
    jhscount = 0
    jhsmatch = []
    for i in range(0, len(IOSec)):
        jhscodelist = []
```

```
        for j in list(HSCodetoIOSecID.values())[i]:
            for hscode in HSCodelist:
                if int(hscode) == int(float(j)):
                    jhscount = jhscount+1
                    jhsmatch.append(j)
                    jhscodelist.append(HSCodelist.index(hscode))
                    Exergy_im_IOSec[i] = sum(Exergy_imP[jhscodelist])
                    Exergy_ex_IOSec[i] = sum(Exergy_exP[jhscodelist])


    #Step3-1: Import data from I/O Table

    sheet_IO = book_comdata.sheet_by_name('IO%s' %year)

    #Sectoral input-output(io) flow data
    data_IO = [[sheet_IO.cell_value(r, c)  for c in IO_c] for r in IO_r]
    M_IO = np.asarray(data_IO)

    #Domestic Sector
    #Domestic Consumption - Private & Government Consumption Expenditure
    data_PGCE = [[sheet_IO.cell_value(r, c)  for c in PGCE_c] for r in IO_r]
    PGCE = np.asarray(data_PGCE)
    PGCE = np.reshape(np.sum(PGCE, axis = 1), (len(PGCE), 1))
    #Domestic Input - Employment data
    EEL_0 = np.zeros((1, len(M_IO[0])))

    #Capital formation - Gross Fixed Capital Formation
    data_GFCF = [[sheet_IO.cell_value(r,  GFCF_c)  for r in IO_r]]
    GFCF = np.asarray(data_GFCF)
    GFCF = np.reshape((GFCF), (np.size(GFCF), 1))
    #Capital Input - Value Added
    data_VA = [sheet_IO.cell_value(VA_r, c) for c in IO_c]
    VA = np.asarray(data_VA)
    VA = np.reshape((data_VA), (1, np.size(data_VA)))

    #Import Change in Inventories
    data_ChangeInv = [[sheet_IO.cell_value(r, ChangeInv_c)  for r in IO_r]]
    #Increase in stock - output from sectors
    Inv_pos = np.copy(data_ChangeInv)
    Inv_pos[Inv_pos <= 0] = 0
    Inv_pos = np.reshape(Inv_pos, (np.size(Inv_pos), 1))
    #Decrease in stock - input to sectors
    Inv_neg = np.copy(data_ChangeInv)
    Inv_neg[Inv_neg >= 0] = 0
    Inv_neg = np.reshape(-1*Inv_neg, (1, np.size(Inv_neg)))

    #Abroad
    #Sectoral import data
    data_IM = [sheet_IO.cell_value(Abroad_r, c) for c in IO_c]
    r_IM = np.transpose(np.array(data_IM))
    r_IM = np.resize(r_IM, (1,len(r_IM)))
    #Sectoral export data
    data_EX = [sheet_IO.cell_value(r, Abroad_c) for r in IO_r]
    c_EX = np.transpose(np.array(data_EX))
```

```
    c_EX = np.resize(c_EX, (len(c_EX),1))


    #Step3-2: Assemble I/O Matrix

    m = len(M_IO)

    MW = np.zeros((m + 5, m + 5))
    MW[0:m, 0:m] = M_IO
    #Domestic consumption
    for i in range(0, len(PGCE)):
        MW[i, m] = PGCE[i, 0]
    #Domestic Input
    for i in range(0, len(EEL_0)):
        MW[m, i] = EEL_0[0, i]

    M_IODO = np.copy(MW[0:m+1, 0:m+1])
    n = len(M_IODO)
    ##################################

    #Capital Formation
    for i in range(0, len(GFCF)):
        MW[i, m+1] = GFCF[i, 0]
    #value Added
    for i in range(0, len(VA[0])):
        MW[m+1, i] = VA[0, i]

    M_IODOC = np.copy(MW[0:m+2, 0:m+2])
    q = len(M_IODOC)
    ###################################

    #Inv Positive
    for i in range(0, len(Inv_pos)):
        MW[i, m+2] = Inv_pos[i, 0]
    #Inv Negative
    for i in range(0, len(Inv_neg[0])):
        MW[m+2, i] = abs(Inv_neg[0, i])

    M_IODOCI = np.copy(MW[0:m+3, 0:m+3])
    r = len(M_IODOCI)

    #Monetary Import
    for i in range(0, len(c_EX)):
        MW[i, m+4] = c_EX[i, 0]
    #Monetary Export
    for i in range(0, len(r_IM[0])):
        MW[m+4, i] = r_IM[0, i]

    s = len(MW)


    #Step4: Sector Classification - I/O Table

    SecDo = [m]
```

```python
    SecC = [m+1]
    SecInv = [m+2]
    SecE = [m+3]
    SecA = [m+4]

    list_AggSec = {x:[] for x in range (0, 15)}
    list_AggSec[0].append(Sec1)
    list_AggSec[1].append(Sec2)
    list_AggSec[2].append(Sec3)
    list_AggSec[3].append(Sec4)
    list_AggSec[4].append(Sec5)
    list_AggSec[5].append(Sec6)
    list_AggSec[6].append(Sec7)
    list_AggSec[7].append(Sec8)
    list_AggSec[8].append(Sec9)
    list_AggSec[9].append(Sec10)
    list_AggSec[10].append(SecDo)
    list_AggSec[11].append(SecC)
    list_AggSec[12].append(SecInv)
    list_AggSec[13].append(SecE)
    list_AggSec[14].append(SecA)

    M_IO_AggSec_sort = np.zeros((len(MW), len(list_AggSec)), float)
    for i in range(0, len(MW)):
        M_IO_AggSec_sort[i, 0] = sum(MW[i, Sec1])
        M_IO_AggSec_sort[i, 1] = sum(MW[i, Sec2])
        M_IO_AggSec_sort[i, 2] = sum(MW[i, Sec3])
        M_IO_AggSec_sort[i, 3] = sum(MW[i, Sec4])
        M_IO_AggSec_sort[i, 4] = sum(MW[i, Sec5])
        M_IO_AggSec_sort[i, 5] = sum(MW[i, Sec6])
        M_IO_AggSec_sort[i, 6] = sum(MW[i, Sec7])
        M_IO_AggSec_sort[i, 7] = sum(MW[i, Sec8])
        M_IO_AggSec_sort[i, 8] = sum(MW[i, Sec9])
        M_IO_AggSec_sort[i, 9] = sum(MW[i, Sec10])
        M_IO_AggSec_sort[i, 10] = sum(MW[i, SecDo])
        M_IO_AggSec_sort[i, 11] = sum(MW[i, SecC])
        M_IO_AggSec_sort[i, 12] = sum(MW[i, SecInv])
        M_IO_AggSec_sort[i, 13] = sum(MW[i, SecE])
        M_IO_AggSec_sort[i, 14] = sum(MW[i, SecA])
    M_IO_AggSec = np.zeros((len(list_AggSec), len(list_AggSec)), float)
    for i in range(0, len(list_AggSec)):
        M_IO_AggSec[0, i] = sum(M_IO_AggSec_sort[Sec1, i])
        M_IO_AggSec[1, i] = sum(M_IO_AggSec_sort[Sec2, i])
        M_IO_AggSec[2, i] = sum(M_IO_AggSec_sort[Sec3, i])
        M_IO_AggSec[3, i] = sum(M_IO_AggSec_sort[Sec4, i])
        M_IO_AggSec[4, i] = sum(M_IO_AggSec_sort[Sec5, i])
        M_IO_AggSec[5, i] = sum(M_IO_AggSec_sort[Sec6, i])
        M_IO_AggSec[6, i] = sum(M_IO_AggSec_sort[Sec7, i])
        M_IO_AggSec[7, i] = sum(M_IO_AggSec_sort[Sec8, i])
        M_IO_AggSec[8, i] = sum(M_IO_AggSec_sort[Sec9, i])
        M_IO_AggSec[9, i] = sum(M_IO_AggSec_sort[Sec10, i])
        M_IO_AggSec[10, i] = sum(M_IO_AggSec_sort[SecDo, i])
        M_IO_AggSec[11, i] = sum(M_IO_AggSec_sort[SecC, i])
        M_IO_AggSec[12, i] = sum(M_IO_AggSec_sort[SecInv, i])
```

```python
        M_IO_AggSec[13, i] = sum(M_IO_AggSec_sort[SecE, i])
        M_IO_AggSec[14, i] = sum(M_IO_AggSec_sort[SecA, i])


    #Step5-1:Sector Classification - Exergy flows to I/O Sectors

    Exergy_im_IOExpn = np.zeros((m+5, 1))
    Exergy_ex_IOExpn = np.zeros((1, m+5))
    for iosec in sorted(HSCodetoIOSec.keys()):
        Exergy_im_IOExpn[int(float(iosec))-1] = Exergy_im_IOSec[(list(sorted(HSCodetoIOSec.keys())).index(iosec))]
        Exergy_ex_IOExpn[0, int(float(iosec))-1] = Exergy_ex_IOSec[(list(sorted(HSCodetoIOSec.keys())).index(iosec))]
    Exergy_im_IOExpn = np.reshape((np.asarray(Exergy_im_IOExpn)), (m+5, 1))
    Exergy_ex_IOExpn = np.reshape((np.asarray(Exergy_ex_IOExpn)), (m+5, 1))


    #Step5-2: Sector Aggregation - Exergy (in goods) Import and Export

    Exergy_im_AggSec = np.zeros((1, len(list_AggSec)), float)
    Exergy_im_AggSec[0, 0] = sum(Exergy_im_IOExpn[Sec1])
    Exergy_im_AggSec[0, 1] = sum(Exergy_im_IOExpn[Sec2])
    Exergy_im_AggSec[0, 2] = sum(Exergy_im_IOExpn[Sec3])
    Exergy_im_AggSec[0, 3] = sum(Exergy_im_IOExpn[Sec4])
    Exergy_im_AggSec[0, 4] = sum(Exergy_im_IOExpn[Sec5])
    Exergy_im_AggSec[0, 5] = sum(Exergy_im_IOExpn[Sec6])
    Exergy_im_AggSec[0, 6] = sum(Exergy_im_IOExpn[Sec7])
    Exergy_im_AggSec[0, 7] = sum(Exergy_im_IOExpn[Sec8])
    Exergy_im_AggSec[0, 8] = sum(Exergy_im_IOExpn[Sec9])
    Exergy_im_AggSec[0, 9] = sum(Exergy_im_IOExpn[Sec10])
    Exergy_im_AggSec[0, 10] = sum(Exergy_im_IOExpn[SecDo])
    Exergy_im_AggSec[0, 11] = sum(Exergy_im_IOExpn[SecC])
    Exergy_im_AggSec[0, 12] = sum(Exergy_im_IOExpn[SecInv])
    Exergy_im_AggSec[0, 13] = sum(Exergy_im_IOExpn[SecE])
    Exergy_im_AggSec[0, 14] = sum(Exergy_im_IOExpn[SecA])

    Exergy_ex_AggSec = np.zeros((len(list_AggSec), 1), float)
    Exergy_ex_AggSec[0, 0] = sum(Exergy_ex_IOExpn[Sec1])
    Exergy_ex_AggSec[1, 0] = sum(Exergy_ex_IOExpn[Sec2])
    Exergy_ex_AggSec[2, 0] = sum(Exergy_ex_IOExpn[Sec3])
    Exergy_ex_AggSec[3, 0] = sum(Exergy_ex_IOExpn[Sec4])
    Exergy_ex_AggSec[4, 0] = sum(Exergy_ex_IOExpn[Sec5])
    Exergy_ex_AggSec[5, 0] = sum(Exergy_ex_IOExpn[Sec6])
    Exergy_ex_AggSec[6, 0] = sum(Exergy_ex_IOExpn[Sec7])
    Exergy_ex_AggSec[7, 0] = sum(Exergy_ex_IOExpn[Sec8])
    Exergy_ex_AggSec[8, 0] = sum(Exergy_ex_IOExpn[Sec9])
    Exergy_ex_AggSec[9, 0] = sum(Exergy_ex_IOExpn[Sec10])
    Exergy_ex_AggSec[10, 0] = sum(Exergy_ex_IOExpn[SecDo])
    Exergy_ex_AggSec[11, 0] = sum(Exergy_ex_IOExpn[SecC])
    Exergy_ex_AggSec[12, 0] = sum(Exergy_ex_IOExpn[SecInv])
    Exergy_ex_AggSec[13, 0] = sum(Exergy_ex_IOExpn[SecE])
    Exergy_ex_AggSec[14, 0] = sum(Exergy_ex_IOExpn[SecA])
```

```
    #Step6-2: Calculate Extended Exergy Capital, EEC

    def EEC_tot(year):
        i = list(YearRange).index(year)
        EEC_tot = data_f[0, i]*esurv*data_Population[0, i]/(np.mean(data_Wages[0:10, i])*sum(data_Employment[0:10, i]*1000))
        return EEC_tot   #in TJ/dollar


    #Step7: Import Local Production Data

    def Extrt(year):
       i = list(YearRange).index(year)
       Extrt = data_Extrt[0, i]
       return Extrt

    #Step8-1: Sectoral Distributiopn - Exegy Import Use

    sheet_IMU = book_comdata.sheet_by_name('IU%s' %year)
    data_IMUS = [[sheet_IMU.cell_value(r, c) for c in IU_c] for r in IU_r]
    data_FD_IM = [[sheet_IMU.cell_value(r, c) for c in IUFD_c] for r in IU_r]
    data_TTL_IM = [[sheet_IMU.cell_value(r, IUTTL_c) for r in IU_r]]
    M_IMUS = np.asarray(data_IMUS)
    M_IMUS [M_IMUS < 0] = 0
    M_FD_IM = np.asarray(data_FD_IM)
    M_TTL_IM = np.asarray(data_TTL_IM)
    M_TTL_IM = np.reshape(M_TTL_IM, (np.size(M_TTL_IM), 1))

    #Normalised exergy import with total monetary import in import use
    Exergy_IMU_norm = np.zeros((len(Exergy_im_IOExpn), 1))
    for i in range(0, len(Exergy_im_IOExpn)):
        if Exergy_im_IOExpn[i, 0] != 0:
            Exergy_IMU_norm[i, 0] = Exergy_im_IOExpn[i, 0]/M_TTL_IM[i, 0]
        else:
            Exergy_IMU_norm[i, 0] = EEC_tot(year)*1e6

    #Multiply with Import Use Matrix
    Exergy_IMUS = np.zeros((np.shape(M_IMUS)))
    for i in range (0, len(M_IMUS)):
        for j in range (0, len(M_IMUS)-1):
            Exergy_IMUS[i, j] = M_IMUS[i, j]*Exergy_IMU_norm[i, 0]
    Exergy_IMUS_IOSec = np.sum(Exergy_IMUS, axis = 0)

    #Multiply with Final Demand Matrix
    Exergy_FD = np.zeros((np.shape(M_FD_IM)))
    for i in range (0, len(M_FD_IM)):
        for j in range (0, len((M_FD_IM[0,:]))):
            Exergy_FD[i, j] = M_FD_IM[i, j]*Exergy_IMU_norm[i, 0]
    Exergy_FD_IOSec = np.sum(Exergy_FD, axis = 0)
    Exergy_FD_Inv = Exergy_FD[0:len(Exergy_FD), 3]
    Exergy_FD_Inv_pos = np.sum(Exergy_FD_Inv[Exergy_FD_Inv >= 0])
    Exergy_FD_Inv_neg = np.sum(Exergy_FD_Inv[Exergy_FD_Inv <= 0])

    #Step8-2: Assemble Imports to AggSec
```

```
    #Sector Aggregation - Exergy, Extended Exergy (goods and services) Import

    Exergy_IMPORT = np.zeros((1, len(list_AggSec)), float)
    Exergy_IMPORT[0, 0] = sum(Exergy_IMUS_IOSec[Sec1])
    Exergy_IMPORT[0, 1] = sum(Exergy_IMUS_IOSec[Sec2])
    Exergy_IMPORT[0, 2] = sum(Exergy_IMUS_IOSec[Sec3])
    Exergy_IMPORT[0, 3] = sum(Exergy_IMUS_IOSec[Sec4])
    Exergy_IMPORT[0, 4] = sum(Exergy_IMUS_IOSec[Sec5])
    Exergy_IMPORT[0, 5] = sum(Exergy_IMUS_IOSec[Sec6])
    Exergy_IMPORT[0, 6] = sum(Exergy_IMUS_IOSec[Sec7])
    Exergy_IMPORT[0, 7] = sum(Exergy_IMUS_IOSec[Sec8])
    Exergy_IMPORT[0, 8] = sum(Exergy_IMUS_IOSec[Sec9])
    Exergy_IMPORT[0, 9] = sum(Exergy_IMUS_IOSec[Sec10])
    Exergy_IMPORT[0, 10] = sum(Exergy_FD_IOSec[list(range(0, 2))])
    Exergy_IMPORT[0, 11] = Exergy_FD_IOSec[2]
    Exergy_IMPORT[0, 12] = Exergy_FD_Inv_pos
    Exergy_IMPORT[0, 13] = 0
    Exergy_IMPORT[0, 14] = 0


    #Step8-3: Sectoral Exergy Export
    #Normalised exergy import with monetary import

    Exergy_EXPORT = np.zeros((1, len(list_AggSec)))
    for i in range(0, len(list_AggSec)-5):
        if Exergy_ex_AggSec[i, 0] != 0:
            Exergy_EXPORT[0, i] = Exergy_ex_AggSec[i, 0]
        else:
            #for services export
            Exergy_EXPORT[0, i] = M_IO_AggSec[i, len(list_AggSec)-1]*EEC_tot(year)*1e6
    Exergy_EXPORT[0, 12] = abs(Exergy_FD_Inv_neg)

    #Step9: Capital flows to/from abroad for Import and Export

    Exergy_IMPORTC = np.zeros((1, len(list_AggSec)))
    for i in range(0, len(list_AggSec)):
        Exergy_IMPORTC[0, i] = (M_IO_AggSec[i, len(list_AggSec)-1]*EEC_tot(year)*1e6)

    Exergy_EXPORTC = np.zeros((1, len(list_AggSec)))
    for i in range(0, len(list_AggSec)):
        Exergy_EXPORTC[0, i] = (M_IO_AggSec[len(list_AggSec)-1, i]*EEC_tot(year)*1e6)


    # Step10: Extended Exergy of Labour Productivity based on each sector employment EEL

    def EEL_AggSec(year):
        i = list(YearRange).index(year)
        EEL_AggSec = np.zeros((1, len(list_AggSec)))
        for sec in range(0, (len(list_AggSec))-5):
```

```
          EEL_AggSec[0, sec] = data_f[0, i]*esurv*data_Population[0, i]/((sum(data_Employment[0:10, i]*1000)*np.mean(data_Hours[0:10, i]*50)))*(data_Hours[sec, i]*50)*(data_Employment[sec, i])
      return EEL_AggSec

  def EEL_tot(year):
      i = list(YearRange).index(year)
      EEL_tot = data_f[0, i]*esurv*data_Population[0, i]/((sum(data_Employment[0:10, i]*1000)*np.mean(data_Hours[0:10, i]*50)))
      return EEL_tot  #TJ/workhour


  #Step11: I/O Flow Normalisation - with total inflow

  Sum_MIOAS_in = np.sum(M_IO_AggSec[:, 0:(len(M_IO_AggSec)-1)], axis = 1)
  MIOAS_in_norm = np.zeros((np.shape(M_IO_AggSec)))
  for i in range(0, len(M_IO_AggSec)):
      for j in range(0, len(M_IO_AggSec)):
          if j == 13:
              MIOAS_in_norm[i, j] = 0
          else:
              MIOAS_in_norm[i, j] = M_IO_AggSec[i, j]/Sum_MIOAS_in[i]
  MIOAS_in_norm[np.isnan(MIOAS_in_norm)] = 0
  MIOAS_in_norm = np.around(MIOAS_in_norm, decimals = 6)

  ExergyIO_MIOAS = np.zeros((np.shape(M_IO_AggSec)))
  for j in range(0, len(M_IO_AggSec)):
      ExergyIO_MIOAS[0, j] = (Exergy_IMPORT[0, 0] + Extrt(year) - Exergy_EXPORT[0, 0])*MIOAS_in_norm[0, j]
      ExergyIO_MIOAS[1, j] = (Exergy_IMPORT[0, 1] - Exergy_EXPORT[0, 1])*MIOAS_in_norm[1, j]
  for i in range(2, len(M_IO_AggSec)):
      for j in range(0, len(M_IO_AggSec)):
          ExergyIO_MIOAS[i, j] = (Exergy_IMPORT[0, i])*MIOAS_in_norm[i, j]
  #Domestic contribution based on workhours and employment
  ExergyIO_MIOAS[(len(list_AggSec)-5), :] = EEL_AggSec(year)
  #Extraction of natural resources
  ExergyIO_MIOAS[(len(list_AggSec))-2, 0] = Extrt(year)
  #Capital flows
  ExergyIO_MIOAS[len(list_AggSec)-4, :] = M_IO_AggSec[len(list_AggSec)-4, :]*EEC_tot(year)*1e6
  ExergyIO_MIOAS[:, len(list_AggSec)-4] = M_IO_AggSec[:, len(list_AggSec)-4]*EEC_tot(year)*1e6
  #Change in Inventories
  ExergyIO_MIOAS[len(list_AggSec)-3, :] = M_IO_AggSec[len(list_AggSec)-3, :]*EEC_tot(year)*1e6
  ExergyIO_MIOAS[:, len(list_AggSec)-3] = M_IO_AggSec[:, len(list_AggSec)-3]*EEC_tot(year)*1e6
  #Import and Export to/from Abraod
  for i in range(0, len(list_AggSec)):
      ExergyIO_MIOAS[len(list_AggSec)-1, i] = Exergy_IMPORT[0, i]
  for i in range(0, len(list_AggSec)):
      ExergyIO_MIOAS[i, len(list_AggSec)-1] = Exergy_EXPORT[0, i]
  #IMPORT and EXPORT capital flows (opposite flow)
```

```
    ExergyIO_MIOAS[len(list_AggSec)-1, len(list_AggSec)-4] =  (M_IO_AggSec[len(list_AggSec)-1, len(list_AggSec)-4]*EEC_tot(year)*1e6) + np.sum(Exergy_IMPORTC)
    ExergyIO_MIOAS[len(list_AggSec)-4, len(list_AggSec)-1] =  (M_IO_AggSec[len(list_AggSec)-4, len(list_AggSec)-1]*EEC_tot(year)*1e6) + np.sum(Exergy_EXPORTC)


    #Sep12:Run OSNEA

    M = np.copy(ExergyIO_MIOAS)
    N = len(M) - 4
    TiM =  M.sum(axis = 0)
    M_diag = np.copy(M)
    for i in range(0, len(M)):
        M_diag[i, i] = 0
    TjM = M_diag.sum(axis = 1)
    Diff = np.subtract(np.transpose(TiM), TjM)
    DiffN = np.reshape(Diff[0:N], (N, 1))
    DiffN = np.vstack((DiffN, (np.zeros((4, 1)))))

    MD = np.c_[M, DiffN]
    MD = np.vstack([MD, np.zeros((1, len(M)+1))])

    def EF_tot(year):
       i = list(YearRange).index(year)
       CO2_specific_exergy = 0.45 #KJ/g
       CH4_specific_exergy = 51.84 #KJ/g
       EF_CO2 = data_EF[0, i]*CO2_specific_exergy*1000/3600 #dimensionless
       EF_CH4 = data_EF[2, i]*CH4_specific_exergy*1000/3600 #dimensionless
       EF_tot = EF_CO2 + EF_CH4
       return EF_tot

    EEC_gen = M[N+3, N] - M[N, N+3]
    Inv_gen = Diff[N+1]
    Exergy_gen = EEC_gen + Inv_gen
    Exergy_waste = EF_tot(year)*Exergy_gen
    Exergy_des = np.sum(DiffN) - Exergy_waste
    Exergy_in = M[N+2, :].sum() + M[N+3, :].sum()
    Exergy_out = M[0:N, N+2].sum() + M[0:N, N+3].sum()

    Eff_utl = Exergy_des / Exergy_in
    Eff_cov = (Exergy_out + Exergy_gen) / Exergy_in
    Tif = np.sum(TiM[0:N])
    Tif_ratio = Tif/Exergy_in

    print(year, Eff_utl, Eff_cov)
```

Appendix 5: ENA results of Singapore case study

Notation

C: Competition; XEY: X exploits Y; YEX: Y exploits X; M: Mutualism

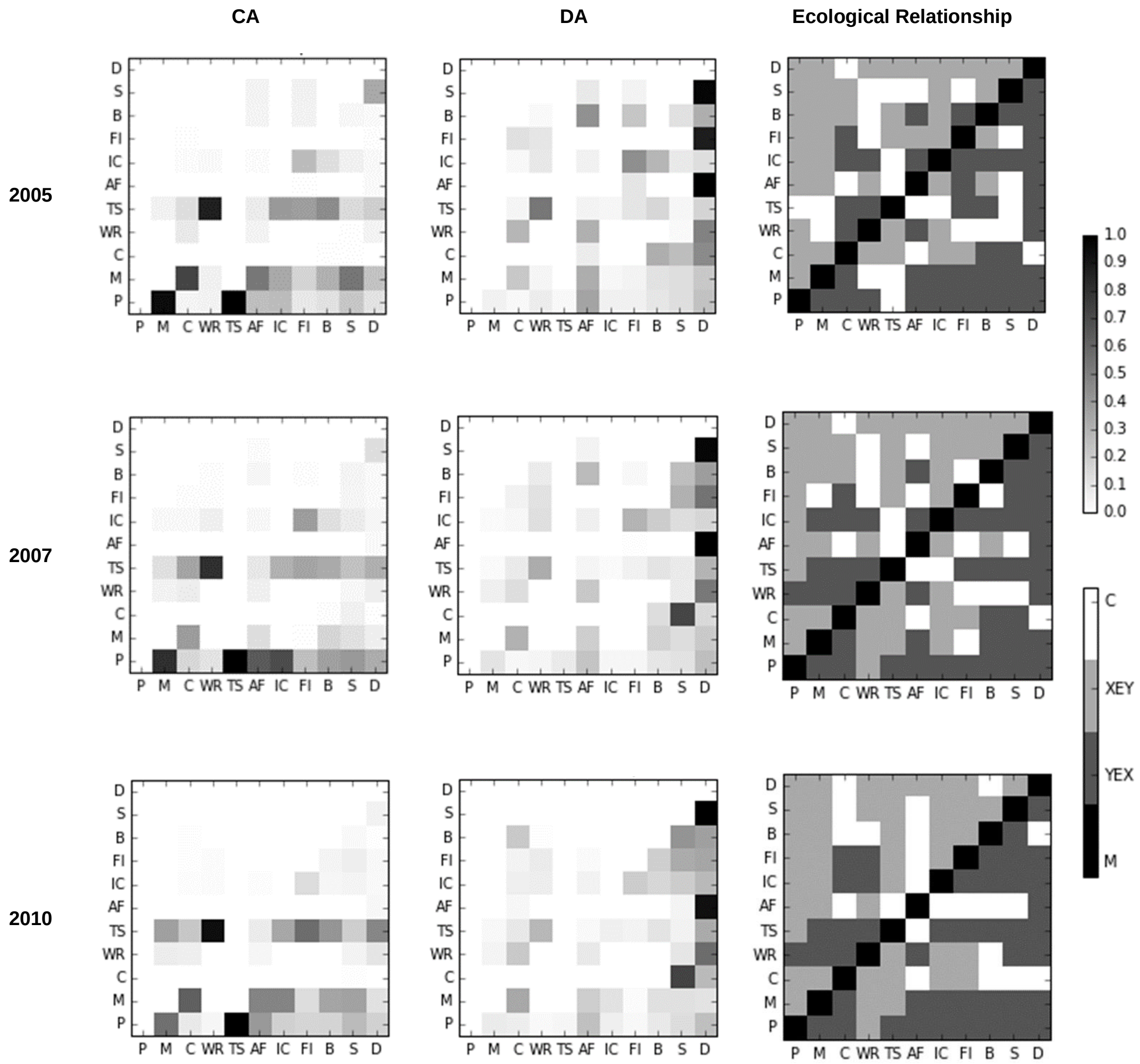

Table A5.1: Singapore ENA Results (Control Allocation, Dependency Allocation and Ecological Relationship) using the exergy input-output flows, for all six years.

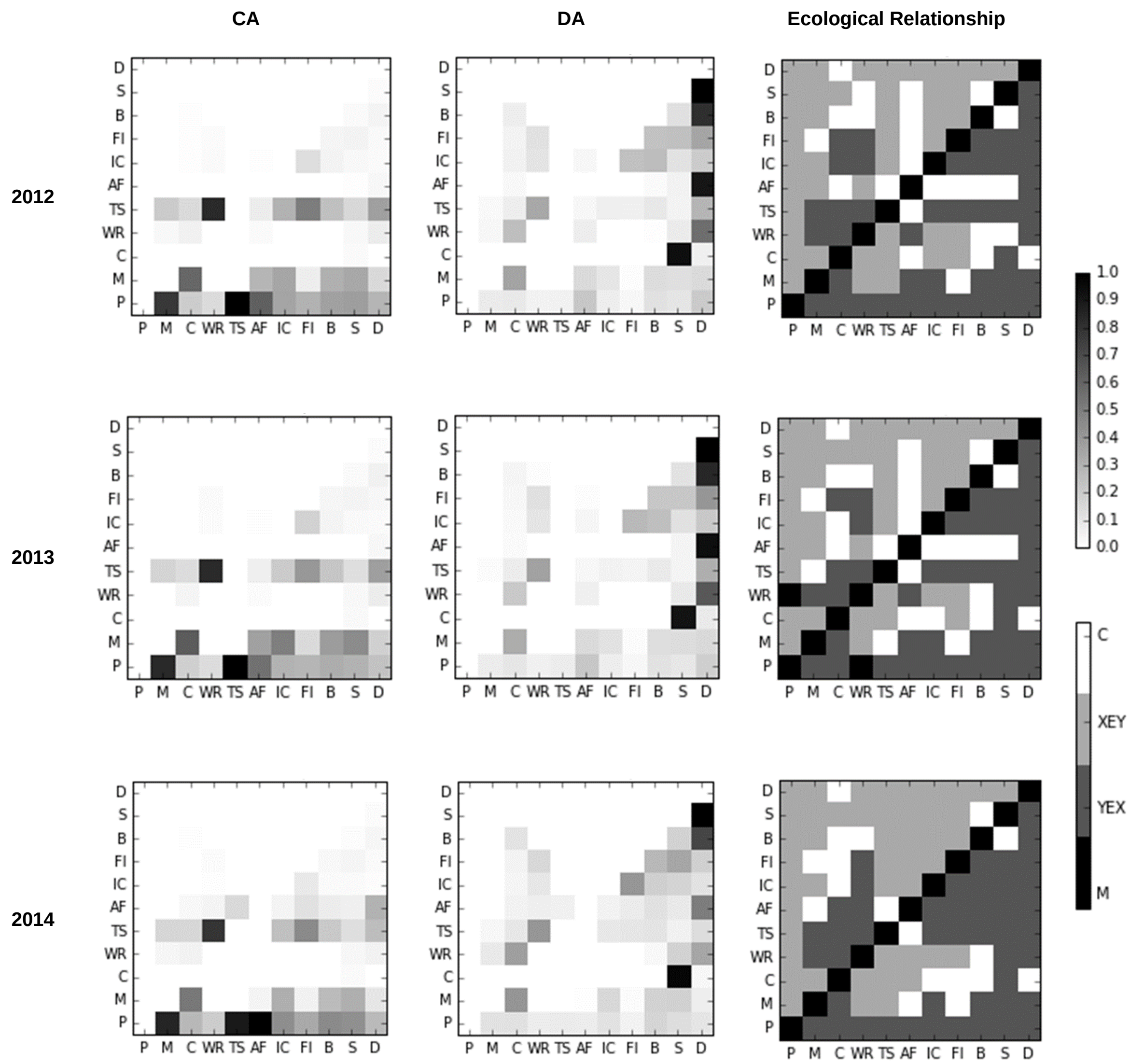

Table A5.1: (Cont'd) Singapore ENA Results (Control Allocation, Dependency Allocation and Ecological Relationship) using the exergy input-output flows, for all six years.

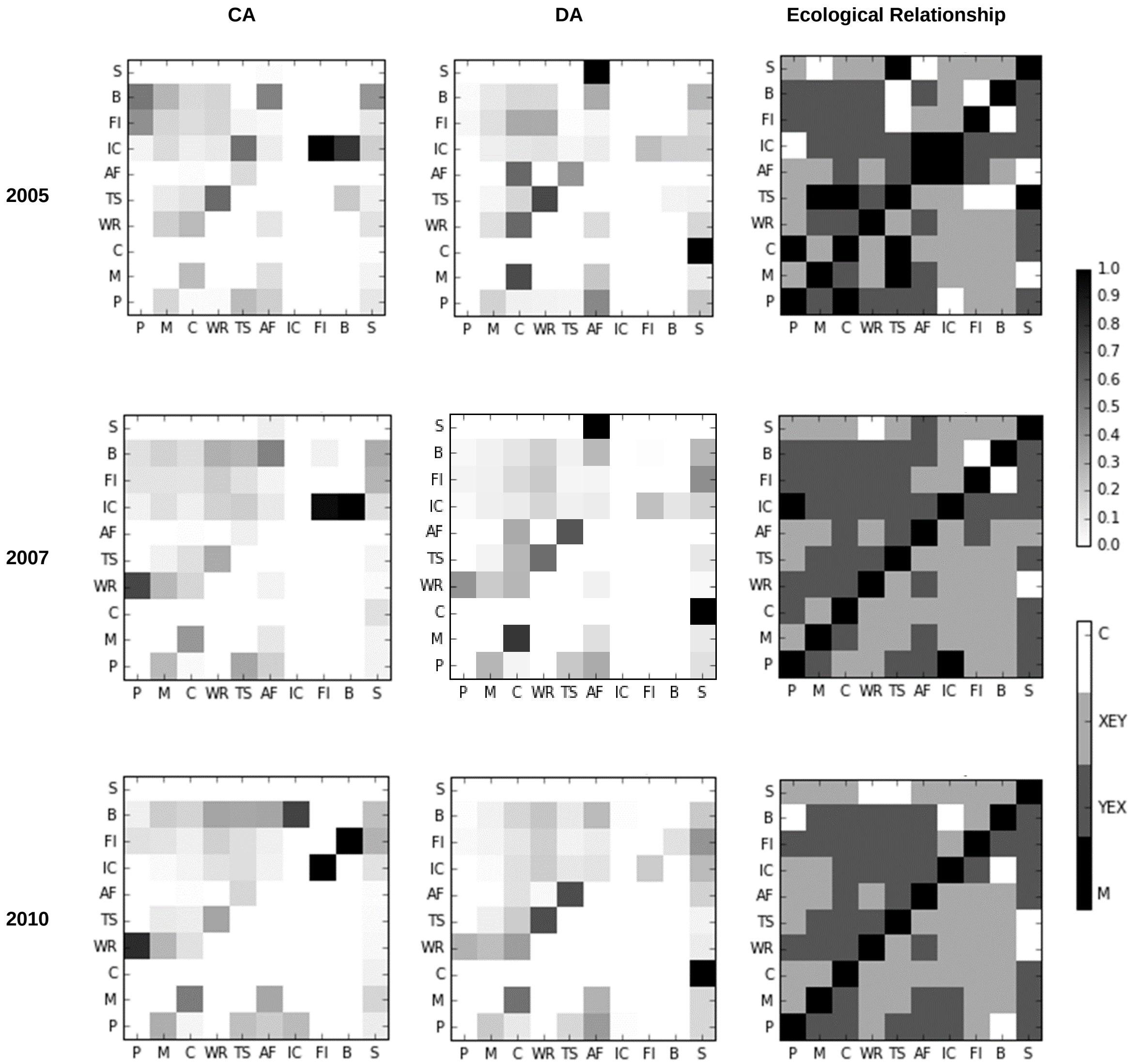

Table A5.2: Singapore ENA Results (Control Allocation, Dependency Allocation and Ecological Relationship) using the monetary input-output flows, for all six years.

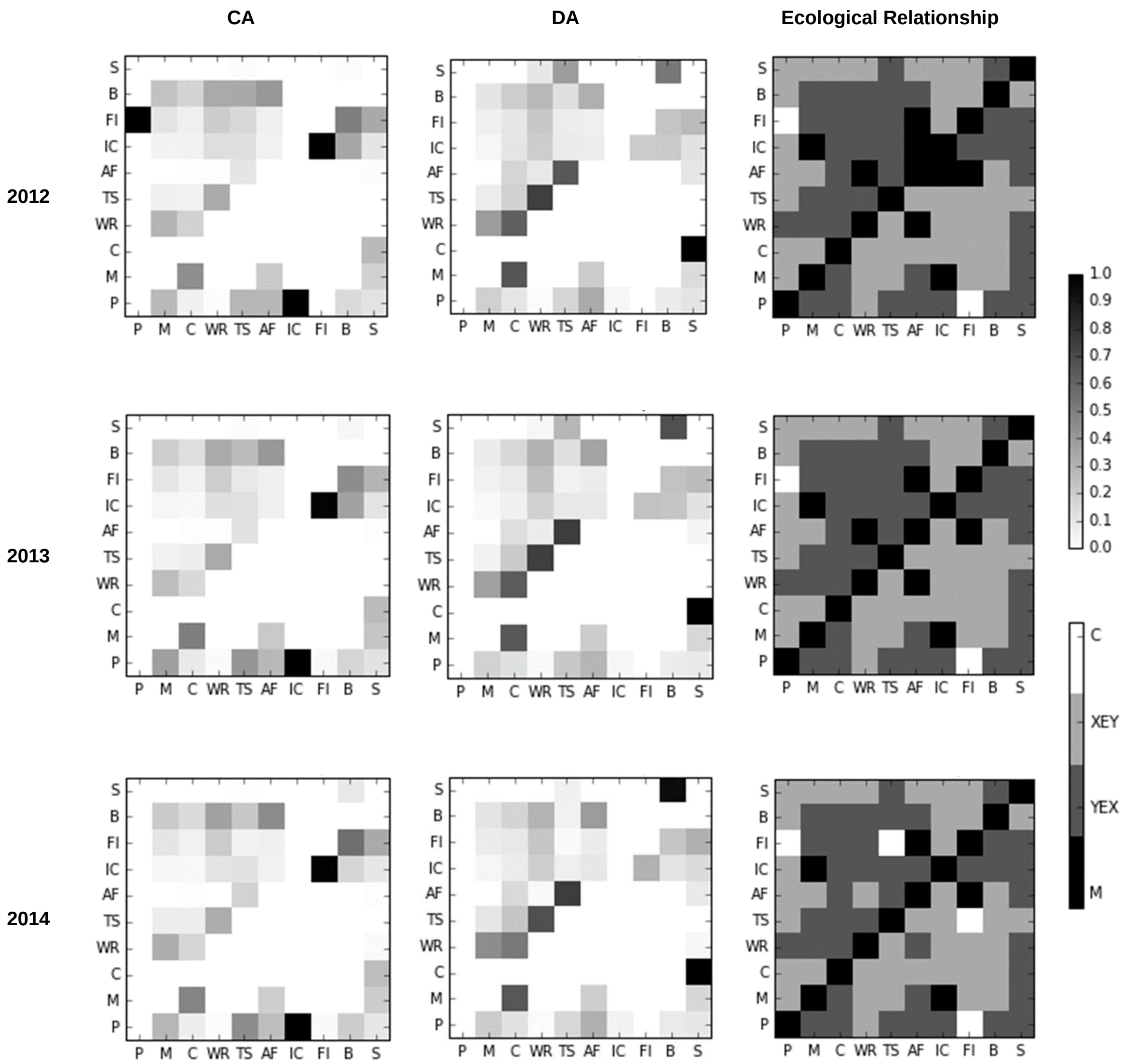

Table A5.2: (Cont'd) Singapore ENA Results (Control Allocation, Dependency Allocation and Ecological Relationship) using the monetary input-output flows, for all six years.

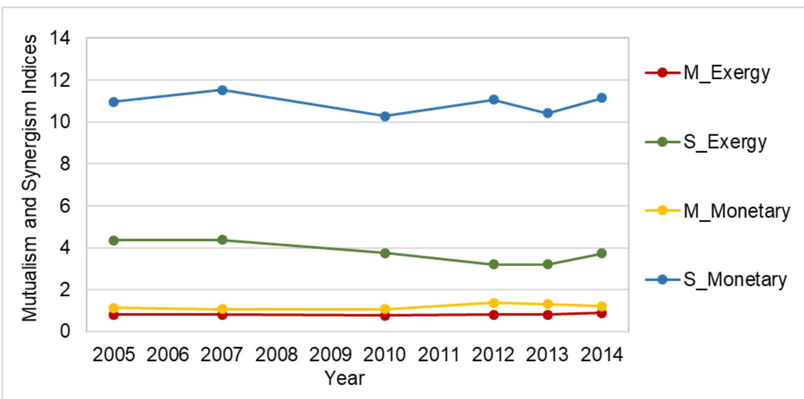

Table A5.3: ENA results of mutualism, M, and synergism, S, indices for exergy and monetary input-output flows, for all six years.

Appendix 6: Script for Great Britain case study

The script and other supplementary data are available for download at:
https://drive.google.com/drive/folders/1DXn2qX4TqEu7xYKkK19og3wdszA65EPV?usp=sharing

```
from openpyxl import Workbook
import xlrd
import numpy as np
import pandas as pd
import EEA as EEA


########################################
wb = Workbook()
ws = wb.active

book_comdata = xlrd.open_workbook('Comtradeflows.xlsx')
sheet_HS = book_comdata.sheet_by_name("HS1996-CPA1996")
data_HS = [[sheet_HS.cell_value(r, c)  for c in range(0, 2)] for r in range(0,
  sheet_HS.nrows)]
data_HS = np.asarray(data_HS)

A_section = range(1, 3)
B_section = range(5, 6)
C_section = range(10, 15)
D_section = range(15, 38)
E_section = range(40, 42)

A = []
B = []
C = []
D = []
E = []
NA = []
HS96_CPA96 = {}
List_HS_4 = []

for i in range(0, len(data_HS)):
    CPA_2 = int(str(data_HS[i, 1])[:2])
    HS_4 = int(str(data_HS[i, 0])[:4])

    if CPA_2 in A_section:
        CPA_list = 'A'
```

```
        if HS_4 not in A:
            A.append(HS_4)
    if CPA_2 in B_section:
        CPA_list = 'B'
        if HS_4 not in B:
            B.append(HS_4)
    if CPA_2 in C_section:
            CPA_list = 'C'
            if HS_4 not in C:
                C.append(HS_4)
    if CPA_2 in D_section:
        CPA_list = 'D'
        if HS_4 not in D:
            D.append(HS_4)
    if CPA_2 in E_section:
        CPA_list = 'E'
        if HS_4 not in E:
            E.append(HS_4)
    if HS_4 in [3704, 3705, 3706]:
        CPA_list = 'D'
        if HS_4 not in D:
            D.append(HS_4)
    if CPA_2 not in A_section:
        if CPA_2 not in B_section:
            if CPA_2 not in C_section:
                if CPA_2 not in D_section:
                    if CPA_2 not in E_section:
                        if HS_4 not in NA:
                            NA.append(HS_4)
    if HS_4 not in NA:
        HS96_CPA96[HS_4] = CPA_list

NA.append(2852)
NA.append(2853)
NA.append(3825)
NA.append(4112)
NA.append(4113)
NA.append(4114)
NA.append(4115)
NA.append(6003)
NA.append(6004)
NA.append(6005)
NA.append(6006)
NA.append(8486)
NA.append(8487)
NA.append(9999)

HSPCount = {}
List_HS_4 = A+B+C+D+E+NA
for i in List_HS_4:
    HSPCount[i] = List_HS_4.count(i)

sheet_exconvdata = book_comdata.sheet_by_name("HS2012ExConv")
ncom_exconvdata = (sheet_exconvdata.nrows)
```

```
data_exconv = [[sheet_exconvdata.cell_value(r, c)  for c in range(0, 2)] for r in
   range(1, ncom_exconvdata)]
ExConv = np.asarray(data_exconv)
list_ExConvCom = list(ExConv[:, 0])

#####################################
book_LAU_FUA = xlrd.open_workbook('LAU_FUA_V_2011.xlsx')
sheet_LAU_FUA = book_LAU_FUA.sheet_by_name('LAU_FUA_V_2011')
Data_LAU_FUA = ([[sheet_LAU_FUA.cell_value(r, c)  for c in range(0, sheet_LAU_FUA
   .ncols)] for r in range(1, sheet_LAU_FUA.nrows)])
df_LAU_FUA = pd.DataFrame(Data_LAU_FUA)

List_FUA = []
List_LAU = []
for FUA_names in df_LAU_FUA.iloc[:,5]:
    if FUA_names not in List_FUA:
        List_FUA.append(FUA_names)
FUA_LAU_Codes = {FUA: [] for FUA in List_FUA}
for FUA in List_FUA:
    for i in range(0, df_LAU_FUA.shape[0]):
        if df_LAU_FUA.iloc[i, 5] == FUA:
          FUA_LAU_Codes[FUA].append(df_LAU_FUA.iloc[i, 0])

book_LAU_NUTS2 = xlrd.open_workbook('LAU_NUTS2_2011.xlsx')
sheet_LAU_NUTS2 = book_LAU_NUTS2.sheet_by_name('LAU_NUTS2_2011')
Data_LAU_NUTS2 = ([[sheet_LAU_NUTS2.cell_value(r, c) for c in [0, 7]] for r in
   range(1, sheet_LAU_NUTS2.nrows)])
df_LAU_NUTS2 = pd.DataFrame(Data_LAU_NUTS2)
List_NUTS2_RCode = range(220, 257)
NUTS2_LAU_Codes = {RCode: [] for RCode in List_NUTS2_RCode}
for RCode in List_NUTS2_RCode:
    for i in range(0, df_LAU_NUTS2.shape[0]):
        if df_LAU_NUTS2.iloc[i, 1] == RCode:
          NUTS2_LAU_Codes[RCode].append(df_LAU_NUTS2.iloc[i, 0])

List_AggSec = ['ABDE Production', 'C Manufacturing', 'F Construction', 'GHI
   Distribution', 'J Information', 'K Finance', 'L Real estate', 'MN Professional'
   , 'OPQ Public services', 'RST Other services', 'Total GVA']
List_AggSec_Combine = ['ABDE Production', 'C Manufacturing', 'F Construction', '
   GHIJ Distribution', 'K Finance', 'L Real estate', 'MNOPQRST Other services', '
   Total GVA']
df_AggSec_GVA = {AggSec: [] for AggSec in List_AggSec}
book_UKGVA = xlrd.open_workbook('Regional GVA by Industry.xlsx')
for sheet_name in List_AggSec:
    sheet_load = book_UKGVA.sheet_by_name(sheet_name)
    Data_load = ([[sheet_load.cell_value(r, c)  for c in range(0, sheet_load.
   ncols)] for r in range(0, sheet_load.nrows)])
    df_dataload = pd.DataFrame(Data_load)
    df_AggSec_GVA[sheet_name].append(df_dataload)

FUA_NUTS2_RCode = {FUA: [] for FUA in List_FUA}
FUA_LAUs_incommon = []
for FUA in List_FUA:
    for LAU in FUA_LAU_Codes[FUA]:
```

```
        for rcode, lau_rlist in NUTS2_LAU_Codes.items():
            if LAU in lau_rlist:
                if rcode not in FUA_NUTS2_RCode[FUA]:
                    FUA_NUTS2_RCode[FUA].append(rcode)
    if len(FUA_NUTS2_RCode[FUA]) > 1:
        FUA_LAUs_incommon.append(FUA)

def Find_RCode_from_FUA(FUA):
    if FUA not in FUA_LAUs_incommon:
        return FUA_NUTS2_RCode[FUA]
    else:
        return FUA_NUTS2_RCode[FUA]
def Find_RCode_from_LAU(LAU):
    for rcode, lau_rlist in NUTS2_LAU_Codes.items():
        if LAU in lau_rlist:
             return rcode
def Find_FUA_from_LAU(LAU):
    for fua, lau_fualist in FUA_LAU_Codes.items():
        if LAU in lau_fualist:
            Find_fua = fua
    return Find_fua

#####################################
YearRange = range(2000, 2011)
FUA_Sector_Import = {FUA: [] for FUA in List_FUA}
FUA_Sector_Export = {FUA: [] for FUA in List_FUA}
FUA_Total_Import = {FUA: [] for FUA in List_FUA}
FUA_Total_Export = {FUA: [] for FUA in List_FUA}
FUA_Eff_Utilization = {FUA: [] for FUA in List_FUA}
FUA_Eff_Conversion = {FUA: [] for FUA in List_FUA}
FUA_Efficiency = {FUA: [] for FUA in List_FUA}

LAU_Sector_Import = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Sector_Export = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Total_Import = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Total_Export = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Eff_Utilization = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Eff_Conversion = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}
LAU_Efficiency = {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in
  List_FUA}

#####################################
#row/col to extract from EUREGIO spreadsheet
UK_NUTS2_RCode = list(range(220, 257))
cols_UK_EUREGIO = range(2974, 3492)
rows_UK_EUREGIO = range(2976, 3494)
nrow_IO = range(8, 3732)
ncol_IO = range(6, 3730)
```

```
ncol_FD = range(3737, 4801)
cols_UK_FD = range(4585, 4733)
rows_VA = range(3739, 3742)
Total_ss = 20
IO_ss = 14
Total_AG = 12
IO_AG = 8
RCode_UK_NUTS2 = np.arange(220, 257, 1)

#####################################
#Primary Sector Aggregation
List_Production_ss = range(0, 2)
List_Manufacturing_ss = range(2, 7)
List_Construction_ss = [7]
List_Distribution_ss = range(8, 11)
List_Finance_ss = [11]
List_RealEstates_ss = [12]
List_OtherServices_ss = [13]
List_Domestic_ss = [14]
List_Capital_ss = [15]

#Secondary sectors
#EEC importing from:
List_EEC_ss = range(7, IO_ss) #including Domestic sector
List_Intercity_EEC_ss = range(7, Total_ss)

#####################################
for year in range(2000,2011):
    #for year in YearRange:
    sheet_tradedata = book_comdata.sheet_by_name('Comtrade%s'%year)
    ncom_tradedata = (sheet_tradedata.nrows)
    data_tradedata = [[sheet_tradedata.cell_value(r, c)  for c in (0, 1, 6)] for
  r in range(1, ncom_tradedata)]
    M_tradedata = np.asarray(data_tradedata)
    M_tradedata = np.ndarray.astype(M_tradedata, float, order = 'K', casting = '
  unsafe', subok = True, copy = True)
    HSCode = M_tradedata[:, 0]
    HSCodelist = np.ndarray.tolist(np.copy(HSCode))

    #Exergy Import/Export in TJ
    Exergy_imCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1))),
  np.zeros((len(HSCode), 1))))
    for i in range(0, len(M_tradedata)):
        for com in list_ExConvCom:
            if Exergy_imCom[i, 0] == com:
                Exergy_imCom[i, 1] = (np.multiply(M_tradedata[i, 1], ExConv[
  list_ExConvCom.index(com), 1])*1e-6)/HSPCount[int(com)]
    Exergy_exCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1))),
  np.zeros((len(HSCode), 1))))
    for i in range(0, len(M_tradedata)):
        for com in list_ExConvCom:
            if Exergy_exCom[i, 0] == com:
                Exergy_exCom[i, 1] = (np.multiply(M_tradedata[i, 2], ExConv[
  list_ExConvCom.index(com), 1])*1e-6)/HSPCount[int(com)]
```

```python

    Exergy_im = Exergy_imCom[:, 1]
    Exergy_ex = Exergy_exCom[:, 1]

#####################################
    Exergy_A = []
    for code in A:
        if code in HSCodelist:
            Exergy_A.append(HSCodelist.index(code))
            Exergy_Import_sectionA = sum(Exergy_im[Exergy_A])
            Exergy_Export_sectionA = sum(Exergy_ex[Exergy_A])

    Exergy_B = []
    for code in B:
        if code in HSCodelist:
            Exergy_B.append(HSCodelist.index(code))
            Exergy_Import_sectionB = sum(Exergy_im[Exergy_B])
            Exergy_Export_sectionB = sum(Exergy_ex[Exergy_B])

    Exergy_C = []
    for code in C:
        if code in HSCodelist:
            Exergy_C.append(HSCodelist.index(code))
            Exergy_Import_sectionC = sum(Exergy_im[Exergy_C])
            Exergy_Export_sectionC = sum(Exergy_ex[Exergy_C])

    Exergy_D = []
    for code in D:
        if code in HSCodelist:
            Exergy_D.append(HSCodelist.index(code))
            Exergy_Import_sectionD = sum(Exergy_im[Exergy_D])
            Exergy_Export_sectionD = sum(Exergy_ex[Exergy_D])

    Exergy_E = []
    for code in E:
        if code in HSCodelist:
            Exergy_E.append(HSCodelist.index(code))
            Exergy_Import_sectionE = sum(Exergy_im[Exergy_E])
            Exergy_Export_sectionE = sum(Exergy_ex[Exergy_E])

    Exergy_Import_Production = Exergy_Import_sectionA + Exergy_Import_sectionB + Exergy_Import_sectionC + Exergy_Import_sectionE
    Exergy_Import_Manufacturing = Exergy_Import_sectionD
    Exergy_Export_Production = Exergy_Export_sectionA + Exergy_Export_sectionB + Exergy_Export_sectionC + Exergy_Export_sectionE
    Exergy_Export_Manufacturing = Exergy_Export_sectionD

    def ExergyImport(Production_or_Manufacturing, year):
        if  Production_or_Manufacturing == 'Production':
            return Exergy_Import_Production
        if  Production_or_Manufacturing == 'Manufacturing':
            return Exergy_Import_Manufacturing

    def ExergyExport(Production_or_Manufacturing, year):
```

```
        if   Production_or_Manufacturing == 'Production':
            return Exergy_Export_Production
        if   Production_or_Manufacturing == 'Manufacturing':
            return Exergy_Export_Manufacturing

    #####################################
    def LessIntercityExport_FuelProducts(year):
        sheet_tradedata = book_comdata.sheet_by_name('Comtrade%s'%year)
        ncom_tradedata = (sheet_tradedata.nrows)
        data_tradedata = [[sheet_tradedata.cell_value(r, c)  for c in (0, 1, 6)]
  for r in range(1, ncom_tradedata)]
        M_tradedata = np.asarray(data_tradedata)
        M_tradedata = np.ndarray.astype(M_tradedata, float, order = 'K', casting
  = 'unsafe', subok = True, copy = True)
        HSCode = M_tradedata[:, 0]
        HSCodelist = np.ndarray.tolist(np.copy(HSCode))

        #Exergy Import/Export in TJ
        Exergy_imCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1)
  )), np.zeros((len(HSCode), 1))))
        for i in range(0, len(M_tradedata)):
            for com in list_ExConvCom:
                if Exergy_imCom[i, 0] == com:
                    Exergy_imCom[i, 1] = (np.multiply(M_tradedata[i, 1], ExConv[
  list_ExConvCom.index(com), 1])*1e-6)/HSPCount[int(com)]
        Exergy_exCom = np.hstack(((np.reshape(M_tradedata[:, 0], (len(HSCode), 1)
  )), np.zeros((len(HSCode), 1))))
        for i in range(0, len(M_tradedata)):
            for com in list_ExConvCom:
                if Exergy_exCom[i, 0] == com:
                    Exergy_exCom[i, 1] = (np.multiply(M_tradedata[i, 2], ExConv[
  list_ExConvCom.index(com), 1])*1e-6)/HSPCount[int(com)]
        Exergy_ex = Exergy_exCom[:, 1]

        for i in range(0, len(Exergy_exCom)):
            if int(Exergy_exCom[i, 0])in range(2700, 2717):
                Exergy_exCom[i, 1] = 0
        Exergy_ex = Exergy_exCom[:, 1]

        Exergy_A = []
        for code in A:
            if code in HSCodelist:
                Exergy_A.append(HSCodelist.index(code))
                Exergy_Export_sectionA = sum(Exergy_ex[Exergy_A])

        Exergy_B = []
        for code in B:
            if code in HSCodelist:
                Exergy_B.append(HSCodelist.index(code))
                Exergy_Export_sectionB = sum(Exergy_ex[Exergy_B])

        Exergy_C = []
        for code in C:
            if code in HSCodelist:
```

```
            Exergy_C.append(HSCodelist.index(code))
            Exergy_Export_sectionC = sum(Exergy_ex[Exergy_C])

    Exergy_E = []
    for code in E:
        if code in HSCodelist:
            Exergy_E.append(HSCodelist.index(code))
            Exergy_Export_sectionE = sum(Exergy_ex[Exergy_E])

    Exergy_Export_Production = Exergy_Export_sectionA + Exergy_Export_sectionB + Exergy_Export_sectionC + Exergy_Export_sectionE
    return Exergy_Export_Production

#####################################
book_EUREGIO = xlrd.open_workbook('RegionalIOtable_%s.xlsx'%year)
sheet_EUREGIO = book_EUREGIO.sheet_by_name("%s"%year)
Data_EUREGIO = [[sheet_EUREGIO.cell_value(r, c)  for c in range(0, sheet_EUREGIO.ncols)] for r in range(0, sheet_EUREGIO.nrows)]
df_EUREGIO = pd.DataFrame(Data_EUREGIO, dtype='float')

#Load import data
Data_UK_Import_df = df_EUREGIO.iloc[nrow_IO,cols_UK_EUREGIO]
Array_UK_Import_df=  Data_UK_Import_df.to_numpy()
Array_UK_Import_df[Array_UK_Import_df == ''] = 0
Array_UK_Import_df = np.ndarray.astype(Array_UK_Import_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
for i in range(2980, 3498):
    Array_UK_Import_df[i, :] = 0
Array_UK_Import = np.copy(Array_UK_Import_df)

#Load export data
Data_UK_Export_df = df_EUREGIO.iloc[rows_UK_EUREGIO,ncol_IO]
Array_UK_Export_df = Data_UK_Export_df.to_numpy()
Array_UK_Export_df[Array_UK_Export_df == ''] = 0
Array_UK_Export_df = np.ndarray.astype(Array_UK_Export_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
for i in range(2984, 3502):
    Array_UK_Export_df[:, i] = 0
Array_UK_Export = np.copy(Array_UK_Export_df)

#Load input-output data
Data_UK_InterIO_df = df_EUREGIO.iloc[rows_UK_EUREGIO,cols_UK_EUREGIO]
Array_UK_InterIO_df = Data_UK_InterIO_df.to_numpy()
Array_UK_InterIO_df[Array_UK_InterIO_df == ''] = 0
Array_UK_InterIO_df = np.ndarray.astype(Array_UK_InterIO_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
Array_UK_InterIO = np.copy(Array_UK_InterIO_df)

#Load final demand data
#[Consumption by household, Consumption by government, Net capital formation, Inventory adjustment]
Data_UK_FD_df = df_EUREGIO.iloc[nrow_IO, cols_UK_EUREGIO]
Array_UK_FD_df = Data_UK_FD_df.to_numpy()
Array_UK_FD_df[Array_UK_FD_df == ''] = 0
```

```
    Array_UK_FD_df = np.ndarray.astype(Array_UK_FD_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
    for i in range(2980, 3498):
        Array_UK_FD_df[i, :] = 0
    Array_UK_FD = np.copy(Array_UK_FD_df)
    #[Import by household consumption]
    List_FinalDemand_HouseholdConsumption = []
    for i in np.arange(0, len(Array_UK_FD[0]), 4):
       List_FinalDemand_HouseholdConsumption.append(i)
    Array_UK_FD_HH = np.r_[Array_UK_FD[:, List_FinalDemand_HouseholdConsumption]]
    #[Import by government consumption]
    List_FinalDemand_GovermentConsumption = []
    for i in np.arange(1, len(Array_UK_FD[0]), 4):
       List_FinalDemand_GovermentConsumption.append(i)
    Array_UK_FD_GOV = np.r_[Array_UK_FD[:, List_FinalDemand_GovermentConsumption]]
    #[Net Capital Formation - Import by UK]
    List_FinalDemand_CapitalFormation = []
    for i in np.arange(2, len(Array_UK_FD[0]), 4):
       List_FinalDemand_CapitalFormation.append(i)
    Array_UK_FD_CF = np.r_[Array_UK_FD[:, List_FinalDemand_CapitalFormation]]

    #Load FD export data
    Data_UK_FD_Export_df = df_EUREGIO.iloc[rows_UK_EUREGIO, ncol_FD]
    Array_UK_FD_Export_df = Data_UK_FD_Export_df.to_numpy()
    Array_UK_FD_Export_df[Array_UK_FD_Export_df == ''] = 0
    Array_UK_FD_Export_df = np.ndarray.astype(Array_UK_FD_Export_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
    for i in range(848, 996):
        Array_UK_FD_Export_df[:, i] = 0
    Array_UK_FD_Export = np.copy(Array_UK_FD_Export_df)
    Array_UK_FD_Export_Sum = np.sum(Array_UK_FD_Export, axis = 1)

    #UK_FD_Inter/Intra
    Data_UK_FD_Intercity_df = df_EUREGIO.iloc[rows_UK_EUREGIO, cols_UK_FD]
    Array_UK_FD_Intercity_df = np.asarray(Data_UK_FD_Intercity_df)
    Array_UK_FD_Intercity_df[Array_UK_FD_Intercity_df == ''] = 0
    Array_UK_FD_Intercity_df = np.ndarray.astype(Array_UK_FD_Intercity_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
    Array_UK_FD_Intercity = np.copy(Array_UK_FD_Intercity_df)
    #[Intercity Import by household consumption]
    List_FinalDemand_HouseholdConsumption_Intercity = []
    for i in np.arange(0, len(Array_UK_FD_Intercity[0]), 4):
       List_FinalDemand_HouseholdConsumption_Intercity.append(i)
    Array_UK_FD_Intercity_HH = np.r_[Array_UK_FD_Intercity[:, List_FinalDemand_HouseholdConsumption_Intercity]]
    Array_UK_FD_Intracity_HH = np.copy(Array_UK_FD_Intercity_HH)
    #[Intercity Import by government consumption]
    List_FinalDemand_GovermentConsumption_Intercity = []
    for i in np.arange(1, len(Array_UK_FD_Intercity[0]), 4):
       List_FinalDemand_GovermentConsumption_Intercity.append(i)
    Array_UK_FD_Intercity_GOV = np.r_[Array_UK_FD_Intercity[:, List_FinalDemand_GovermentConsumption_Intercity]]
    Array_UK_FD_Intracity_GOV = np.copy(Array_UK_FD_Intercity_GOV)
```

```
    #[Intercity Net Capital Formation Import and Export]
    List_FinalDemand_CapitalFormation_Intercity = []
    for i in np.arange(2, len(Array_UK_FD_Intercity[0]), 4):
        List_FinalDemand_CapitalFormation_Intercity.append(i)
    Array_UK_FD_Intercity_CF = np.r_[Array_UK_FD_Intercity[:, List_FinalDemand_CapitalFormation_Intercity]]
    Array_UK_FD_Intracity_CF = np.copy(Array_UK_FD_Intercity_CF)

    #[IntraInventory adjustment] #Intrasystem Inventory
    List_FinalDemand_IntraInventory = []
    for i in np.arange(3, len(Array_UK_FD_Intercity[0]), 4):
        List_FinalDemand_IntraInventory.append(i)
        Array_UK_FD_IntraInv = np.r_[Array_UK_FD_Intercity[:, List_FinalDemand_IntraInventory]]
    Array_UK_FD_IntraInv_Addition = np.copy(Array_UK_FD_IntraInv)
    Array_UK_FD_IntraInv_Addition[Array_UK_FD_IntraInv_Addition <= 0] = 0
    Array_UK_FD_IntraInv[Array_UK_FD_IntraInv >= 0] = 0
    Array_UK_FD_IntraInv_Reduction = np.absolute(Array_UK_FD_IntraInv)

    #load value added data
    Data_UK_VA_df = df_EUREGIO.iloc[rows_VA,cols_UK_EUREGIO]
    Array_UK_VA_df = Data_UK_VA_df.to_numpy()
    Array_UK_VA_df[Array_UK_VA_df == ''] = 0
    Array_UK_VA_df = np.ndarray.astype(Array_UK_VA_df, float, order = 'K', casting = 'unsafe', subok = True, copy = True)
    Array_UK_VA = np.copy(Array_UK_VA_df)
    Array_UK_VA_Sum = np.sum(Array_UK_VA, axis = 0)

    #####################################
    #Create dictionaries for UK NUTS2 regions:

    UK_NUTS2_IntraIO_AggSec = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Total = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Sector = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}

    UK_NUTS2_Intercity_Export_Exergy_Total = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Export_Exergy_Sector = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Export_Exergy_EEC = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Export_Exergy_Goods = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Import_Exergy_Total = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Import_Exergy_Sector = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Import_Exergy_EEC = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Import_Exergy_Goods = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Export = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Import = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
```

```
    UK_NUTS2_Intercity_Import_CapitalOut = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity_Export_CapitalIn = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_Intercity_CF_Export = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Intercity = {reg: [] for reg in UK_NUTS2_RCode}

    UK_NUTS2_Import_CapitalOut = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_CapitalIn = {reg: [] for reg in UK_NUTS2_RCode}

    UK_NUTS2_IntraIO = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_VA_Sum = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}

    UK_NUTS2_Export_Exergy_Total_LESS = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Sector_LESS = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_EEC_LESS = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Goods_LESS = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}

    UK_NUTS2_Export_Exergy_Total = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Sector = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_EEC = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export_Exergy_Goods = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Import_Exergy_Total = {reg:[] for reg in UK_NUTS2_RCode}
    UK_NUTS2_Import_Exergy_Sector = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Import_Exergy_EEC = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Import_Exergy_Goods = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Import = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_Export = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_HH = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_GOV = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_CF = {reg: {ss: [] for ss in range (0, Total_ss)} for reg in UK_NUTS2_RCode}
    UK_NUTS2_InterIO = {reg: {ss: [] for ss in range (0, 1)} for reg in UK_NUTS2_RCode}

    UK_NUTS2_IntraIO = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_IntraInv_Addition = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_IntraInv_Reduction = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_Intercity_HH = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_Intercity_GOV = {reg: [] for reg in UK_NUTS2_RCode}
    UK_NUTS2_FD_Intercity_CF = {reg: [] for reg in UK_NUTS2_RCode}
```

```
    EEC_EURO_RCode = {reg: [] for reg in UK_NUTS2_RCode}
    for RCode in UK_NUTS2_RCode:
        EEC_EURO_RCode[RCode] = EEA.ExchangeRate_EURO_GBP(year)*EEA.EEC_RCode(year, RCode)*1e6

    ######################################
    #International flows - from EUREGIO

    #UK_NUTS2_Importer_Exporter(UK_NUTS2_RCode_Import, ss_Importer, ss_Exporter):
    for RCode in UK_NUTS2_Import.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            j_list = []
            for j in range(0, IO_ss):
                k_list = []
                k_sum = 0
                for k in (np.arange(0,  len(Array_UK_Import), IO_ss)+j):
                    k_list.append(Array_UK_Import[(k), nkey_RCode*IO_ss+i])
                    k_sum = k_sum + Array_UK_Import[(k), nkey_RCode*IO_ss+i]
                j_list.append(k_sum)
            UK_NUTS2_Import[RCode][i].append(j_list)
            UK_NUTS2_Import[RCode][i].append(np.sum(j_list)) #total import

    #UK_NUTS2_Exporter_Importer(UK_NUTS2_RCode_Import, ss_Importer, ss_Exporter):
    for RCode in UK_NUTS2_Export.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            j_list = []
            for j in range(0, IO_ss):
                k_list = []
                k_sum = 0
                for k in (np.arange(0,  len(Array_UK_Export), IO_ss)+j):
                    k_list.append(Array_UK_Export[nkey_RCode*IO_ss+i, (k)])
                    k_sum = k_sum + Array_UK_Export[nkey_RCode*IO_ss + i, (k)]
                j_list.append(k_sum)
            UK_NUTS2_Export[RCode][i].append(j_list)
            UK_NUTS2_Export[RCode][i].append(np.sum(j_list)) #total export

                #UK_NUTS2_FD_Export - Add to UK_NUTS_Export sum
    for RCode in UK_NUTS2_Export:
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        FD_Export_sum = 0
        for i in range(0, IO_ss):
            FD_Export_sum = FD_Export_sum + Array_UK_FD_Export_Sum[i+(IO_ss*nkey_RCode)]
            #UK_NUTS2_Export[RCode][i].append(UK_NUTS2_Export[RCode][i][1])
        UK_NUTS2_Export[RCode][15].append(FD_Export_sum)
    #UK_NUTS2_Export[RCode][15] gives total capital FD export
        #UK_NUTS2_Export[RCode][i][3] gives total export incl. FD export

    #UK_NUTS2_FD_HH
    for RCode in UK_NUTS2_FD_HH.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, 1):
```

```
            j_list = []
            for j in range(0, IO_ss):
                k_list = []
                k_sum = 0
                for k in (np.arange(0,  len(Array_UK_FD_HH), IO_ss)+j):
                    k_list.append(Array_UK_FD_HH[(k), nkey_RCode])
                    k_sum = k_sum + Array_UK_FD_HH[(k), nkey_RCode]
                j_list.append(k_sum)
            UK_NUTS2_FD_HH[RCode][i].append(j_list)
            UK_NUTS2_FD_HH[RCode][i].append(np.sum(j_list)) #total household import

    #UK_NUTS2_FD_GOV
    for RCode in UK_NUTS2_FD_GOV.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, 1):
            j_list = []
            for j in range(0, IO_ss):
                k_list = []
                k_sum = 0
                for k in (np.arange(0,  len(Array_UK_FD_GOV), IO_ss)+j):
                    k_list.append(Array_UK_FD_GOV[(k), nkey_RCode])
                    k_sum = k_sum + Array_UK_FD_GOV[(k), nkey_RCode]
                j_list.append(k_sum)
            UK_NUTS2_FD_GOV[RCode][i].append(j_list)
            UK_NUTS2_FD_GOV[RCode][i].append(np.sum(j_list)) #total government import

    #UK_NUTS2_FD_CF #Import of stock capital formation
    for RCode in UK_NUTS2_FD_CF.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        FD_Export_sum = 0
        for i in range(0, IO_ss):
            FD_Export_sum = FD_Export_sum + Array_UK_FD_Export_Sum[i+(IO_ss*nkey_RCode)]
            j_list = []
            for j in range(0, IO_ss):
                k_list = []
                k_sum = 0
                for k in (np.arange(0,  len(Array_UK_FD_CF), IO_ss)+j):
                    k_list.append(Array_UK_FD_CF[(k), nkey_RCode])
                    k_sum = k_sum + Array_UK_FD_CF[(k), nkey_RCode]
                j_list.append(k_sum+FD_Export_sum)
            UK_NUTS2_FD_CF[RCode][i].append(j_list)
            UK_NUTS2_FD_CF[RCode][i].append(np.sum(j_list)+UK_NUTS2_Export[RCode][15])
      #total stock import capital formation

    #Merge UK_NUTS2_FD_HH and UK_NUTS2_FD_CF with UK_NUTS2_Import
    for RCode in UK_NUTS2_Import.keys():
       UK_NUTS2_Import[RCode][14].append(UK_NUTS2_FD_HH[RCode][0][0])
       UK_NUTS2_Import[RCode][14].append(UK_NUTS2_FD_HH[RCode][0][1])
     #sum of household import per sector
       UK_NUTS2_Import[RCode][15].append(UK_NUTS2_FD_CF[RCode][0][0])
```

```
        UK_NUTS2_Import[RCode][15].append(UK_NUTS2_FD_CF[RCode][0][1])
      #sum of capital import (by capital formation) per sector


    #UK_NUTS2_VA_Sum
    for RCode in UK_NUTS2_VA_Sum.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        i_list = []
        for i in range(0, IO_ss):
            i_list.append(Array_UK_VA_Sum[(nkey_RCode*IO_ss)+i])
        UK_NUTS2_VA_Sum[RCode][0].append(i_list)
        UK_NUTS2_VA_Sum[RCode][0].append(np.sum(i_list))

    #UK_NUTS2_Import_CapitalOut
    for RCode in UK_NUTS2_Import_CapitalOut:
        i_sum = 0
        for i in range(0, IO_ss+1):
            i_sum = i_sum + UK_NUTS2_Import[RCode][i][1]
        UK_NUTS2_Import_CapitalOut[RCode].append(i_sum)

    #UK_NUTS2_Export_CapitalIn
    for RCode in UK_NUTS2_Export_CapitalIn:
        i_sum = 0
        for i in range(0, IO_ss):
            i_sum = i_sum + UK_NUTS2_Export[RCode][i][1]
        UK_NUTS2_Export_CapitalIn[RCode].append(i_sum)

    #####################################
    #Intercity flows- from EUREGIO

    #UK_NUTS2_FD_Intercity_HH
    for RCode in UK_NUTS2_FD_Intercity_HH.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            Array_UK_FD_Intercity_HH[i+(IO_ss*nkey_RCode), nkey_RCode] = 0 #
  Intra_IO = 0
        j_list = []
        for j in range(0, IO_ss):
            k_list = []
            k_sum = 0
            for k in (np.arange(0,  len(Array_UK_FD_Intercity_HH), IO_ss)+j):
                k_list.append(Array_UK_FD_Intercity_HH[(k), nkey_RCode])
                k_sum = k_sum + Array_UK_FD_Intercity_HH[(k), nkey_RCode]
            j_list.append(k_sum)
        UK_NUTS2_FD_Intercity_HH[RCode].append(j_list)
        UK_NUTS2_FD_Intercity_HH[RCode].append(np.sum(j_list))
    #total household intercity import

    #UK_NUTS2_FD_Intercity_GOV
    for RCode in UK_NUTS2_FD_Intercity_GOV.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            Array_UK_FD_Intercity_GOV[i+(IO_ss*nkey_RCode), nkey_RCode] = 0 #
  Intra_IO = 0
```

```
        j_list = []
        for j in range(0, IO_ss):
            k_list = []
            k_sum = 0
            for k in (np.arange(0,  len(Array_UK_FD_Intercity_GOV), IO_ss)+j):
                k_list.append(Array_UK_FD_Intercity_GOV[(k), nkey_RCode])
                k_sum = k_sum + Array_UK_FD_Intercity_GOV[(k), nkey_RCode]
            j_list.append(k_sum)
        UK_NUTS2_FD_Intercity_GOV[RCode].append(j_list)
        UK_NUTS2_FD_Intercity_GOV[RCode].append(np.sum(j_list))
    #total government intercity import

    #UK_NUTS2_FD_Intercity_CF
    for RCode in UK_NUTS2_FD_Intercity_CF.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            Array_UK_FD_Intercity_CF[i+(IO_ss*nkey_RCode), nkey_RCode] = 0 # Intra_IO = 0
        Array_UK_FD_Intercity_CF_Sum = np.sum(Array_UK_FD_Intercity_CF, axis = 1)

        i_list = []
        for i in range(0, IO_ss):
            i_list.append(Array_UK_FD_Intercity_CF_Sum[i+(IO_ss*nkey_RCode)])
        UK_NUTS2_FD_Intercity_CF_Export[RCode].append(i_list)
        UK_NUTS2_FD_Intercity_CF_Export[RCode].append(np.sum(i_list))
    #total capital formation intercity export

        j_list = []
        for j in range(0, IO_ss):
            k_list = []
            k_sum = 0
            for k in (np.arange(0,  len(Array_UK_FD_Intercity_CF), IO_ss)+j):
                k_list.append(Array_UK_FD_Intercity_CF[(k), nkey_RCode])
                k_sum = k_sum + Array_UK_FD_Intercity_CF[(k), nkey_RCode]
            j_list.append(k_sum+UK_NUTS2_FD_Intercity_CF_Export[RCode][0][j])
        UK_NUTS2_FD_Intercity_CF[RCode].append(j_list)
        UK_NUTS2_FD_Intercity_CF[RCode].append(np.sum(j_list)+UK_NUTS2_FD_Intercity_CF_Export[RCode][1])
    #total capital formation intercity import

    #UK_NUTS2_FD_IntraInventory
    for RCode in UK_NUTS2_FD_IntraInv_Addition.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        j_list = []
        for j in range(0, IO_ss):
            k_list = []
            k_sum = 0
            for k in (np.arange(0,  len(Array_UK_FD_IntraInv_Addition), IO_ss)+j):
                k_list.append(Array_UK_FD_IntraInv_Addition[(k), nkey_RCode])
                k_sum = k_sum + Array_UK_FD_IntraInv_Addition[(k), nkey_RCode]
            j_list.append(k_sum)
        UK_NUTS2_FD_IntraInv_Addition[RCode].append(j_list)
        UK_NUTS2_FD_IntraInv_Addition[RCode].append(np.sum(j_list))
```

```
  #total intra inventory addition

  for RCode in UK_NUTS2_FD_IntraInv_Reduction.keys():
      nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
      j_list = []
      for j in range(0, IO_ss):
          k_list = []
          k_sum = 0
          for k in (np.arange(0,  len(Array_UK_FD_IntraInv_Reduction), IO_ss)+j):
              k_list.append(Array_UK_FD_IntraInv_Reduction[(k), nkey_RCode])
              k_sum = k_sum + Array_UK_FD_IntraInv_Reduction[(k), nkey_RCode]
          j_list.append(k_sum)
      UK_NUTS2_FD_IntraInv_Reduction[RCode].append(j_list)
      UK_NUTS2_FD_IntraInv_Reduction[RCode].append(np.sum(j_list))
  #total intra inventory reduction

  #Intercity flows
  #UK_NUTS2_Intercity_Importer_Exporter(UK_NUTS2_RCode_Import, ss_Importer, ss_Exporter):
  Array_UK_Inter_Import = np.copy(Array_UK_InterIO)
  for RCode in UK_NUTS2_Intercity_Import.keys():
      nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
      for i in range(0, IO_ss):
          for j in range(0, IO_ss):
             Array_UK_Inter_Import[i+(IO_ss*nkey_RCode), j+(IO_ss*nkey_RCode)] = 0 #Intra_IO = 0
      for k in range(0, IO_ss):
          m_list = []
          for m in range(0, IO_ss):
              n_list = []
              n_sum = 0
              for n in (np.arange(0,  len(Array_UK_Inter_Import), IO_ss) + m):
                  n_list.append(Array_UK_Inter_Import[(n), nkey_RCode*IO_ss + k])
                  n_sum = n_sum + Array_UK_Inter_Import[(n), nkey_RCode*IO_ss + k]
              m_list.append(n_sum)
          UK_NUTS2_Intercity_Import[RCode][k].append(m_list)
          UK_NUTS2_Intercity_Import[RCode][k].append(np.sum(m_list))
    #UK_NUTS2_Intercity_Import[RCode][0][1] gives total inter import

  #Merge UK_NUTS2_FD_Intercity_HH and UK_NUTS2_FD_Intercity_CF with UK_NUTS2_Inter_Import
  for RCode in UK_NUTS2_Import.keys():
     UK_NUTS2_Intercity_Import[RCode][14].append(UK_NUTS2_FD_Intercity_HH[RCode][0])
     UK_NUTS2_Intercity_Import[RCode][14].append(UK_NUTS2_FD_Intercity_HH[RCode][1])
   #sum of intercity household import per sector
     UK_NUTS2_Intercity_Import[RCode][15].append(UK_NUTS2_FD_Intercity_CF[RCode][0])
     UK_NUTS2_Intercity_Import[RCode][15].append(UK_NUTS2_FD_Intercity_CF[RCode][1])
```

```
     #sum of intercity capital import (by capital formation) per sector

    #UK_NUTS2_Intercity_Exporter_Importer(UK_NUTS2_RCode_Import, ss_Exporter, ss_Importer):
    Array_UK_Inter_Export = np.copy(Array_UK_InterIO)
    for RCode in UK_NUTS2_Intercity_Export.keys():
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        for i in range(0, IO_ss):
            for j in range(0, IO_ss):
                Array_UK_Inter_Export[i+(14*nkey_RCode), j+(IO_ss*nkey_RCode)] = 0 #Intra_IO = 0
        for k in range(0, IO_ss):
            m_list = []
            for m in range(0, IO_ss):
                n_list = []
                n_sum = 0
                for n in (np.arange(0,  len(Array_UK_Inter_Export), IO_ss) + m):
                    n_list.append(Array_UK_Inter_Export[nkey_RCode*IO_ss + k, n])
                    n_sum = n_sum + Array_UK_Inter_Export[nkey_RCode*IO_ss + k, n]
                m_list.append(n_sum)
            UK_NUTS2_Intercity_Export[RCode][k].append(m_list)
            UK_NUTS2_Intercity_Export[RCode][k].append(np.sum(m_list))
      #UK_NUTS2_Intercity_Export[RCode][0][1] gives total inter export
        UK_NUTS2_Intercity_Export[RCode][15].append(UK_NUTS2_FD_Intercity_CF_Export[RCode][1])
            #UK_NUTS2_Intercity_Export[RCode][k][3] gives total intercity export incl. CF export

    #UK_NUTS2_Intercity_Import_CapitalOut
    for RCode in UK_NUTS2_Intercity_Import_CapitalOut:
        i_sum = 0
        for i in range(0, IO_ss+1):
            i_sum = i_sum + UK_NUTS2_Intercity_Import[RCode][i][1]
        UK_NUTS2_Intercity_Import_CapitalOut[RCode].append(i_sum)

    #UK_NUTS2_Intercity_Export_CapitalIn
    for RCode in UK_NUTS2_Intercity_Export_CapitalIn:
        i_sum = 0
        for i in range(0, IO_ss):
            i_sum = i_sum + UK_NUTS2_Intercity_Export[RCode][i][1]
        UK_NUTS2_Intercity_Export_CapitalIn[RCode].append(i_sum)

    #####################################
    #IntraIO Sector Aggregation and Normalization
    #UK_NUTS2_IntraIO
    for RCode in UK_NUTS2_InterIO:
        nkey_RCode = np.ndarray.tolist(RCode_UK_NUTS2).index(RCode)
        Intra_IO = np.zeros((Total_ss, Total_ss))
        for i in range (0, IO_ss):
            for j in range (0, IO_ss):
                Intra_IO[i, j] = Array_UK_InterIO[i+(IO_ss*nkey_RCode), j+(IO_ss*nkey_RCode)]
        for i in range(0, IO_ss):
```

```
          Intra_IO[i, IO_ss] = Array_UK_FD_Intracity_HH[i+(IO_ss*nkey_RCode), nkey_RCode]
    #attach intracity Do consumption
          Intra_IO[i, IO_ss+1] = Array_UK_FD_Intracity_CF[i+(IO_ss*nkey_RCode), nkey_RCode]+Array_UK_FD_Export_Sum[i+(IO_ss*nkey_RCode)]+Array_UK_FD_Intercity_CF_Sum[i+(IO_ss*nkey_RCode)]
    #attach intracity Capital Formation
          Intra_IO[i, IO_ss+2] = UK_NUTS2_FD_IntraInv_Addition[RCode][0][i]
    #attach intracity inventory addition
      for j in range(0, IO_ss):
          Intra_IO[IO_ss+1, j] = UK_NUTS2_VA_Sum[RCode][0][0][j]
    #attach GVA input to each sector
          Intra_IO[IO_ss+2, j] = UK_NUTS2_FD_IntraInv_Reduction[RCode][0][j]
    #attach intracity inventory reduction
      Intra_IO[IO_ss+4, IO_ss] = UK_NUTS2_FD_HH[RCode][0][1]
      #Capital extended exergy flow to be computed from EEC
      Intra_IO[IO_ss+4, IO_ss+1] = UK_NUTS2_FD_CF[RCode][0][1]
      Intra_IO[IO_ss+1, IO_ss+4] = UK_NUTS2_Export[RCode][15][0]
      UK_NUTS2_IntraIO[RCode].append(Intra_IO)

  for RCode in UK_NUTS2_IntraIO_AggSec:
      IntraIO_AggSec_sort = np.zeros((Total_ss, Total_AG))
      for i in range(0, Total_ss):
          IntraIO_AggSec_sort[i, 0] = sum(UK_NUTS2_IntraIO[RCode][0][i, list(range(0, 2))])
          IntraIO_AggSec_sort[i, 1] = sum(UK_NUTS2_IntraIO[RCode][0][i, list(range(2,7))])
          IntraIO_AggSec_sort[i, 2] = UK_NUTS2_IntraIO[RCode][0][i, 7]
          IntraIO_AggSec_sort[i, 3] = sum(UK_NUTS2_IntraIO[RCode][0][i, list(range(8, 11))])
          IntraIO_AggSec_sort[i, 4] = UK_NUTS2_IntraIO[RCode][0][i, 11]
          IntraIO_AggSec_sort[i, 5] = UK_NUTS2_IntraIO[RCode][0][i, 12]
          IntraIO_AggSec_sort[i, 6] = UK_NUTS2_IntraIO[RCode][0][i, 13]
          IntraIO_AggSec_sort[i, 7] = UK_NUTS2_IntraIO[RCode][0][i, 14]
          IntraIO_AggSec_sort[i, 8] = UK_NUTS2_IntraIO[RCode][0][i, 15]
      IntraIO_AggSec = np.zeros((Total_AG, Total_AG))
      for j in range(0, Total_AG):
          IntraIO_AggSec[0, j] = sum(IntraIO_AggSec_sort[list(range(0, 2)), j])
          IntraIO_AggSec[1, j] = sum(IntraIO_AggSec_sort[list(range(2, 7)), j])
          IntraIO_AggSec[2, j] = IntraIO_AggSec_sort[7, j]
          IntraIO_AggSec[3, j] = sum(IntraIO_AggSec_sort[list(range(8, 11)), j])
          IntraIO_AggSec[4, j] = IntraIO_AggSec_sort[11, j]
          IntraIO_AggSec[5, j] = IntraIO_AggSec_sort[12, j]
          IntraIO_AggSec[6, j] = IntraIO_AggSec_sort[13, j]
          IntraIO_AggSec[7, j] = IntraIO_AggSec_sort[14, j]
          IntraIO_AggSec[8, j] = IntraIO_AggSec_sort[15, j]
      UK_NUTS2_IntraIO_AggSec[RCode].append(IntraIO_AggSec)
      UK_NUTS2_IntraIO_AggSec[RCode].append(np.sum(IntraIO_AggSec, axis = 1)) # total inflow

  #Matrix normalization - based on total import
  for RCode in UK_NUTS2_IntraIO_AggSec:
      IntraIO_AggSec_Normalization = np.zeros((Total_AG, Total_AG))
```

```
      for i in range(0, Total_AG-3):
          for j in range(0, Total_AG-3):
              if i == 7:
                  IntraIO_AggSec_Normalization[i, j] = 0
              else:
                  IntraIO_AggSec_Normalization[i, j] = UK_NUTS2_IntraIO_AggSec[RCode][0][i, j]/UK_NUTS2_IntraIO_AggSec[RCode][1][i]
      UK_NUTS2_IntraIO_AggSec[RCode].append(IntraIO_AggSec_Normalization)

  UK_FUA_IntraIO_AggSec = {FUA: [] for FUA in List_FUA}
  for FUA in UK_FUA_IntraIO_AggSec:
      FUA_IntraIO = np.zeros((Total_AG, Total_AG))
      for RCode in FUA_NUTS2_RCode[FUA]:
          for i in range(0, Total_AG):
              for j in range(0, Total_AG):
                  FUA_IntraIO[i, j] = FUA_IntraIO[i, j]+UK_NUTS2_IntraIO_AggSec[RCode][0][i, j]
      UK_FUA_IntraIO_AggSec[FUA].append(FUA_IntraIO)
      UK_FUA_IntraIO_AggSec[FUA].append(np.sum(UK_FUA_IntraIO_AggSec[FUA][0], axis = 1))
  #Matrix normalization - based on total import
  for FUA in UK_FUA_IntraIO_AggSec:
      FUA_IntraIO_AggSec_Normalization = np.zeros((Total_AG, Total_AG))
      for i in range(0, Total_AG-3):
          for j in range(0, Total_AG-3):
              if i == 7:
                  FUA_IntraIO_AggSec_Normalization[i, j] = 0
              else:
                  FUA_IntraIO_AggSec_Normalization[i, j] = UK_FUA_IntraIO_AggSec[FUA][0][i, j]/UK_FUA_IntraIO_AggSec[FUA][1][i]
      UK_FUA_IntraIO_AggSec[FUA].append(FUA_IntraIO_AggSec_Normalization)

  def UK_NUTS2_IntraIO_AggSec_NormalizedMatrix(RCode):
      return UK_NUTS2_IntraIO_AggSec[RCode][2]
  def UK_FUA_IntraIO_AggSec_NormalizedMatrix(FUA):
      return UK_FUA_IntraIO_AggSec[FUA][2]
  def UK_LAU_IntraIO_AggSec_NormalizedMatrix(LAU):
      return UK_NUTS2_IntraIO_AggSec[Find_RCode_from_LAU(LAU)][2]

  #####################################
  #To work out the total intercity import
  List_UK_Intercity_Import_from_Production = []
  List_UK_Intercity_Import_from_Manufacturing = []
  for RCode in UK_NUTS2_Intercity_Import:
      for i in range(0, IO_ss+1):
          for ss in List_Production_ss:
              List_UK_Intercity_Import_from_Production.append(UK_NUTS2_Intercity_Import[RCode][i][0][ss])
          for ss in List_Manufacturing_ss:
              List_UK_Intercity_Import_from_Manufacturing.append(UK_NUTS2_Intercity_Import[RCode][i][0][ss])
  UK_Intercity_Import_from_Production = np.sum(List_UK_Intercity_Import_from_Production)
```

```
    UK_Intercity_Import_from_Manufacturing = np.sum(List_UK_Intercity_Import_from_Manufacturing)

    List_UK_Intercity_Export_from_Production = []
    List_UK_Intercity_Export_from_Manufacturing = []
    for RCode in UK_NUTS2_Intercity_Export:
        for i in range(0, IO_ss):
            for ss in List_Production_ss:
                List_UK_Intercity_Export_from_Production.append(UK_NUTS2_Intercity_Export[RCode][i][0][ss])
            for ss in List_Manufacturing_ss:
                List_UK_Intercity_Export_from_Manufacturing.append(UK_NUTS2_Intercity_Export[RCode][i][0][ss])
    UK_Intercity_Export_from_Production = np.sum(List_UK_Intercity_Export_from_Production)
    UK_Intercity_Export_from_Manufacturing = np.sum(List_UK_Intercity_Export_from_Manufacturing)

    #####################################
    #Normalized based on total goods import
    List_UK_Import_from_Production = []
    List_UK_Import_from_Manufacturing = []
    for RCode in UK_NUTS2_Import:
        for i in range(0, IO_ss+1):
            for ss in List_Production_ss:
                List_UK_Import_from_Production.append(UK_NUTS2_Import[RCode][i][0][ss])
            for ss in List_Manufacturing_ss:
                List_UK_Import_from_Manufacturing.append(UK_NUTS2_Import[RCode][i][0][ss])
    UK_Import_from_Production = np.sum(List_UK_Import_from_Production)
    UK_Import_from_Manufacturing = np.sum(List_UK_Import_from_Manufacturing)
    UK_Import_Production_Normalized = ExergyImport('Production', year)/UK_Import_from_Production
    UK_Import_Manufacturing_Normalized = ExergyImport('Manufacturing', year)/UK_Import_from_Manufacturing

    #Exergy (goods) imports into each sec in each Reg:
    for RCode in UK_NUTS2_Import_Exergy_Goods.keys():
        for i in range(0, IO_ss+2):
            production_list = []
            manufacturing_list = []
            for ss in List_Production_ss:
                UK_NUTS2_Import_from_Production = UK_Import_Production_Normalized*UK_NUTS2_Import[RCode][i][0][ss]
                production_list.append(UK_NUTS2_Import_from_Production)
            UK_NUTS2_Import_Exergy_Goods[RCode][i].append(production_list)
      #UK_NUTS2_Import_Exergy_Goods[RCode][i][0] Import from Production
            for ss in List_Manufacturing_ss:
                UK_NUTS2_Import_from_Manufacturing = UK_Import_Manufacturing_Normalized*UK_NUTS2_Import[RCode][i][0][ss]
                manufacturing_list.append(UK_NUTS2_Import_from_Manufacturing)
            UK_NUTS2_Import_Exergy_Goods[RCode][i].append(manufacturing_list)
      #UK_NUTS2_Import_Exergy_Goods[RCode][i][1] Import from Manufacturing
```

```
            UK_NUTS2_Import_Exergy_Goods[RCode][i].append(sum(UK_NUTS2_Import_Exergy_Goods[RCode][i][0])+sum(UK_NUTS2_Import_Exergy_Goods[RCode][i][1]))
            #UK_NUTS2_Import_Exergy_Goods[RCode][i][2] Total exergy imports in goods

    ######################################
    #Exergy (EEC) imports into each sec in each Reg:
    for RCode in UK_NUTS2_Import_Exergy_EEC.keys():
        for i in range(0, IO_ss+2):
            EEC_list = []
            for ss in List_EEC_ss:
                UK_NUTS2_Import_from_EEC = EEC_EURO_RCode[RCode]*(UK_NUTS2_Import[RCode][i][0][ss])
                EEC_list.append(UK_NUTS2_Import_from_EEC)
            UK_NUTS2_Import_Exergy_EEC[RCode][i].append(EEC_list)
      #UK_NUTS2_Import_Exergy_EEC[RCode][i][0] Import from EEC
            EEC_sum = np.sum(UK_NUTS2_Import_Exergy_EEC[RCode][i])
            UK_NUTS2_Import_Exergy_EEC[RCode][i].append(EEC_sum)
            #UK_NUTS2_Import_Exergy_EEC[RCode][i][1] Total exergy imports in EEC

    #Total exergy import into each sec in each Reg
    for RCode in UK_NUTS2_Import_Exergy_Sector.keys():
        ExergyExport_CapitalIn = EEC_EURO_RCode[RCode]*(UK_NUTS2_Export_CapitalIn[RCode][0])
        Region_sum = 0
        i_sum = 0
        for i in range(0, IO_ss+2):
            i_sum = i_sum + UK_NUTS2_Import_Exergy_Goods[RCode][i][2]
            if i == 15:
                UK_NUTS2_Import_Sector = i_sum + UK_NUTS2_Import_Exergy_EEC[RCode][i][1]
            else:
                UK_NUTS2_Import_Sector = i_sum + UK_NUTS2_Import_Exergy_EEC[RCode][i][1]
            UK_NUTS2_Import_Exergy_Sector[RCode][i].append(UK_NUTS2_Import_Sector)
            Region_sum = Region_sum + UK_NUTS2_Import_Sector
        UK_NUTS2_Import_Exergy_Total[RCode].append(Region_sum)
        #UK_NUTS2_Import_Exergy_Sector Total exergy import by region - gives a list

    ######################################
    #Normalized based on total goods export - from Production and Manufacturing sectors only
    List_UK_Export_from_Production = []
    List_UK_Export_from_Manufacturing = []
    for RCode in UK_NUTS2_Export:
        for ss in List_Production_ss:
            List_UK_Export_from_Production.append(UK_NUTS2_Export[RCode][ss][1])
        for ss in List_Manufacturing_ss:
            List_UK_Export_from_Manufacturing.append(UK_NUTS2_Export[RCode][ss][1])
    UK_Export_from_Production = np.sum(List_UK_Export_from_Production)
```

```
    UK_Export_from_Manufacturing = np.sum(List_UK_Export_from_Manufacturing)
    UK_Export_Production_Normalized = ExergyExport('Production', year)/UK_Export_from_Production
    UK_Export_Manufacturing_Normalized = ExergyExport('Manufacturing', year)/UK_Export_from_Manufacturing

    #Exergy (goods) exports from Production and Manufacturing sectors in each Reg:
    for RCode in UK_NUTS2_Export_Exergy_Goods.keys():
        production_list = []
        manufacturing_list = []
        for ss in List_Production_ss:
            UK_NUTS2_Export_from_Production = UK_Export_Production_Normalized*UK_NUTS2_Export[RCode][ss][1]
            production_list.append(UK_NUTS2_Export_from_Production)
        UK_NUTS2_Export_Exergy_Goods[RCode][0].append(production_list)
        UK_NUTS2_Export_Exergy_Goods[RCode][0].append(sum(production_list))
    #UK_NUTS2_Export_Exergy_Goods[RCode][0][1] Total export from Production
        for ss in List_Manufacturing_ss:
            UK_NUTS2_Export_from_Manufacturing = UK_Export_Manufacturing_Normalized*UK_NUTS2_Export[RCode][ss][1]
            manufacturing_list.append(UK_NUTS2_Export_from_Manufacturing)
        UK_NUTS2_Export_Exergy_Goods[RCode][1].append(manufacturing_list)
        UK_NUTS2_Export_Exergy_Goods[RCode][1].append(sum(manufacturing_list))
    #UK_NUTS2_Import_Exergy_Goods[RCode][1][1] Total export from Manufacturing
        UK_NUTS2_Export_Exergy_Goods[RCode][2].append(sum(UK_NUTS2_Export_Exergy_Goods[RCode][0][0])+sum(UK_NUTS2_Export_Exergy_Goods[RCode][1][0]))
        #UK_NUTS2_Export_Exergy_Goods[RCode][2][0] Total exergy exports in goods (from Production and Manufacturing)

    UK_Export_Production_Normalized_LESS = LessIntercityExport_FuelProducts(year)/UK_Export_from_Production
    for RCode in UK_NUTS2_Export_Exergy_Goods_LESS.keys():
        production_list = []
        manufacturing_list = []
        for ss in List_Production_ss:
            UK_NUTS2_Export_from_Production = UK_Export_Production_Normalized_LESS*UK_NUTS2_Export[RCode][ss][1]
            production_list.append(UK_NUTS2_Export_from_Production)
        UK_NUTS2_Export_Exergy_Goods_LESS[RCode][0].append(production_list)
        UK_NUTS2_Export_Exergy_Goods_LESS[RCode][0].append(sum(production_list))
    #UK_NUTS2_Export_Exergy_Goods_LESS[RCode][0][1] Total export from Production
        for ss in List_Manufacturing_ss:
            UK_NUTS2_Export_from_Manufacturing = UK_Export_Manufacturing_Normalized*UK_NUTS2_Export[RCode][ss][1]
            manufacturing_list.append(UK_NUTS2_Export_from_Manufacturing)
        UK_NUTS2_Export_Exergy_Goods_LESS[RCode][1].append(manufacturing_list)
        UK_NUTS2_Export_Exergy_Goods_LESS[RCode][1].append(sum(manufacturing_list))
    #UK_NUTS2_Import_Exergy_Goods_LESS[RCode][1][1] Total export from Manufacturing
        UK_NUTS2_Export_Exergy_Goods_LESS[RCode][2].append(sum(UK_NUTS2_Export_Exergy_Goods_LESS[RCode][0][0])+sum(
```

```
UK_NUTS2_Export_Exergy_Goods_LESS[RCode][1][0]))

  ######################################
  #Exergy (EEC) exports into each sec in each Reg:
  for RCode in UK_NUTS2_Export_Exergy_EEC.keys():
      EEC_list = []
      for ss in List_EEC_ss:
          UK_NUTS2_Export_from_EEC = EEC_EURO_RCode[RCode]*(UK_NUTS2_Export[RCode][ss][1])
          EEC_list.append(UK_NUTS2_Export_from_EEC)
          UK_NUTS2_Export_Exergy_EEC[RCode][ss].append(EEC_list)
    #UK_NUTS2_Import_Exergy_EEC[RCode][i][0] Export from EEC
          EEC_sum = np.sum(UK_NUTS2_Export_Exergy_EEC[RCode][ss])
          UK_NUTS2_Export_Exergy_EEC[RCode][ss].append(EEC_sum)
    #UK_NUTS2_Export_Exergy_EEC[RCode][i][1] Total exergy imports in EEC

  #Total exergy export into each sec in each Reg
  for RCode in UK_NUTS2_Export_Exergy_Sector.keys():
      Region_sum = 0
      for i in range(0, IO_ss):
          i_sum = 0
          if i == 0: #Production export altogether
              i_sum = i_sum + UK_NUTS2_Export_Exergy_Goods[RCode][0][1]
          if i == 2: #Manufacturing export altogether
              i_sum = i_sum + UK_NUTS2_Export_Exergy_Goods[RCode][1][1]
          if i in List_EEC_ss:
              i_sum = i_sum + UK_NUTS2_Export_Exergy_EEC[RCode][i][1]
         # UK_NUTS2_Export_Sector = i_sum + UK_NUTS2_Export_Exergy_EEC[RCode][i][1]
          UK_NUTS2_Export_Exergy_Sector[RCode][i].append(i_sum)
          Region_sum = Region_sum + i_sum
      UK_NUTS2_Export_Exergy_Sector[RCode][14].append(0) #Domestic export = 0
      CF_Exergy_Export = EEC_EURO_RCode[RCode]*(UK_NUTS2_Export[RCode][15][0])
      ExergyImport_CapitalOut = EEC_EURO_RCode[RCode]*(UK_NUTS2_Import_CapitalOut[RCode][0])
      UK_NUTS2_Export_Exergy_Sector[RCode][15].append(CF_Exergy_Export)#+ExergyImport_CapitalOut)
      UK_NUTS2_Export_Exergy_Total[RCode].append(Region_sum+UK_NUTS2_Export_Exergy_Sector[RCode][15][0])
      #UK_NUTS2_Export_Exergy_Sector Total exergy export by region - gives a list

  for RCode in UK_NUTS2_Export_Exergy_Sector_LESS.keys():
      Region_sum = 0
      for i in range(0, IO_ss):
          i_sum = 0
          if i == 0: #Production export altogether
              i_sum = i_sum + UK_NUTS2_Export_Exergy_Goods_LESS[RCode][0][1]
          if i == 2: #Manufacturing export altogether
              i_sum = i_sum + UK_NUTS2_Export_Exergy_Goods_LESS[RCode][1][1]
          if i in List_EEC_ss:
              i_sum = i_sum + UK_NUTS2_Export_Exergy_EEC[RCode][i][1]
          UK_NUTS2_Export_Exergy_Sector_LESS[RCode][i].append(i_sum)
          Region_sum = Region_sum + i_sum
```

```
      UK_NUTS2_Export_Exergy_Sector_LESS[RCode][14].append(0) #Domestic export = 0
      CF_Exergy_Export = EEC_EURO_RCode[RCode]*(UK_NUTS2_Export[RCode][15][0])
      ExergyImport_CapitalOut = EEC_EURO_RCode[RCode]*(UK_NUTS2_Import_CapitalOut[RCode][0])
      UK_NUTS2_Export_Exergy_Sector_LESS[RCode][15].append(CF_Exergy_Export)#+ExergyImport_CapitalOut)
      UK_NUTS2_Export_Exergy_Total_LESS[RCode].append(Region_sum+UK_NUTS2_Export_Exergy_Sector_LESS[RCode][15][0])
      #UK_NUTS2_Export_Exergy_Sector Total exergy export by region - gives a list

  ######################################
  #Sector Exergy Import and Export Total Aggregation
  def UK_AggSec_ExergyImport(RCode):
      UKAggSec_ExergyImport = np.zeros(((1, Total_AG)), float)
      UKAggSec_ExergyImport[0, 0] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[0:2]) #List_Manufacturing_ss
      UKAggSec_ExergyImport[0, 1] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[2:7]) #List_Manufacturing_ss]
      UKAggSec_ExergyImport[0, 2] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[7]) #List_Construction_ss]
      UKAggSec_ExergyImport[0, 3] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[8:11]) #List_Distribution_ss]
      UKAggSec_ExergyImport[0, 4] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[11]) #List_Finance_ss]
      UKAggSec_ExergyImport[0, 5] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[12]) #List_RealEstates_ss]
      UKAggSec_ExergyImport[0, 6] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[13]) #List_OtherServices_ss]
      UKAggSec_ExergyImport[0, 7] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[14]) #List_Domestic_ss]
      UKAggSec_ExergyImport[0, 8] = np.sum(list(UK_NUTS2_Import_Exergy_Sector[RCode].values())[15]) #List_Capital_ss]
      return UKAggSec_ExergyImport

  def UK_AggSec_ExergyExport(RCode):
      UKAggSec_ExergyExport = np.zeros(((1, Total_AG)), float)
      UKAggSec_ExergyExport[0, 0] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[0:2]) #List_Manufacturing_ss
      UKAggSec_ExergyExport[0, 1] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[2:7]) #List_Manufacturing_ss]
      UKAggSec_ExergyExport[0, 2] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[7]) #List_Construction_ss]
      UKAggSec_ExergyExport[0, 3] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[8:11]) #List_Distribution_ss]
      UKAggSec_ExergyExport[0, 4] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[11]) #List_Finance_ss]
      UKAggSec_ExergyExport[0, 5] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[12]) #List_RealEstates_ss]
      UKAggSec_ExergyExport[0, 6] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[13]) #List_OtherServices_ss]
      UKAggSec_ExergyExport[0, 7] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[14]) #List_Domestic_ss]
```

```
        UKAggSec_ExergyExport[0, 8] = np.sum(list(UK_NUTS2_Export_Exergy_Sector[RCode].values())[15]) #List_Capital_ss]
        return UKAggSec_ExergyExport

    def UK_AggSec_ExergyExport_LESS(RCode):
        UKAggSec_ExergyExport_LESS = np.zeros(((1, Total_AG)), float)
        UKAggSec_ExergyExport_LESS[0, 0] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[0:2]) #List_Manufacturing_ss
        UKAggSec_ExergyExport_LESS[0, 1] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[2:7]) #List_Manufacturing_ss]
        UKAggSec_ExergyExport_LESS[0, 2] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[7]) #List_Construction_ss]
        UKAggSec_ExergyExport_LESS[0, 3] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[8:11]) #List_Distribution_ss]
        UKAggSec_ExergyExport_LESS[0, 4] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[11]) #List_Finance_ss]
        UKAggSec_ExergyExport_LESS[0, 5] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[12]) #List_RealEstates_ss]
        UKAggSec_ExergyExport_LESS[0, 6] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[13]) #List_OtherServices_ss]
        UKAggSec_ExergyExport_LESS[0, 7] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[14]) #List_Domestic_ss]
        UKAggSec_ExergyExport_LESS[0, 8] = np.sum(list(UK_NUTS2_Export_Exergy_Sector_LESS[RCode].values())[15]) #List_Capital_ss]
        return UKAggSec_ExergyExport_LESS

    #####################################
    #Intercity imports and exports

    #Exergy (goods) intercity imports into each sec in each Reg:
        for RCode in UK_NUTS2_Intercity_Import_Exergy_Goods.keys():
        for i in range(0, IO_ss+1):
            production_list = []
            manufacturing_list = []
            for ss in List_Production_ss:
                UK_NUTS2_Intercity_Import_from_Production = UK_Import_Production_Normalized*UK_NUTS2_Intercity_Import[RCode][i][0][ss]
                production_list.append(UK_NUTS2_Intercity_Import_from_Production)
            UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i].append(production_list)
      #UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i][0] Intercity Import from Production
            for ss in List_Manufacturing_ss:
                UK_NUTS2_Intercity_Import_from_Manufacturing = UK_Import_Manufacturing_Normalized*UK_NUTS2_Intercity_Import[RCode][i][0][ss]
                manufacturing_list.append(UK_NUTS2_Intercity_Import_from_Manufacturing)
            UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i].append(manufacturing_list)
```

```
      #UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i][1] Import from Manufacturing
            UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i].append(sum(UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i][0])+sum(UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i][1]))

    for RCode in UK_NUTS2_Intercity_Import_Exergy_EEC.keys():
        for i in range(0, IO_ss+2):
            Intercity_EEC_list = []
            for ss in List_EEC_ss:
                UK_NUTS2_Intercity_Import_from_EEC = EEC_EURO_RCode[RCode]*(UK_NUTS2_Intercity_Import[RCode][i][0][ss])
                Intercity_EEC_list.append(UK_NUTS2_Intercity_Import_from_EEC)
            UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i].append(Intercity_EEC_list)
      #UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i][0] Import from EEC
            Intercity_EEC_sum = np.sum(UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i])
            UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i].append(Intercity_EEC_sum)
            #UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i][1] Total exergy imports in EEC

    #Total itnercity exergy import into each sec in each Reg
    for RCode in UK_NUTS2_Intercity_Import_Exergy_Sector.keys():
        Intercity_sum = 0
        for i in range(0, IO_ss+2):
            i_sum = 0
            if i <= IO_ss:
                i_sum = i_sum + UK_NUTS2_Intercity_Import_Exergy_Goods[RCode][i][2]
            UK_NUTS2_Intercity_Import_Sector = i_sum + UK_NUTS2_Intercity_Import_Exergy_EEC[RCode][i][1]
            UK_NUTS2_Intercity_Import_Exergy_Sector[RCode][i].append(UK_NUTS2_Intercity_Import_Sector)
            Intercity_sum = Intercity_sum + UK_NUTS2_Intercity_Import_Sector
        UK_NUTS2_Intercity_Import_Exergy_Total[RCode].append(Intercity_sum)

    List_UK_Intercity_Export_from_Production = []
    List_UK_Intercity_Export_from_Manufacturing = []
    for RCode in UK_NUTS2_Intercity_Export:
        for i in range(0, IO_ss):
            for ss in List_Production_ss:
                List_UK_Intercity_Export_from_Production.append(UK_NUTS2_Intercity_Export[RCode][i][0][ss])
            for ss in List_Manufacturing_ss:
                List_UK_Intercity_Export_from_Manufacturing.append(UK_NUTS2_Intercity_Export[RCode][i][0][ss])
    UK_Intercity_Export_from_Production = np.sum(List_UK_Intercity_Export_from_Production)
    UK_Intercity_Export_from_Manufacturing = np.sum(List_UK_Intercity_Export_from_Manufacturing)

    #Exergy (goods) intercity exports into each sec in each Reg:
```

```python
  UK_Intercity_Export_Production_Normalized = LessIntercityExport_FuelProducts(year)/UK_Intercity_Export_from_Production
  for RCode in UK_NUTS2_Intercity_Export_Exergy_Goods.keys():
      for i in range(0, IO_ss):
          production_list = []
          manufacturing_list = []
          for ss in List_Production_ss:
              UK_NUTS2_Intercity_Export_from_Production = UK_Intercity_Export_Production_Normalized*UK_NUTS2_Intercity_Export[RCode][i][0][ss]
              production_list.append(UK_NUTS2_Intercity_Export_from_Production)
          UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i].append(production_list)
    #UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i][0] Intercity Export from Production
          for ss in List_Manufacturing_ss:
              UK_NUTS2_Intercity_Export_from_Manufacturing = UK_Export_Manufacturing_Normalized*UK_NUTS2_Intercity_Export[RCode][i][0][ss]
              manufacturing_list.append(UK_NUTS2_Intercity_Export_from_Manufacturing)
          UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i].append(manufacturing_list)
    #UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i][1] Export from Manufacturing
          UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i].append(sum(UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i][0])+sum(UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i][1]))

  for RCode in UK_NUTS2_Intercity_Export_Exergy_EEC.keys():
      for i in range(0, IO_ss):
          Intercity_EEC_list = []
          for ss in List_EEC_ss:
              UK_NUTS2_Intercity_Export_from_EEC = EEC_EURO_RCode[RCode]*(UK_NUTS2_Intercity_Export[RCode][i][0][ss])
              Intercity_EEC_list.append(UK_NUTS2_Intercity_Export_from_EEC)
          UK_NUTS2_Intercity_Export_Exergy_EEC[RCode][i].append(Intercity_EEC_list)
    #UK_NUTS2_Intercity_Export_Exergy_EEC[RCode][i][0] Export from EEC
          Intercity_EEC_sum = np.sum(UK_NUTS2_Intercity_Export_Exergy_EEC[RCode][i])
          UK_NUTS2_Intercity_Export_Exergy_EEC[RCode][i].append(Intercity_EEC_sum)
          #UK_NUTS2_Export_Exergy_EEC[RCode][i][1] Total exergy exports in EEC

  #Total intercity exergy export into each sec in each Reg
  for RCode in UK_NUTS2_Intercity_Export_Exergy_Sector.keys():
      Intercity_sum = 0
      for i in range(0, IO_ss):
          i_sum = 0
          if i <= IO_ss:
              i_sum = i_sum + UK_NUTS2_Intercity_Export_Exergy_Goods[RCode][i][2]
          UK_NUTS2_Intercity_Export_Sector = i_sum + UK_NUTS2_Intercity_Export_Exergy_EEC[RCode][i][1]
```

```
            UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][i].append(UK_NUTS2_Intercity_Export_Sector)
            Intercity_sum = Intercity_sum + UK_NUTS2_Intercity_Export_Sector
        Intercity_CF_Exergy_Export = EEC_EURO_RCode[RCode]*(UK_NUTS2_Intercity_Export[RCode][15][0])
        UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][14].append(0) #Domestic export = 0)
        UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][15].append(Intercity_CF_Exergy_Export)
        UK_NUTS2_Intercity_Export_Exergy_Total[RCode].append(Intercity_sum+UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][14][0]+UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][15][0])

    #UK_NUTS2_Intercity - no conversion adjustment
    for RCode in UK_NUTS2_Intercity.keys():
        Intercity_rowIC = np.zeros((1, Total_ss))
        Intercity_colIC = np.zeros((Total_ss, 1))
        for i in range(0, IO_ss+2):
            Intercity_rowIC[0, i] = UK_NUTS2_Intercity_Import_Exergy_Sector[RCode][i][0]
      #Intercity import incl. domestic and CF imports
        Intercity_rowIC[0, IO_ss+1] = UK_NUTS2_Intercity_Import_Exergy_Sector[RCode][IO_ss+1][0]
    #Intercity capital import
        for j in range (0, IO_ss):
            Intercity_colIC[j, 0] = UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][j][0]
      #Intercity export incl. CF exports
        Intercity_colIC[IO_ss+1, 0] = UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][IO_ss+1][0]+UK_NUTS2_Intercity_Export_Exergy_Sector[RCode][15][0]
    #Intercity capital export
        UK_NUTS2_Intercity[RCode].append(Intercity_rowIC)
    #UK_NUTS2_Intercity[RCode][0] intercity import
        UK_NUTS2_Intercity[RCode].append(Intercity_colIC)
    #UK_NUTS2_Intercity[RCode][1] intercity export

    def UK_AggSec_Intercity_ExergyImport(RCode):
        UKAggSec_Intercity_ExergyImport = np.zeros(((1, Total_AG)), float)
        UKAggSec_Intercity_ExergyImport[0, 0] = np.sum(UK_NUTS2_Intercity[RCode][0][0][0:2]) #List_Manufacturing_ss
        UKAggSec_Intercity_ExergyImport[0, 1] = np.sum(UK_NUTS2_Intercity[RCode][0][0][2:7]) #List_Manufacturing_ss]
        UKAggSec_Intercity_ExergyImport[0, 2] = np.sum(UK_NUTS2_Intercity[RCode][0][0][7]) #List_Construction_ss]
        UKAggSec_Intercity_ExergyImport[0, 3] = np.sum(UK_NUTS2_Intercity[RCode][0][0][8:11]) #List_Distribution_ss]
        UKAggSec_Intercity_ExergyImport[0, 4] = np.sum(UK_NUTS2_Intercity[RCode][0][0][11]) #List_Finance_ss]
        UKAggSec_Intercity_ExergyImport[0, 5] = np.sum(UK_NUTS2_Intercity[RCode][0][0][12]) #List_RealEstates_ss]
        UKAggSec_Intercity_ExergyImport[0, 6] = np.sum(UK_NUTS2_Intercity[RCode][0][0][13]) #List_OtherServices_ss]
        UKAggSec_Intercity_ExergyImport[0, 7] = np.sum(UK_NUTS2_Intercity[RCode][0][0][14]) #List_Domestic_ss]
```

```
        UKAggSec_Intercity_ExergyImport[0, 8] = np.sum(UK_NUTS2_Intercity[RCode][0][0][15]) #List_Capital_ss]
        return UKAggSec_Intercity_ExergyImport

    def UK_AggSec_Intercity_ExergyExport(RCode): #year?
        UKAggSec_Intercity_ExergyExport = np.zeros(((1, Total_AG)), float)
        UKAggSec_Intercity_ExergyExport[0, 0] = np.sum(UK_NUTS2_Intercity[RCode][1][0:2]) #List_Manufacturing_ss
        UKAggSec_Intercity_ExergyExport[0, 1] = np.sum(UK_NUTS2_Intercity[RCode][1][2:7]) #List_Manufacturing_ss]
        UKAggSec_Intercity_ExergyExport[0, 2] = np.sum(UK_NUTS2_Intercity[RCode][1][7]) #List_Construction_ss]
        UKAggSec_Intercity_ExergyExport[0, 3] = np.sum(UK_NUTS2_Intercity[RCode][1][8:11]) #List_Distribution_ss]
        UKAggSec_Intercity_ExergyExport[0, 4] = np.sum(UK_NUTS2_Intercity[RCode][1][11]) #List_Finance_ss]
        UKAggSec_Intercity_ExergyExport[0, 5] = np.sum(UK_NUTS2_Intercity[RCode][1][12]) #List_RealEstates_ss]
        UKAggSec_Intercity_ExergyExport[0, 6] = np.sum(UK_NUTS2_Intercity[RCode][1][13]) #List_OtherServices_ss]
        UKAggSec_Intercity_ExergyExport[0, 7] = np.sum(UK_NUTS2_Intercity[RCode][1][14]) #List_Domestic_ss]
        UKAggSec_Intercity_ExergyExport[0, 8] = np.sum(UK_NUTS2_Intercity[RCode][1][15]) #List_Capital_ss]
        return UKAggSec_Intercity_ExergyExport

    #####################################
    #for GVA ratios

    year_col = YearRange.index(year)+7

    AggSec_NUTS2_GVA = {AggSec: {RCode: [] for RCode in List_NUTS2_RCode} for AggSec in List_AggSec}
    for AggSec in List_AggSec:
        for RCode in List_NUTS2_RCode:
            NUTS2_GVA_Sum = 0
            for LAU in NUTS2_LAU_Codes[RCode]:
                for i in range(3, len(df_AggSec_GVA[AggSec][0].iloc[:, 1])):
                    if LAU == df_AggSec_GVA[AggSec][0].iloc[i, 1]:
                        NUTS2_GVA_Sum = NUTS2_GVA_Sum + df_AggSec_GVA[AggSec][0].iloc[i, year_col]
            AggSec_NUTS2_GVA[AggSec][RCode].append(NUTS2_GVA_Sum)

    AggSec_FUA_GVA = {AggSec: {FUA: [] for FUA in List_FUA} for AggSec in List_AggSec}
    for AggSec in List_AggSec:
        for FUA in List_FUA:
            FUA_GVA_Sum = 0
            for LAU in FUA_LAU_Codes[FUA]:
                for i in range(3, len(df_AggSec_GVA[AggSec][0].iloc[:, 1])):
                    if LAU == df_AggSec_GVA[AggSec][0].iloc[i, 1]:
                        FUA_GVA_Sum = FUA_GVA_Sum + df_AggSec_GVA[AggSec][0].iloc[i, year_col]
            AggSec_FUA_GVA[AggSec][FUA].append(FUA_GVA_Sum)
```

```
  AggSec_LAU_GVA = {AggSec: {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in List_FUA} for AggSec in List_AggSec}
  for AggSec in List_AggSec:
      for FUA in List_FUA:
          for LAU in FUA_LAU_Codes[FUA]:
              for i in range(3, len(df_AggSec_GVA[AggSec][0].iloc[:, 1])):
                  if LAU == df_AggSec_GVA[AggSec][0].iloc[i, 1]:
                      LAU_GVA = df_AggSec_GVA[AggSec][0].iloc[i, year_col]
              AggSec_LAU_GVA[AggSec][FUA][LAU].append(LAU_GVA)

  AggSec_LAU_GVA_Ratio = {AggSec: {FUA: {LAU: [] for LAU in FUA_LAU_Codes[FUA]} for FUA in List_FUA} for AggSec in List_AggSec}
  for AggSec in List_AggSec:
      for FUA in List_FUA:
          for LAU in FUA_LAU_Codes[FUA]:
              for rcode, lau_rlist in NUTS2_LAU_Codes.items():
                  if LAU in lau_rlist:
                      AggSec_LAU_GVA_Ratio[AggSec][FUA][LAU].append((AggSec_LAU_GVA[AggSec][FUA][LAU][0])/(AggSec_NUTS2_GVA[AggSec][rcode][0]))
  for FUA in List_FUA:
      AggSec1 = 'GHI Distribution'
      AggSec2 = 'J Information'
      for LAU in FUA_LAU_Codes[FUA]:
          for rcode, lau_rlist in NUTS2_LAU_Codes.items():
              if LAU in lau_rlist:
                  CombineGVA = (AggSec_LAU_GVA[AggSec1][FUA][LAU][0]+AggSec_LAU_GVA[AggSec2][FUA][LAU][0])/(AggSec_NUTS2_GVA[AggSec1][rcode][0]+AggSec_NUTS2_GVA[AggSec2][rcode][0])
          AggSec_LAU_GVA_Ratio['GHI Distribution'][FUA][LAU][0] = (CombineGVA)
  AggSec_LAU_GVA_Ratio['GHIJ Distribution'] = AggSec_LAU_GVA_Ratio.pop('GHI Distribution')
  del AggSec_LAU_GVA_Ratio['J Information']
  for FUA in List_FUA:
      AggSec1 = 'MN Professional'
      AggSec2 = 'OPQ Public services'
      AggSec3 = 'RST Other services'
      for LAU in FUA_LAU_Codes[FUA]:
          for rcode, lau_rlist in NUTS2_LAU_Codes.items():
              if LAU in lau_rlist:
                  CombineGVA = (AggSec_LAU_GVA[AggSec1][FUA][LAU][0]+AggSec_LAU_GVA[AggSec2][FUA][LAU][0]+AggSec_LAU_GVA[AggSec3][FUA][LAU][0])/(AggSec_NUTS2_GVA[AggSec1][rcode][0]+AggSec_NUTS2_GVA[AggSec2][rcode][0]+AggSec_NUTS2_GVA[AggSec3][rcode][0])
          AggSec_LAU_GVA_Ratio['MN Professional'][FUA][LAU][0] = (CombineGVA)
  AggSec_LAU_GVA_Ratio['MNOPQRST Other services'] = AggSec_LAU_GVA_Ratio.pop('MN Professional')
  del AggSec_LAU_GVA_Ratio['OPQ Public services']
  del AggSec_LAU_GVA_Ratio['RST Other services']

  AggSec_FUA_GVA_Ratio = {AggSec: {FUA: {RCode: [] for RCode in FUA_NUTS2_RCode[FUA]} for FUA in List_FUA} for AggSec in List_AggSec}
  for AggSec in List_AggSec:
      for FUA in List_FUA:
```

```
            for RCode in FUA_NUTS2_RCode[FUA]:
                lau_rcode_sum = 0
                for LAU in FUA_LAU_Codes[FUA]:
                    if LAU in NUTS2_LAU_Codes[RCode]:
                        lau_rcode_sum = lau_rcode_sum + AggSec_LAU_GVA[AggSec][
FUA][LAU][0]
                AggSec_FUA_GVA_Ratio[AggSec][FUA][RCode].append(lau_rcode_sum/
AggSec_NUTS2_GVA[AggSec][RCode][0])

    for FUA in List_FUA:
        for RCode in FUA_NUTS2_RCode[FUA]:
            lau_rcode_sum = 0
            total_rcode_sum = 0
            for AggSec in ['GHI Distribution', 'J Information']:
                for LAU in FUA_LAU_Codes[FUA]:
                    if LAU in NUTS2_LAU_Codes[RCode]:
                        lau_rcode_sum = lau_rcode_sum + AggSec_LAU_GVA[AggSec][
FUA][LAU][0]
                total_rcode_sum = total_rcode_sum + AggSec_NUTS2_GVA[AggSec][
RCode][0]
            AggSec_FUA_GVA_Ratio['GHI Distribution'][FUA][RCode][0] = (
lau_rcode_sum/total_rcode_sum)
    AggSec_FUA_GVA_Ratio['GHIJ Distribution'] = AggSec_FUA_GVA_Ratio.pop('GHI
Distribution')
    del AggSec_FUA_GVA_Ratio['J Information']
    for FUA in List_FUA:
        for RCode in FUA_NUTS2_RCode[FUA]:
            lau_rcode_sum = 0
            total_rcode_sum = 0
            for AggSec in ['MN Professional', 'OPQ Public services', 'RST Other
services']:
                for LAU in FUA_LAU_Codes[FUA]:
                    if LAU in NUTS2_LAU_Codes[RCode]:
                        lau_rcode_sum = lau_rcode_sum + AggSec_LAU_GVA[AggSec][
FUA][LAU][0]
                total_rcode_sum = total_rcode_sum + AggSec_NUTS2_GVA[AggSec][
RCode][0]
            AggSec_FUA_GVA_Ratio['MN Professional'][FUA][RCode][0] = (
lau_rcode_sum/total_rcode_sum)
    AggSec_FUA_GVA_Ratio['MNOPQRST Other services'] = AggSec_FUA_GVA_Ratio.pop('
MN Professional')
    del AggSec_FUA_GVA_Ratio['OPQ Public services']
    del AggSec_FUA_GVA_Ratio['RST Other services']

    #####################################
    # for UK_FUA

    def UK_FUA_ExergyImport(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        FUA_ExergyImport = np.zeros((1, 10))
        for i in range(0, 7):
            for RCode in RCode_in_FUA:
                FUA_ExergyImport[0, i] = FUA_ExergyImport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[i]][FUA][RCode][0]*
```

```
UK_AggSec_ExergyImport(RCode)[0,i])
        for i in range(7, 10):
            for RCode in RCode_in_FUA:
                FUA_ExergyImport[0, i] = FUA_ExergyImport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0]*
UK_AggSec_ExergyImport(RCode)[0,i])
        return FUA_ExergyImport

    def UK_FUA_ExergyExport(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        FUA_ExergyExport = np.zeros((1, 10))
        for i in range(0, 7):
            for RCode in RCode_in_FUA:
                FUA_ExergyExport[0, i] = FUA_ExergyExport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[i]][FUA][RCode][0]*
UK_AggSec_ExergyExport(RCode)[0,i])
        for i in range(7, 10):
            for RCode in RCode_in_FUA:
                FUA_ExergyExport[0, i] = FUA_ExergyExport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0]*
UK_AggSec_ExergyExport(RCode)[0,i])
        return np.transpose(FUA_ExergyExport)

    #EEL FUA Scaling
    def UK_FUA_EEL(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        EEL = np.zeros((1, 10))
        for RCode in RCode_in_FUA:
            EEL_RCode = EEA.EEL_AggSec_RCode(year, RCode)
            for i in range(0, 7):
                EEL[0, i] = EEL[0, i] + (AggSec_FUA_GVA_Ratio[List_AggSec_Combine
[i]][FUA][RCode][0]*EEL_RCode[0,i])
        return EEL

    def UK_FUA_Intercity_ExergyImport(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        FUA_Intercity_ExergyImport = np.zeros((1, 10))
        for i in range(0, 7):
            for RCode in RCode_in_FUA:
                FUA_Intercity_ExergyImport[0, i] = FUA_Intercity_ExergyImport[0,
i] + (AggSec_FUA_GVA_Ratio[List_AggSec_Combine[i]][FUA][RCode][0]*
UK_AggSec_Intercity_ExergyImport(RCode)[0,i])
        for i in range(7, 10):
            for RCode in RCode_in_FUA:
                FUA_Intercity_ExergyImport[0, i] = FUA_Intercity_ExergyImport[0,
i] + (AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0]*
UK_AggSec_Intercity_ExergyImport(RCode)[0,i])
        return FUA_Intercity_ExergyImport

    def UK_FUA_Intercity_ExergyExport(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        FUA_Intercity_ExergyExport = np.zeros((1, 10))
        for i in range(0, 7):
            for RCode in RCode_in_FUA:
```

```
                FUA_Intercity_ExergyExport[0, i] = FUA_Intercity_ExergyExport[0,
i] + (AggSec_FUA_GVA_Ratio[List_AggSec_Combine[i]][FUA][RCode][0]*
UK_AggSec_Intercity_ExergyExport(RCode)[0,i])
        for i in range(7, 10):
            for RCode in RCode_in_FUA:
                FUA_Intercity_ExergyExport[0, i] = FUA_Intercity_ExergyExport[0,
i] + (AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0]*
UK_AggSec_Intercity_ExergyExport(RCode)[0,i])
        return np.transpose(FUA_Intercity_ExergyExport)

    def UK_FUA_ExergyExport_LESS(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        FUA_ExergyExport = np.zeros((1, 10))
        for i in range(0, 7):
            for RCode in RCode_in_FUA:
                FUA_ExergyExport[0, i] = FUA_ExergyExport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[i]][FUA][RCode][0]*
UK_AggSec_ExergyExport_LESS(RCode)[0,i])
        for i in range(7, 10):
            for RCode in RCode_in_FUA:
                FUA_ExergyExport[0, i] = FUA_ExergyExport[0, i] + (
AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0]*
UK_AggSec_ExergyExport_LESS(RCode)[0,i])
        return np.transpose(FUA_ExergyExport)

    def UK_FUA_ExergyImport_CapitalOut(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        CapitalOut = 0
        for RCode in RCode_in_FUA:
            CapitalOut = CapitalOut + EEC_EURO_RCode[RCode]*(
UK_NUTS2_Import_CapitalOut[RCode][0]+UK_NUTS2_Intercity_Import_CapitalOut[RCode
][0])*(AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0])
        return CapitalOut

    def UK_FUA_ExergyExport_CapitalIn(FUA):
        RCode_in_FUA = Find_RCode_from_FUA(FUA)
        CapitalIn = 0
        for RCode in RCode_in_FUA:
            CapitalIn = CapitalIn + EEC_EURO_RCode[RCode]*(
UK_NUTS2_Export_CapitalIn[RCode][0]+UK_NUTS2_Intercity_Export_CapitalIn[RCode
][0])*(AggSec_FUA_GVA_Ratio[List_AggSec_Combine[7]][FUA][RCode][0])
        return CapitalIn

    def UK_FUA_IntraIO_AggSec_TotalExergy(FUA):
        FUA_IntraIO_AggSec = np.zeros((10, 10))
        IOMatrix = UK_FUA_IntraIO_AggSec_NormalizedMatrix(FUA)
        Import = UK_FUA_ExergyImport(FUA) + UK_FUA_Intercity_ExergyImport(FUA)
        Export = UK_FUA_ExergyExport(FUA) + UK_FUA_Intercity_ExergyExport(FUA)
        Net_vector = Import - Export.T
        if Net_vector[0, 0] <= 0 or Net_vector[0, 1] <= 0 :
            Export = UK_FUA_ExergyExport_LESS(FUA) +
UK_FUA_Intercity_ExergyExport(FUA)
        for i in range(0, 9): #row
            for j in range(0, 9): #col
```

```
              FUA_IntraIO_AggSec[i, j] = (Import - Export.T)[0, i]*IOMatrix[i, j]
      EEL_row = UK_FUA_EEL(FUA)
      for k in range (0, 9):
          FUA_IntraIO_AggSec[7, k] = EEL_row[0, k]
      for m in range (0, 9):
          FUA_IntraIO_AggSec[9, m] = Import[0, m]
          FUA_IntraIO_AggSec[m, 9] = Export[m, 0]
      FUA_IntraIO_AggSec[9, 8] = FUA_IntraIO_AggSec[9, 8] + UK_FUA_ExergyExport_CapitalIn(FUA) #Capital IN
      FUA_IntraIO_AggSec[8, 9] = FUA_IntraIO_AggSec[8, 9] + UK_FUA_ExergyImport_CapitalOut(FUA) #Capital OUT
      return FUA_IntraIO_AggSec


#####################################
  for FUA in List_FUA:
      Import = UK_FUA_ExergyImport(FUA)[0].tolist()
      Import_Sum = np.sum(Import)
      Intercity_Import = UK_FUA_Intercity_ExergyImport(FUA)[0].tolist()
      Intercity_Import_Sum = np.sum(Intercity_Import)
      Total_Import = (UK_FUA_ExergyImport(FUA) + UK_FUA_Intercity_ExergyImport(FUA))[0].tolist()
      Total_Import_Sum = np.sum(Total_Import)

      Export = UK_FUA_ExergyExport(FUA).T[0].tolist()
      Export_Sum = np.sum(Export)
      Intercity_Export = UK_FUA_Intercity_ExergyExport(FUA).T[0].tolist()
      Intercity_Export_Sum = np.sum(Intercity_Export)
      Total_Export = (UK_FUA_ExergyExport(FUA) + UK_FUA_Intercity_ExergyExport(FUA)).T[0].tolist()
      Total_Export_Sum = np.sum(Total_Export)

      with open(r'44osnea_fua_import.txt', 'a') as save_fua_import:
          print(year, 'FUA', ' ', FUA, Import, Import_Sum, Intercity_Import, Intercity_Import_Sum, Total_Import, Total_Import_Sum, file = save_fua_import)
      with open(r'44osnea_fua_export.txt', 'a') as save_fua_export:
          print(year, 'FUA', ' ', FUA, Export, Export_Sum, Intercity_Export, Intercity_Export_Sum, Total_Export, Total_Export_Sum, file = save_fua_export)

      M = np.copy(UK_FUA_IntraIO_AggSec_TotalExergy(FUA))
      N = len(M) - 2
      TiM =  M.sum(axis = 0)
      M_diag = np.copy(M)
      for i in range(0, len(M)):
          M_diag[i, i] = 0
      TjM = M_diag.sum(axis = 1)

      Exergy_efficiency = np.zeros((1, len(M)-2))
      for i in range(0, (len(M)-2)):
          Exergy_efficiency[0, i] = TjM[i]/TiM[i]
      Efficiency_mean = np.mean(Exergy_efficiency[0])

      with open(r'44osnea_fua_efficiency.txt', 'a') as save_fua_efficiency:
```

```
            print(year, 'FUA', ' ', FUA, Exergy_efficiency[0].tolist(),
Efficiency_mean, file = save_fua_efficiency)

        Diff = np.subtract(np.transpose(TiM), TjM)
        DiffN = np.reshape(Diff[0:N], (N, 1))
        DiffN = np.vstack((DiffN, (np.zeros((2, 1)))))

        MD = np.c_[M, DiffN]
        MD = np.vstack([MD, np.zeros((1, len(M)+1))])

        EEC_gen = M[N+1, N] - M[N, N+1]
        Exergy_gen = EEC_gen
        Exergy_in = M[N+1, :].sum()
        Exergy_waste = EEA.EI_GHG(year)*M[:, 0].sum()
        Exergy_des = sum(DiffN[0:N]) - Exergy_waste
        Exergy_out = M[0:N, N+1].sum()
        FD_out = M[N, N+1] - UK_FUA_ExergyImport_CapitalOut(FUA)

        Eff_utl = Exergy_des / Exergy_in
        Eff_cov = (Exergy_out + Exergy_gen + FD_out ) / Exergy_in

        with open(r'44osnea_fua.txt', 'a') as save_fua:
            print(year, 'FUA', ' ', FUA, Eff_utl[0], Eff_cov, file = save_fua)
```

Appendix 7: Dendrogram and clustermap for clustering analysis

The following dendrograms presented are used to identify the clustering hierarchy among the FUAs. The dendrograms in Figures A7.1 and A7.2 are produced based on the Euclidean distance between the FUAs in terms of their overall R and θ values.

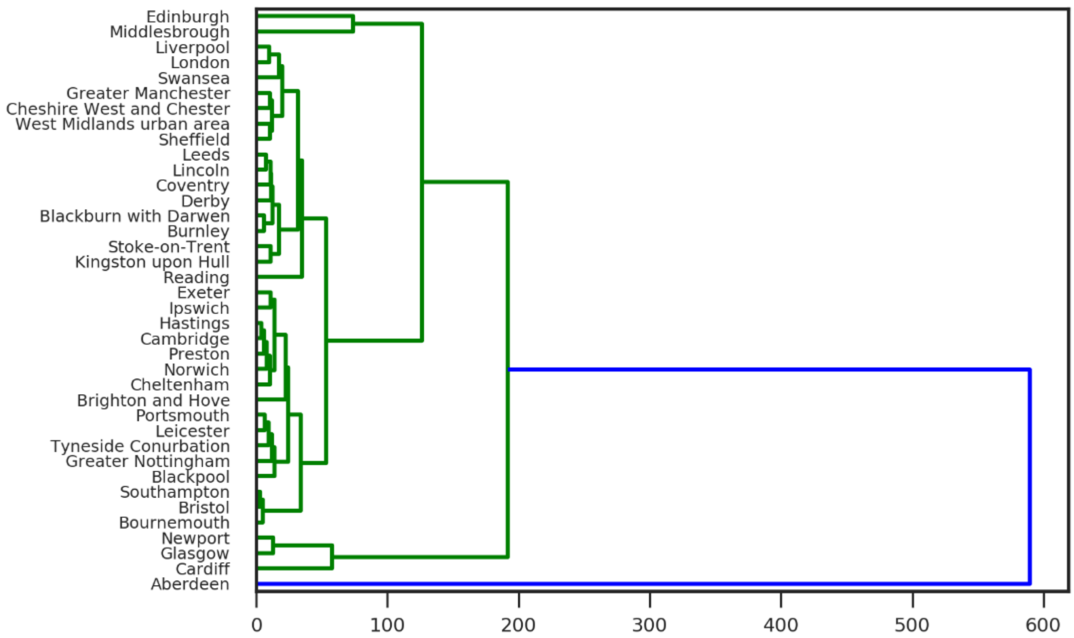

Figure A7.1: Dendrogram for clustering classificatio showing the clustering hierarchy based on the pairwise Euclidean θ values, averaging across all years, that shows that Aberdeen has very different behaviour in comparison to other FUAs due to lower smaller θ values at distance > 200°.

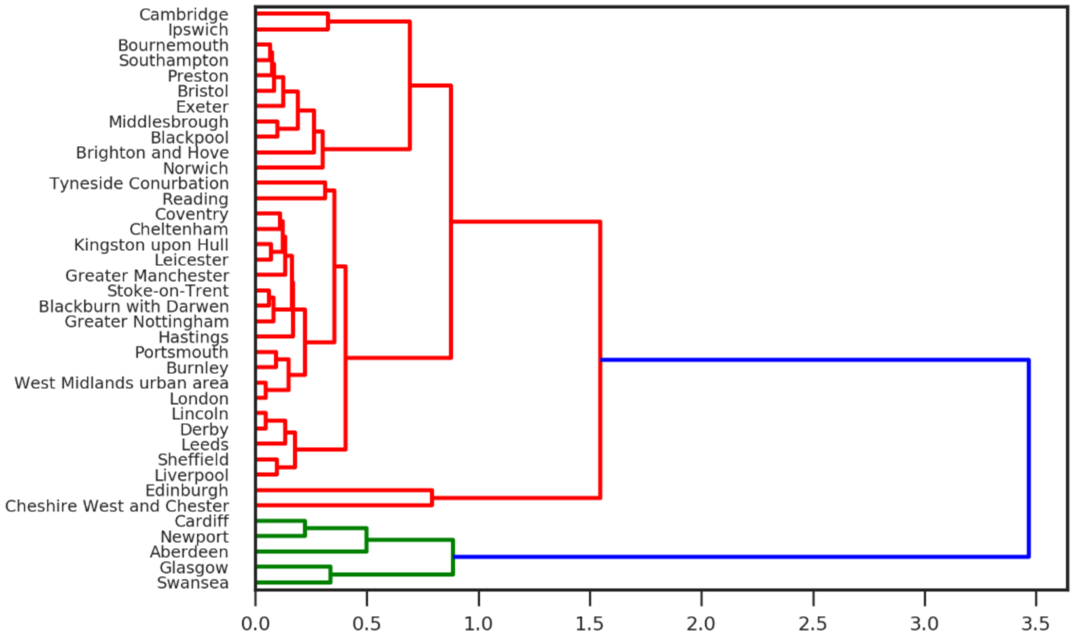

Figure A7.2: Dendrogram for clustering classification showing the clustering hierarchy based on the pairwise Euclidean distance for R values, averaging across all years, that gives four other clusters at distance > 0.9.

For more details, see Figure A7.3 for the clustermap of the average pairwise Euclidean θ values and Figure A7.4 for the clustermap of the average pairwise Euclidean R values.

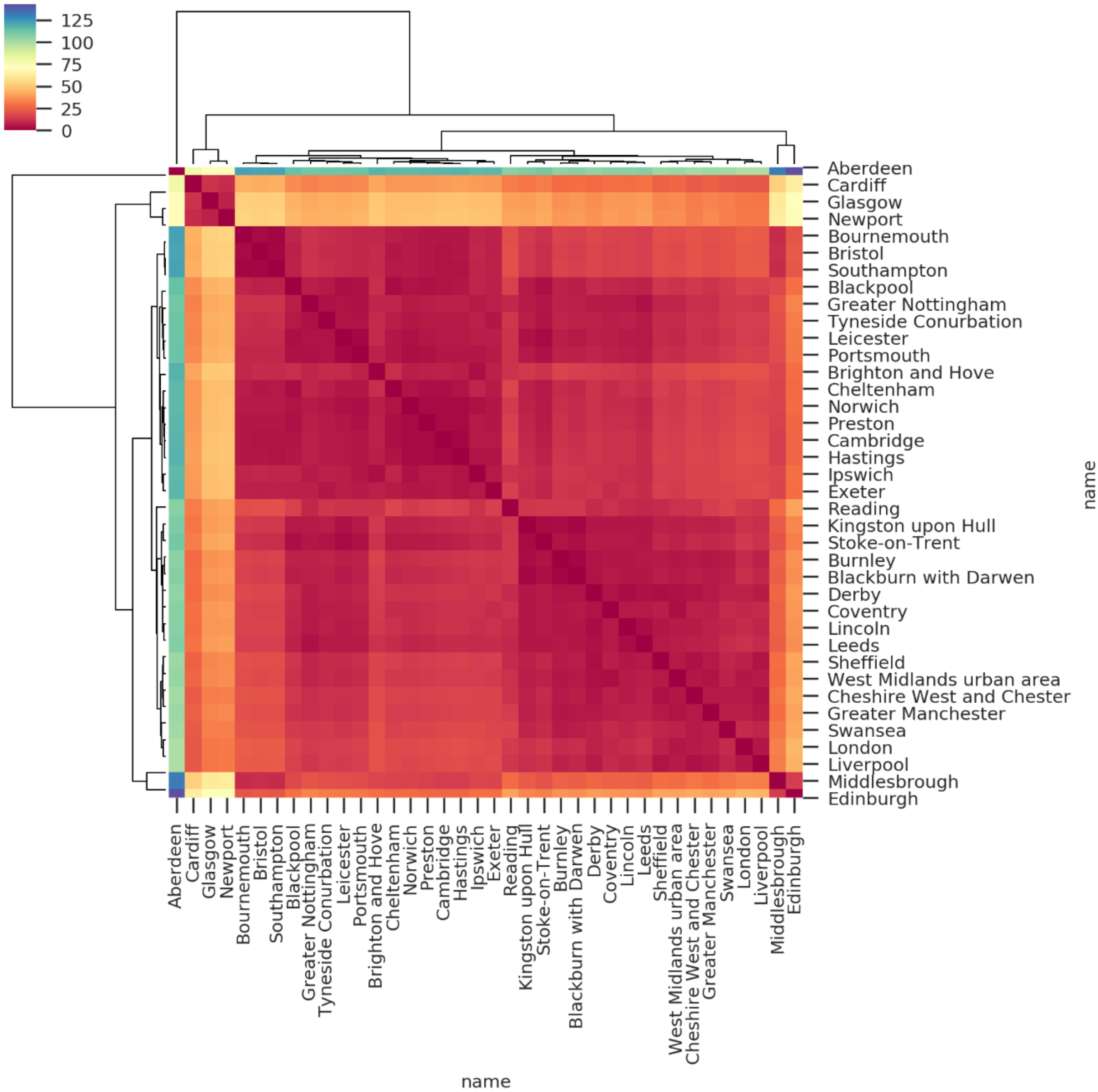

Figure A7.3: Clustermap of the average pairwise Euclidean θ values across the years.

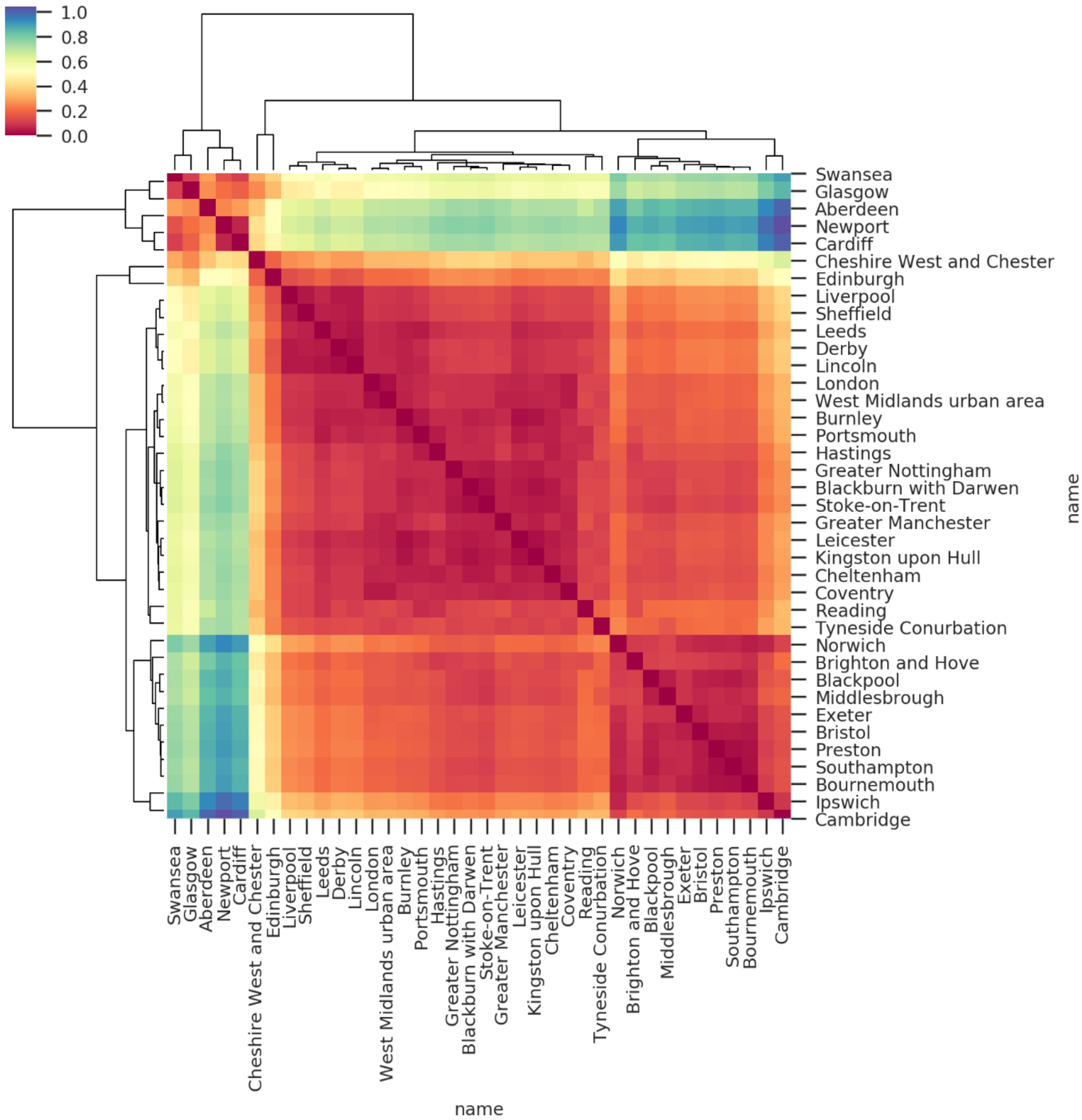

Figure A7.4: Clustermap of the average pairwise Euclidean R values across the years.